



Management of the London Basin Chalk Aquifer

Status Report – 2018

August 2018

Foreword

We are the Environment Agency. It's our job to look after your environment and make it a better place - for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Contents

Introduction	1
1 Overview of the London Basin Aquifer	1
2 Why we need to manage groundwater levels	5
3 How we manage groundwater levels.....	6
4 Recent abstraction trends	9
5 Groundwater levels for January 2017.....	12
Recent Changes in Groundwater Levels	13
Long Term Changes in Groundwater Levels.....	13
6 Current licensing strategy	20
7 Open loop ground source heating and cooling (GSHC) schemes status	26
8 Conclusions	30
9 References	31

Figures

Figure 1 Area of the London Basin.....	1
Figure 2 Bedrock Geology and faults of the London Basin.....	4
Figure 3 Observation Borehole Network in the London Basin	7
Figure 4 Active and Historic Key Wells in the London Basin.....	8
Figure 5 Total Annual Water Company Abstraction in 2017	10
Figure 6 Water Company Licensed Abstraction from the London Basin Chalk Aquifer.....	10
Figure 7 Difference between Water Company Total Abstractions 2016-2017.....	11
Figure 8 Recharge Scheme Operation.....	11
Figure 9 Monitored Groundwater Levels for January 2000.....	15
Figure 10 Monitored Groundwater levels in January 2017	16
Figure 11 Groundwater Level Contours for January 2018	17
Figure 12 Change in Groundwater Levels between January 2018 and January 2017	18
Figure 13 Change in Groundwater Levels between January 2018 and January 2000	19
Figure 14 Watertable Geology Maps for 1965, 2000, 2017 and 2018.....	23
Figure 15 London Licensing Policy Map 2018	24
Figure 16 Hydrographs from Key Wells at different Areas in London.	25
Figure 17 London Open-loop Ground Source Heating and Cooling Systems Status 2017 .	28
Figure 18 Temperature Monitoring within the Chalk of Central London from 2010 to 2017 .	29

Introduction

The Environment Agency produces an annual report on the state of groundwater levels in the Chalk aquifer beneath London. This is the twenty-seventh such report (previously called ‘Groundwater Levels in the Chalk-Basal Sands Aquifer of the London Basin’). The study area for this report is shown in Figure 1.

The reports were started in the 1990s to record the rise in groundwater levels, resulting from a significant reduction in groundwater abstraction from the Chalk aquifer since the mid-1960s. In the early 2000s the rising groundwater level trend slowed and the levels stabilised in many parts of London. Since then it is observed that Chalk groundwater levels are again locally falling, owing to increased abstraction and dewatering pressure. Parts of Chalk at the centre of the London Basin also remain unsaturated. The recent reports aim to report the changes to the abstraction regime and its influence on groundwater levels in the past year using monitoring data, and review and update the London groundwater abstraction licensing strategy.

Groundwater levels in the London Basin Chalk Aquifer need careful management to safeguard the aquifer as a sustainable, secure and high quality water resource, and to protect infrastructure from flooding and potential structural damage. Details of our management approach for the London Basin aquifer are included in Chapters 0 and 3. Chapters 4 and 5 summarise the recent changes in abstraction volume and groundwater level, and discuss areas where significant changes have been observed. Chapter 6 then sets out the licensing strategy. Chapter 7 discusses our approach to manage impacts of Ground Source Heating and Cooling (GSHC) schemes in the London Basin.

1 Overview of the London Basin Aquifer

The structure and hydrogeology of the London Basin Aquifer are subjects to a large volume of studies and are well reported. This chapter provides a brief synthesis of the features integral to our groundwater management approach. A list of references for further reading is included at the end of this report.

The bedrock geology of the London Basin is shown in Table 1. Table 1 shows the geological formations found within the London Basin, the geological age that they were formed and their typical thickness.

Table 1 Geology of the London Basin

Era	Group	Formation	Thickness (m)
Palaeogene	Bracklesham	Barton Sand Bagshot	10–25
	Thames	London Clay (including Claygate Member)	30-90
		Harwich	0-10
	Lambeth	Woolwich and Reading Beds	10-20
		Upnor	5-7
	Montrose	Thanet	0-30
Cretaceous	Chalk		180-245

Modified from Ellison, et al., 2004 and <http://www.bgs.ac.uk/lexicon/>

As Table 1 shows, the Cretaceous sediments of the Chalk Group are overlain by Palaeogene deposits of Thanet Formation, which consists of fine sand; the Lambeth Group, comprising sands, silts and clays; and Harwich Formation, comprising sands and gravels. Overlying the Harwich Formation is London Clay Formation, a dense blue/grey fissured clay. The Bracklesham Group which include the Bagshot Formation overlie the London Clay. Approximately half of the surface of the London Basin's bedrock is formed by these younger deposits.

These deposits form the London Basin Syncline, which is asymmetric in shape. The northern limb of the syncline dips at around 1 degree to the south east, from its high point in the Chilterns. The southern limb in places dips towards the north at up to 55 degrees at the Hogsback near Guildford in Surrey, decreasing in an easterly direction to 18 degrees at Gomshall and then to 1 degree at Dorking. This asymmetry could also be observed in folding

structure: in the northern part of the basin structural contours indicate gentle, low amplitude and long wavelength folding, whilst in the south folding is more numerous, higher in amplitude and shorter in wavelength. The depth to chalk varies significantly across the London Basin: The Chalk is buried deep under high ground such as Hampstead, Highgate, Wimbledon and Blackheath, but is brought to shallow depths within the basin in the Lee Valley, or to outcrop at Deptford, Lewisham, and near the River Thames from Greenwich to Woolwich.

The Chalk, combined with the Thanet Formation and the Upnor Formation, make up the Chalk-Basal Sands aquifer of the London Basin. As the main groundwater storage unit, the Chalk is a low storage, high transmissivity aquifer comprising dual porosity, with flow and storage occurring both in the fractures and in the matrix. Most flow occurs in the fractures with storage in the matrix, released to the fractures as the groundwater level falls.

Variation in burial depth described earlier is an important control of the hydraulic properties of the Chalk in the London Basin. In the southwest part of the London Basin where depth to Chalk is often in excess of 100 m from surface, the Chalk has much lower transmissivity, whilst under the valleys of the rivers Thames and Lee, where the Chalk is at shallow depth, or at surface, high transmissivity corridors are present.

The Chalk is concealed in the basin by the overlying Tertiary formations, which means recharge largely occurs in areas of outcrop: the Chilterns to the north and northwest, and the North Downs to the south (Figure 2). The natural areas of groundwater discharge near the centre of the Basin would be areas of chalk outcrop, such as in the River Thames area from Greenwich to Woolwich, and where chalk groundwater could discharge through the Lambeth Group sediments to the surface, such as in Hackney and the Lee Valley. However, as a result of historic and current abstraction, the reduction in groundwater levels means that there is no longer a significant natural groundwater outlet in the centre of the London Basin. Instead, saline river water from the tidal Thames interacts with Chalk groundwater at the outcrop from Greenwich to Woolwich, leading to risk of saline intrusion.

The London Clay Formation confines the Chalk and Lower Palaeogene Formations when these are fully saturated and the groundwater is flowing under pressure. As groundwater pressure increases on the London Clay Formation, it is slowly saturated, and unevenly deforms. The London Clay Formation is also extensively fissured locally, and rapid ingress of groundwater at higher elevations is possible on a small scale (CIRIA, 1989). Re-saturation of the London Clay Formation as a result of these mechanisms could affect the stability of certain foundations and deep basements, and cause ingress of water into buried service tunnels and underground lines (CIRIA, 1989). On the other hand, further abstraction from the Chalk may lead to repeated aerating and rewetting of the Sandy deposits in the Lower Palaeogene Formations, either by seepage from consolidation of the London Clay (Rainey and Rosenbaum, 1989), or fluctuating watertable between the top of the Chalk and Basal Sands (Kinniburgh et al., 1994). This creates favourable conditions for pyrite oxidation, which releases sulphate-rich, acidic groundwater (Bierens de Haan et al., 1994; Kinniburgh et al., 1994), and has led to incidents of corrosion to tunnel linings (Rainey and Rosenbaum, 1989). There is also concern over the impact of such acidic drainage to the Chalk groundwater quality and the integrity of the Chalk matrix, although this is an area where further research is required.

In 2008 the British Geological Survey (BGS) completed a geological study of the London Basin for the Environment Agency (Royse, 2008). In the central basin area the study proposed a new interpretation of the fault pattern (Figure 2). Faulting often alters the hydraulic properties of Chalk: both to increase and decrease permeability. Where boreholes with groundwater level data were present either side of the major faults identified in the BGS study, these were analysed to confirm whether these faults act as groundwater flow barriers (Figure 2).

This analysis suggests that:

- Greenwich Fault, Rotherhithe Fault and Mitcham Fault at the centre of the Basin are likely flow barriers.
- Whilst there is no evidence for Wimbledon and Streatham to impede the groundwater flow, flow barrier exists along the Streatham Fault towards the east.
- For the Northern Boundary Fault, hydrographs on either side of the fault show similar trends and water levels, suggesting that the fault may not act as a barrier. However, the lack of a steep horizontal hydraulic gradient across the western part of this fault may be a result of the local direction of groundwater flow, and flow across this fault may be restricted here. Nevertheless, the small faults branching to the south of the main Northern Boundary Fault appear to act as barriers.
- The Sutton Fault has been inferred on the basis of a large difference in groundwater levels over a small area at the southern boundary of the confined Basin, and does not feature in the interpretation of the BGS Chalk model. The steep hydraulic gradient across the Sutton fault appears to suggest that it acts as a barrier.

Legend

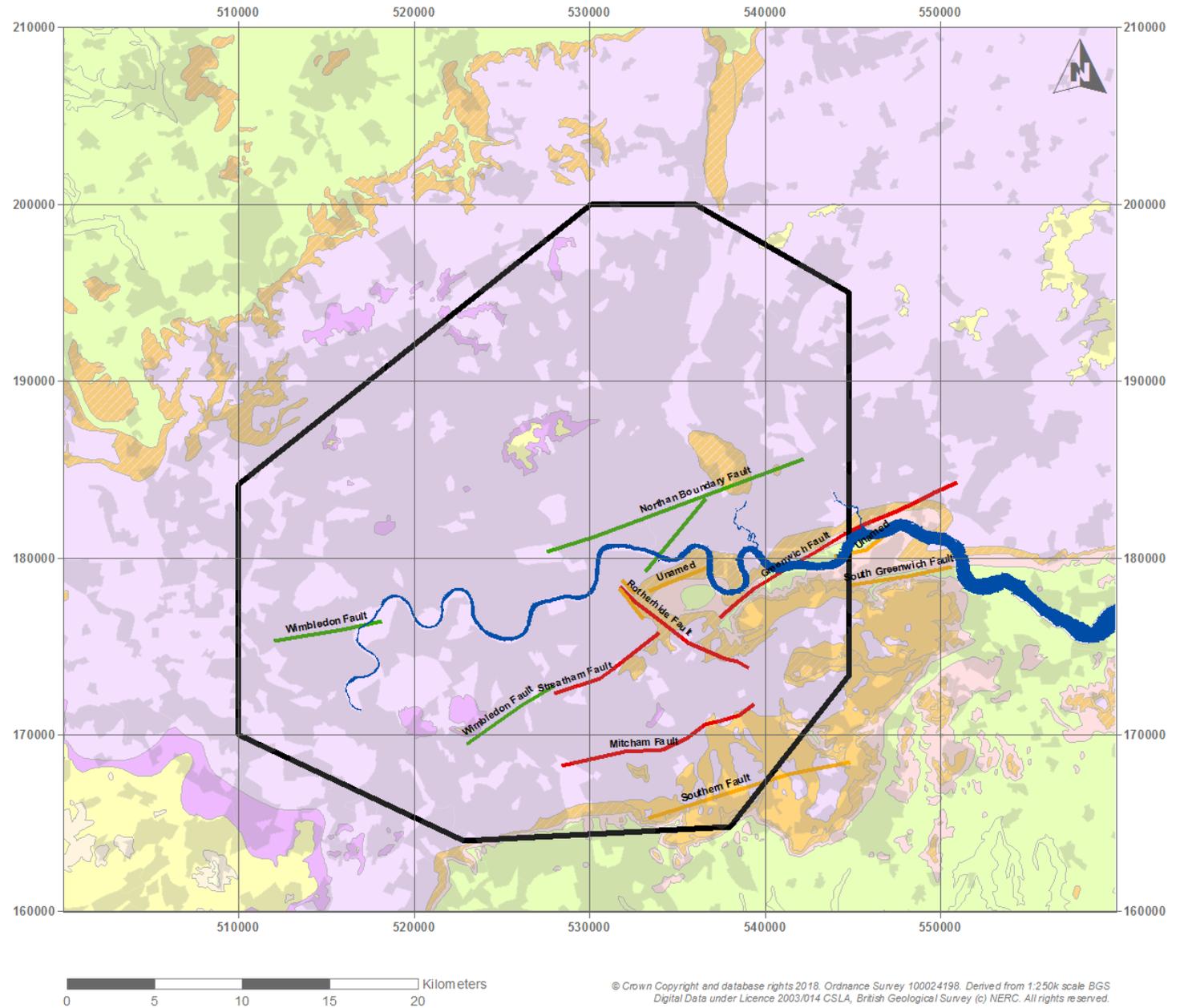
- River Thames
- Urban Areas
- Basin Study Area

London Chalk Faults

- Impermeable
- Permeable
- Uncertain

Bedrock Geology

- Bracklesham Group
- Barton Sand Formation
- Bagshot Formation
- Claygate Member
- London Clay Formation
- Harwich Formation
- Lambeth Group
- Thanet Sand Formation
- Chalk Formation



© Crown Copyright and database rights 2018. Ordnance Survey 100024198. Derived from 1:250k scale BGS Digital Data under Licence 2003/014 CSLA, British Geological Survey (c) NERC. All rights reserved.

Figure 2 Bedrock Geology and faults of the London Basin

2 Why we need to manage groundwater levels

During the 19th century and first part of the 20th century, the Chalk aquifer had been increasingly exploited, as a result of increased industrialisation and the associated development of groundwater sources. At the peak of abstraction in the 1960s, groundwater levels beneath central London had dropped to 88 metres below sea level, creating a large depression in the water table.

Since the mid-1960s industries in central London relocated or were closed down and business turned more to commerce than heavy industry. The subsequent reduction in abstraction resulted in a gradual rebound of the water table as groundwater levels recovered. The continuous rise of groundwater levels posed threat to structures in the London Basin, such as London Underground and building foundations. In response, the General Aquifer Research, Development and Investigation Team (GARDIT) implemented a strategy to control water levels in 1992. Numerous large public water supply abstractions were licensed to Thames Water under the strategy, in order to slow the rise in groundwater levels and eventually stabilise them. These additional abstractions came into operation in the late 1990s with further abstractions developed through until 2004.

The GARDIT strategy did result in significant additional abstraction volumes to assist with the management of groundwater levels. We have observed that since 2000 groundwater levels have become more stable; where the deep cone of depression from historic abstraction has recovered, groundwater gradient has reduced, and the rate of groundwater level rise in key well hydrographs slowed. However, monitoring data also suggest that in parts of London groundwater levels are falling again. In the centre of the basin, where recharge takes very long to reach and is often intercepted in its path, a few areas of deep groundwater depression also persist, with potential issues described in Chapter 1. These observations led us to restrict further abstraction using new abstraction licensing strategies for London, which became an integral part of this report (Chapter 6).

As water levels in most areas have stabilised, the London Basin Chalk aquifer has become an entity that is artificially managed by changes in abstraction. The great advantage of controlling this confined aquifer is that there are no negative environmental implications. No ecosystems depend on a specific groundwater level under London, and therefore, provided that levels are kept below that which is required to protect structures, the aquifer presents a very secure, stable and sustainable water resource. Our role is to continue to monitor levels and advise the major abstractors on the current situation so that abstraction can slowly be adjusted to achieve the required balance.

3 How we manage groundwater levels

The Environment Agency has a long-term commitment to monitor and report on the state of groundwater levels beneath London. This is done through an observation borehole network, which is used to monitor absolute groundwater levels and rates of change of levels in the Chalk-Basal Sands aquifer of the London Basin. Observation boreholes are chosen on the basis of achieving a good spatial distribution across London, and boreholes with long data history of consistent quality are chosen as "key wells" to assess long term groundwater level trend. Over time some observations are no longer monitored and new observations need to be chosen for a given area. There are currently 86 live observation boreholes available for the purpose of this report, of which 82 produced data this year. This is down from nearly 200 observation boreholes in the early 2000's. Figure 3 shows the distribution and change in the observation borehole network, including those that we used to monitor in the past but have since lost or have had recent access issues. Figure 4 shows similar changes amongst the key wells.

We also obtain data from other organisations, particularly water companies, and the availability of these data could be compromised in the future by modifications to these monitoring networks and by previously monitored boreholes becoming unavailable. Several longstanding observation boreholes have been lost in central London in recent years and any knowledge of, or data from, alternative boreholes would be very helpful to the Environment Agency. Similarly, where redevelopment and ground investigations offer the opportunity of obtaining one-off or short-term groundwater datasets, these data will be utilised wherever possible.

The Water Information Management System Kisters (WISKI) database is the Environment Agency's hydrometric archiving, analysis and reporting system. Groundwater level data for all boreholes within the London Basin is stored within this system. We use this database to extract groundwater levels for our review.

Abstraction data, both licensed and actual volumes, is stored in the Environment Agency's National Abstraction Licensing Database (NALD), and includes returns data from all large abstractions such as from water companies. Thames Water and Sutton and East Surrey (SES) Water also operate Artificial Recharge schemes in this aquifer: the North London Artificial Recharge Scheme (NLARS) run by Thames Water; and the Wandle Artificial Recharge Scheme (WARS) operated by SES Water. Abstraction and recharge data for these schemes are also stored and compared to data from previous years.

Legend

Groundwater Site Status

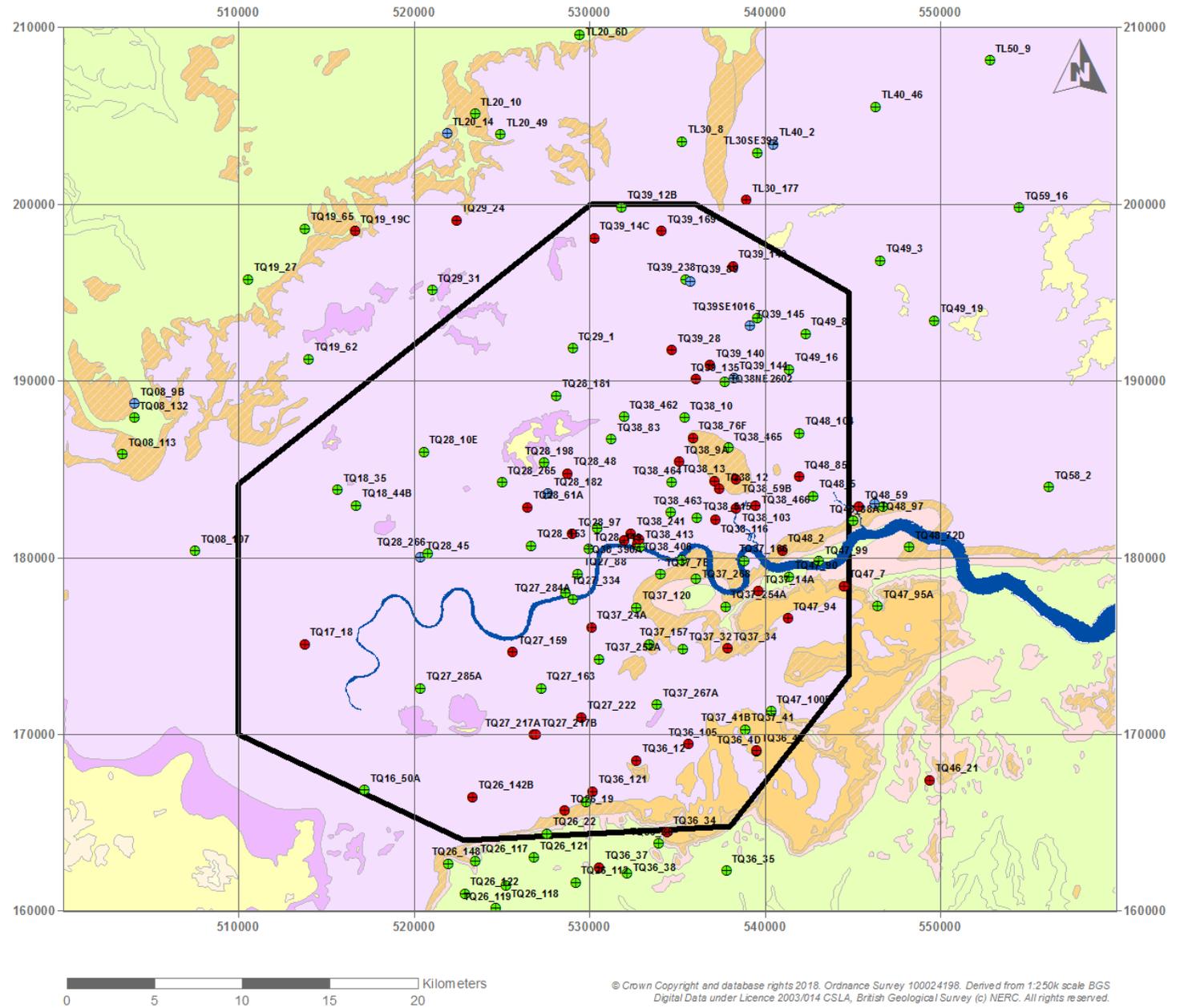
- Active
- ⊕ Replaced
- Closed or Lost

▬ River Thames

Basin Study Area

Bedrock Geology

- Bracklesham Group
- Barton Sand Formation
- Bagshot Formation
- Claygate Member
- London Clay Formation
- Harwich Formation
- Lambeth Group
- Thanet Sand Formation
- Chalk Formation



© Crown Copyright and database rights 2018. Ordnance Survey 100024198. Derived from 1:250k scale BGS Digital Data under Licence 2003/014 CSLA, British Geological Survey (c) NERC. All rights reserved.

Figure 3 Observation Borehole Network in the London Basin

Legend

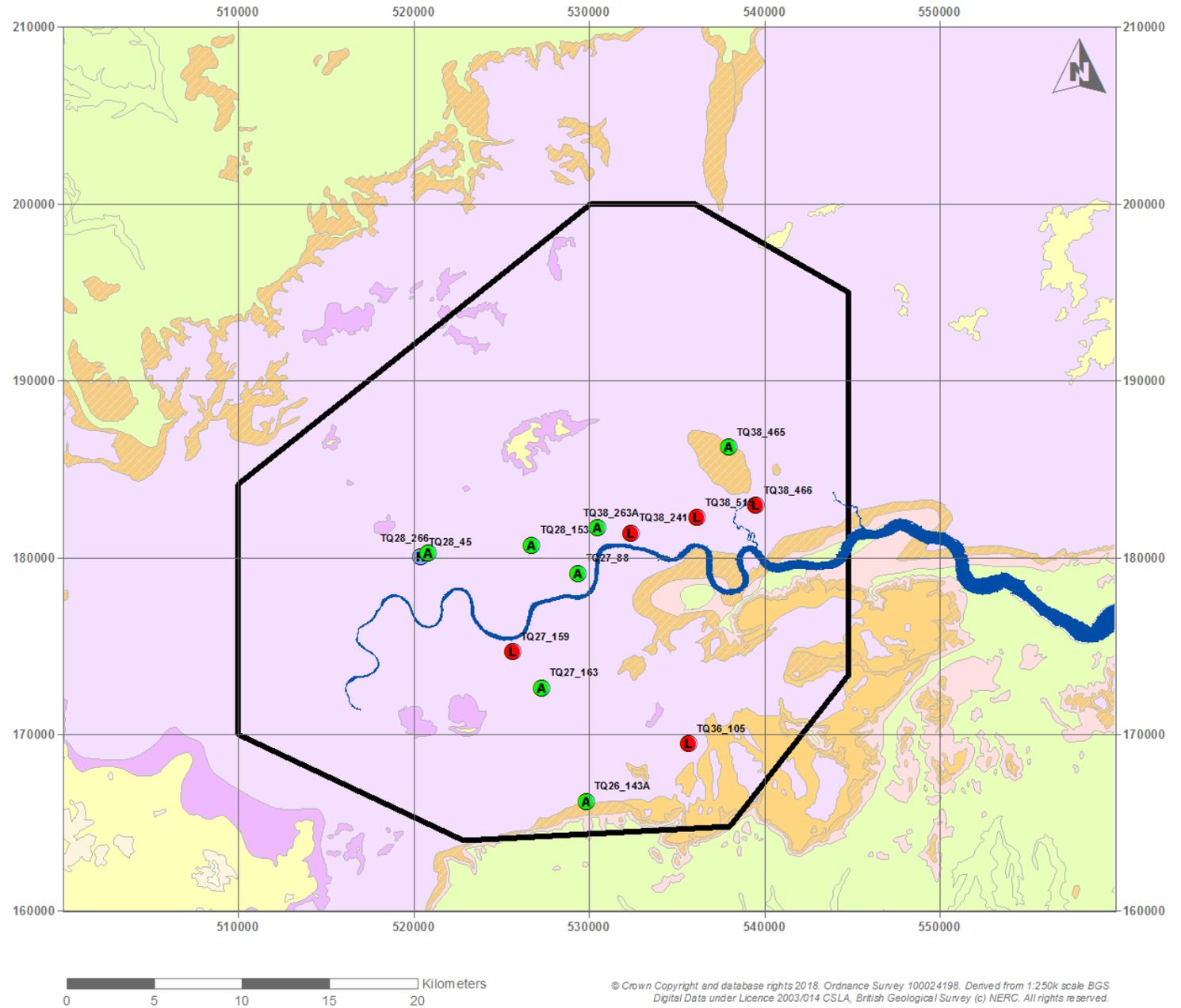
Key Wells 2018

- Ⓡ Replacement Key Well
- Ⓐ Active Key Well
- Ⓛ Lost Key Well

- █ River Thames
- Basin Study Area

Bedrock Geology

- Bracklesham Group
- Barton Sand Formation
- Bagshot Formation
- Claygate Member
- London Clay Formation
- Harwich Formation
- Lambeth Group
- Thanet Sand Formation
- Chalk Formation



© Crown Copyright and database rights 2018. Ordnance Survey 100024198. Derived from 1:250k scale BGS Digital Data under Licence 2003/014 CSLA, British Geological Survey (c) NERC. All rights reserved.

Figure 4 Active and Historic Key Wells in the London Basin

4 Recent abstraction trends

New abstraction licence applications or changes to existing licences are handled by the National Permitting Service (NPS) of the Environment Agency. The NPS is also charged with collating licence returns data. As water company returns make up the bulk of consumptive abstraction this report only describes the recent abstraction trends for water company abstractions, which form around 80% of abstraction in the study area.

Figure 5 shows the distribution of total actual water company annual abstraction over the course of 2017 in the London Basin. In 2017 the largest abstractions in south London continued to be at Deptford, Bell Green, Catford and Shortlands, as well as Brantwood Road, Hackbridge and Goatbridge in Surrey. In north London, significant abstraction continues to take place at Waltham Abbey in the North London Artificial Recharge Scheme (NLARS) well field, as well as at Wanstead Avenue in east London. The Windmill Lane and East Ham abstractions in the East London Resource Development (ELReD) well field are also notable in size.

Figure 6 shows the variation in annual licensed and actual abstraction since 1990. Abstraction quantities licensed to Water companies have not changed since 2009. Actual quantity abstracted from water company licences in 2017 decreased 5.5% from the previous year.

Figure 7 shows the spatial change in actual abstraction between 2016 and 2017. Increases in abstraction occurred in East and South London, with largest increases in South London at Catford, Brixton, Bell Green and Brantwood Road. The reductions were mostly concentrated along the Lower Lee corridor (NLARS) with a significant reduction at Eade Road. However, a very large reduction occurred at Shortlands.

Abstraction from the North London Artificial Recharge Scheme (NLARS) in 2017 was 49% lower than the abstraction volume in 2016. Totals were 2400 ML in 2017 compared to 4661 ML in 2016, as shown in Figure 8. In NLARS, a total of 667 ML was re-injected in 2017, representing 28% of NLARS abstraction.

The Wandle Artificial Recharge Scheme (WARS) shows increased abstraction (1686 ML) since 2016 because historically, Goatbridge abstraction was incorrectly used instead of Hackbridge (Figure 8). Recharge during the winter was 51% lower than recharge in 2016, at 299 ML one of the lowest annual totals since recharge began in 2008.

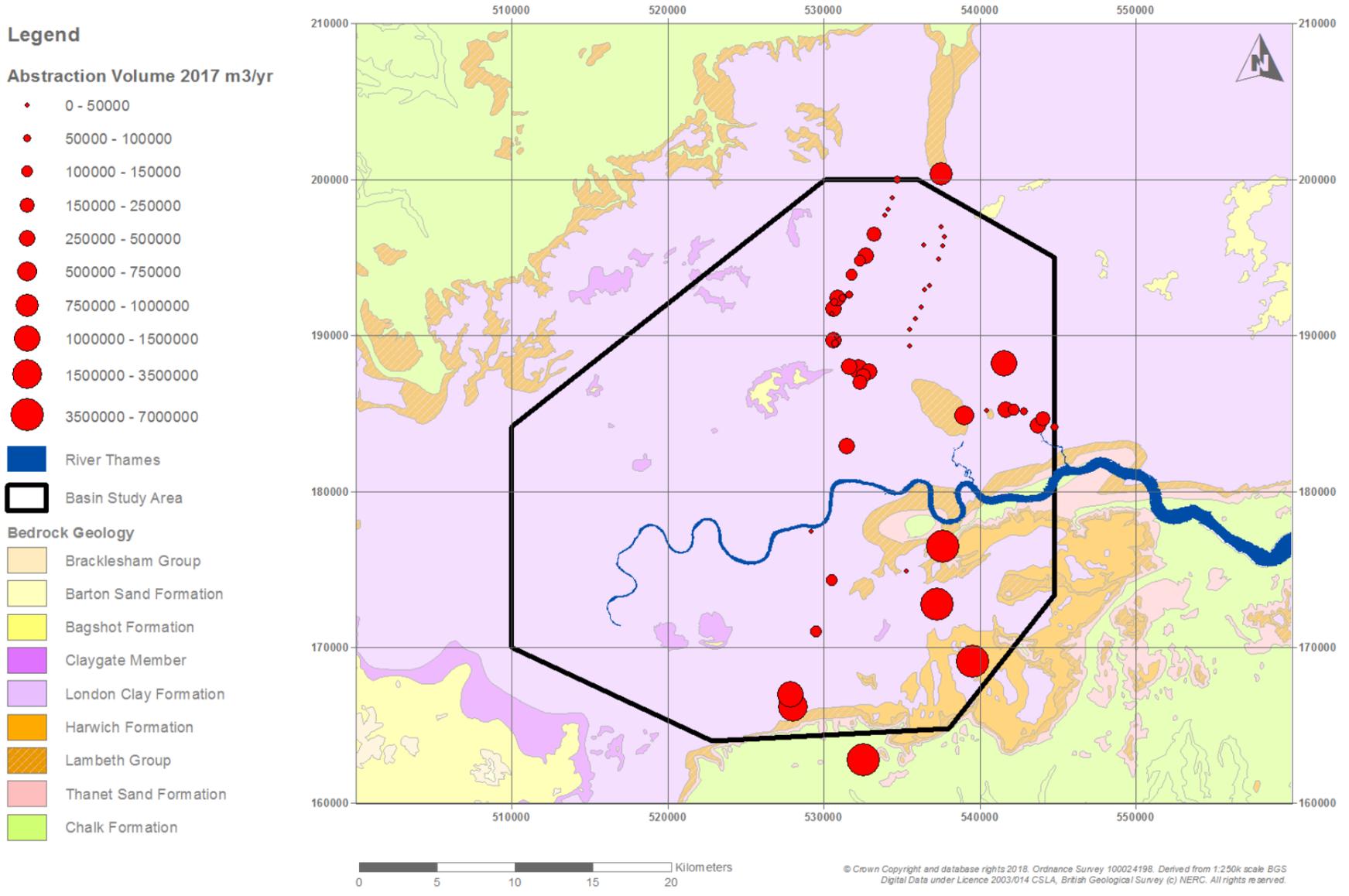


Figure 5 Total Annual Water Company Abstraction in 2017

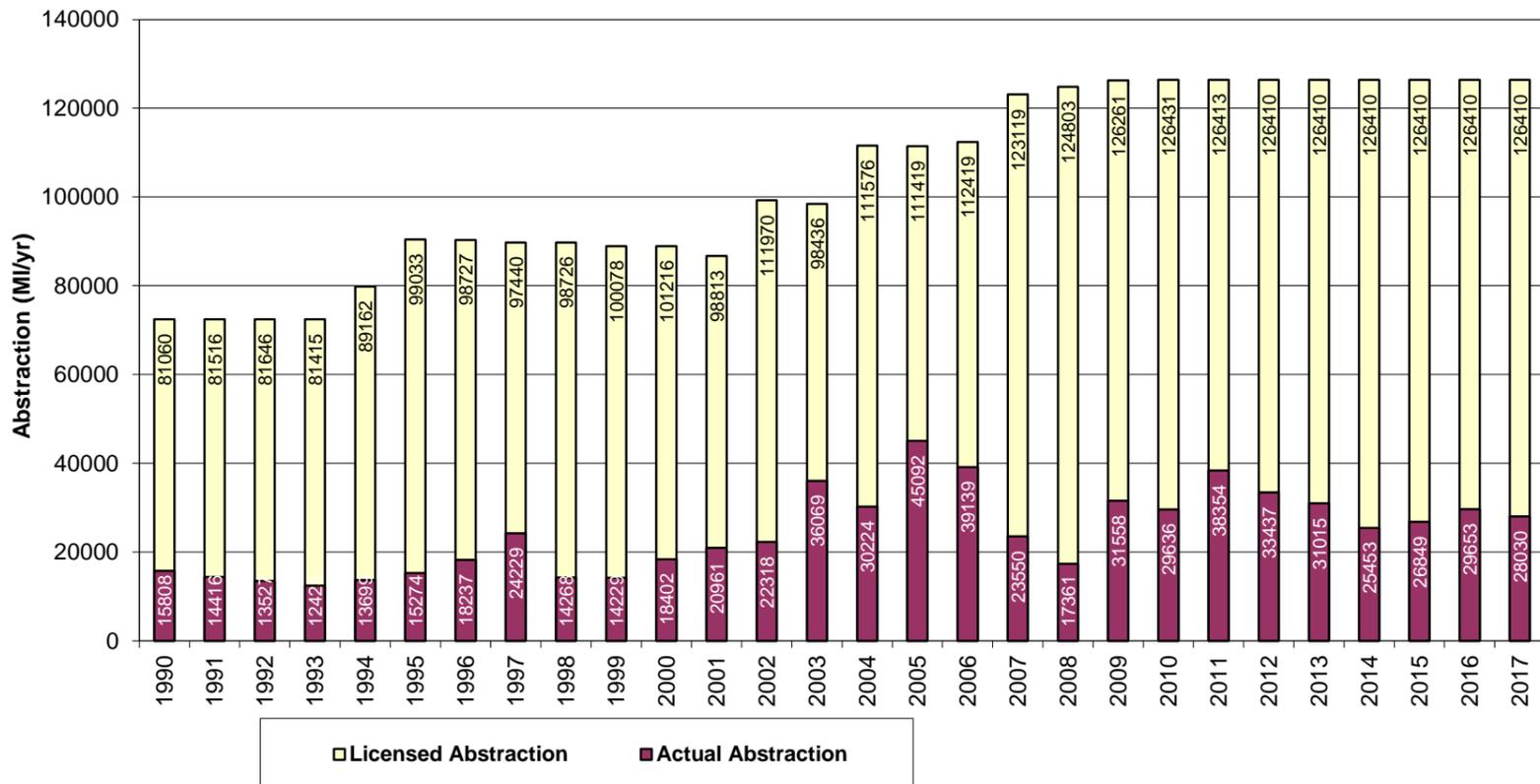


Figure 6 Water Company Licensed Abstraction from the London Basin Chalk Aquifer

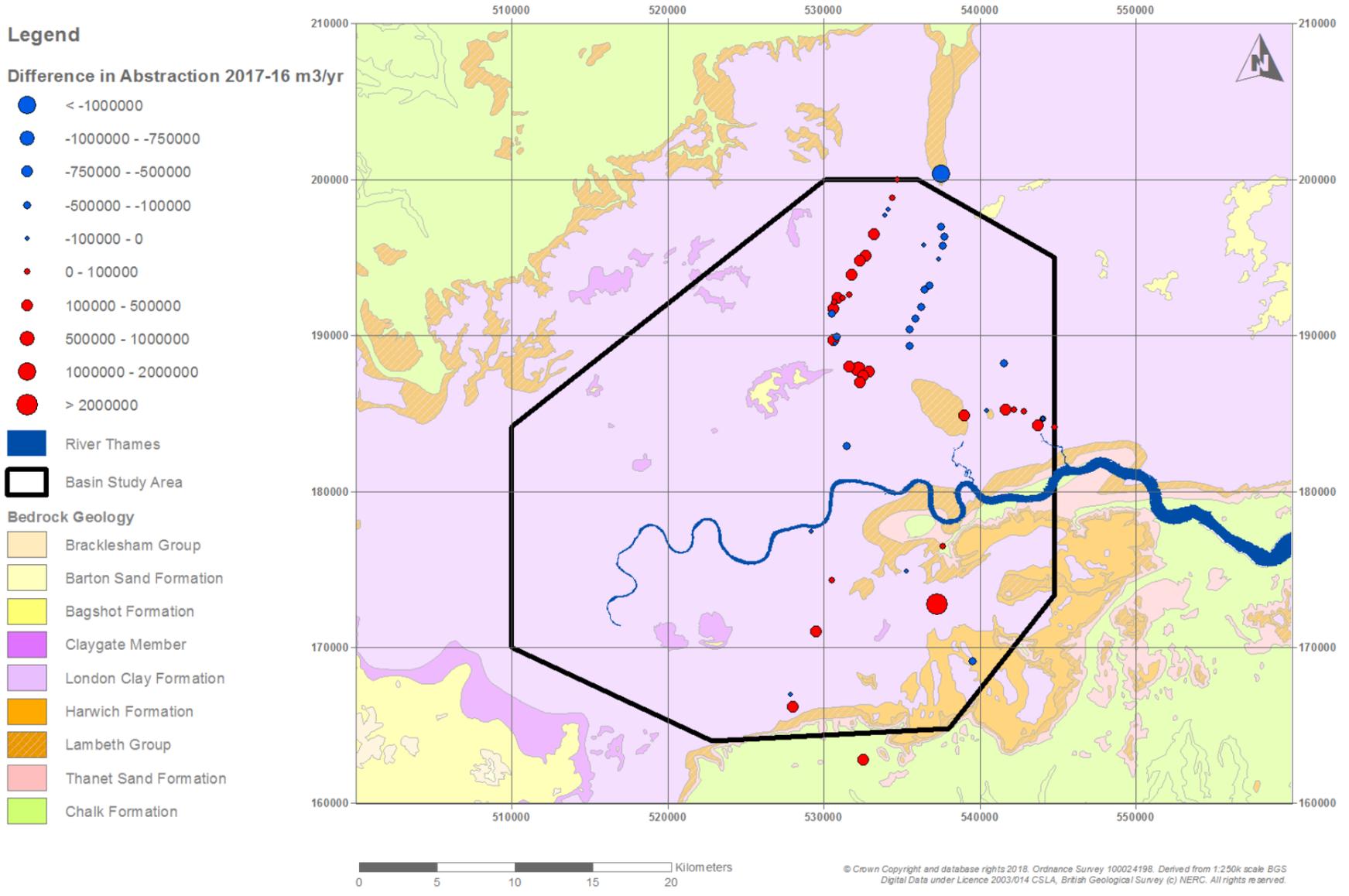


Figure 7 Difference between Water Company Total Abstractions 2016-2017

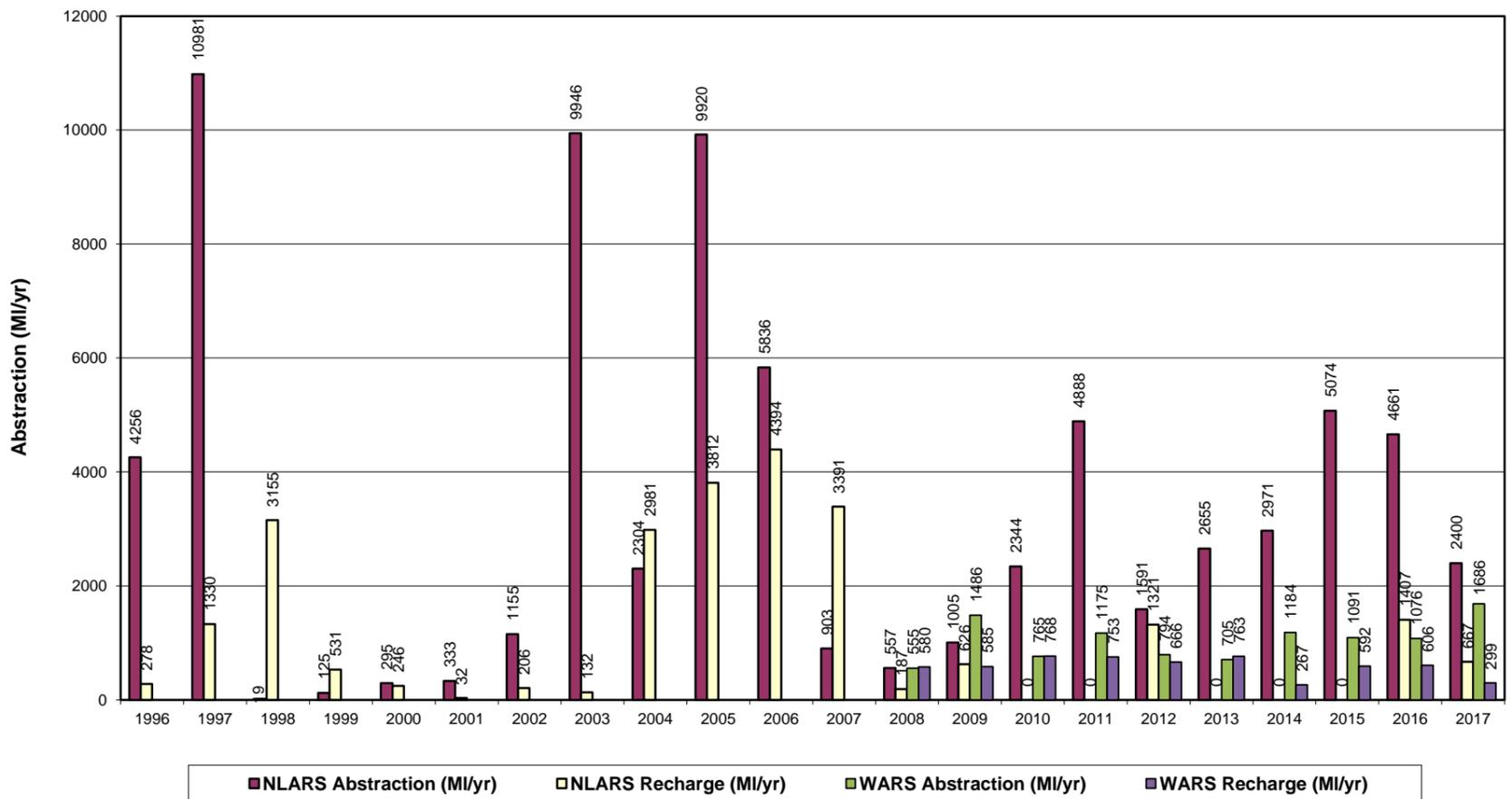


Figure 8 Recharge Scheme Operation

5 Groundwater levels for January 2017

Since the beginning of this report in the 1990's, January data from the observation boreholes network each year have been used to provide a snapshot of the Chalk groundwater levels across the London Basin. Figure 9 to Figure 11 show the recorded groundwater levels and associated level contours within the London Basin for January 2000, January 2017 and January 2018. They show a similar pattern: lowest groundwater levels in west central London, with levels increasing to the northwest and south towards the Chilterns and North Downs chalk outcrops.

The January 2018 contours display the potential effect of the major faults as groundwater flow barriers, based on the interpretation in the BGS 2008 study (summary in Chapter 1), and the available data. Where sufficient data points exist across barrier faults (i.e. Northern Branch Faults, Greenwich Fault, Rotherhide Fault, Streatham Fault, and Mitcham Fault), groundwater levels on either side are contoured independently so that contour lines are discontinuous, and simulating the observed step changes in water levels. Where only limited data points exist (i.e. across Sutton Fault), the contours rely on data over a wider area, and therefore do not simulate the step changes. Effects on groundwater levels of faults interpreted as flow conduits, or whose controls on groundwater flow are uncertain, are not inferred or represented by the contours.

As a result of losses to the observation network, in the past few years this report made use of surrogate or extrapolated data at a number of key observation points to control the distribution of the contours. 2018 is the second year that January data from new and replacement boreholes have been available for this report. This has improved year on year groundwater level change analysis. These boreholes have been installed to maintain network coverage, but are often some distance away from ones which they are replacing. As such whilst their data improves the quality of the 2017 and 2018 contours (Figure 10 and Figure 11), they introduce irregularities in the contours comparing long term changes in groundwater levels (Figure 13) in a number of areas, because there is no directly comparable data.

Recent Changes in Groundwater Levels

Figure 12 compares the change in groundwater levels between January 2017 and January 2018. Examining Figure 10 and Figure 11, the following changes can be seen:

- The shape of the central London groundwater depression has not changed significantly, and have remained above the -40 mAOD contour compared to previous years.
- The eastern extent of the -10 mAOD contour in east London was constrained in 2017 by a new monitoring borehole, Bastable Avenue, which we installed in Ilford, filling a gap in the network. The 2018 contour is similarly constrained.
- The small -20 mAOD contour that appeared in east London in 2014 is no longer present in 2018.
- Groundwater levels in west-central London that were continuing to rise in 2016 seem to stabilise during 2017.
- The recovery around the Battersea-Brixton area reported in 2016 is now being reversed, with groundwater levels falling on average between 1 to 3 m between 2017 and 2018.
- In south east and north east London, groundwater levels have risen while levels across much of central and north London are stable.

Some observation boreholes are located near abstraction licences. This can mean that at certain locations, the groundwater level contours based on January data each year may display local changes, owing to the short-term fluctuations influenced by abstractions. The level changes shown at the northwest boundary and north London near Cheshunt are examples of this, both compounded by data comparability issues arising from recent network changes.

Long Term Changes in Groundwater Levels

The rise in groundwater that the GARDIT strategy was designed to arrest had largely been achieved by 2000, so that year provides a useful baseline year for comparison. By comparing the groundwater levels in January 2000 to 2018, it is possible to track long term changes. These difference contours are strongly influenced by abstraction particularly in south London, and as a result these contours can change significantly from year to year.

The difference in groundwater levels between January 2000 and January 2018 is shown in Figure 13, which shows that:

- Groundwater levels have risen across north London, due to limited abstraction. The levels have risen in the order of 8 to 15 m since 2000, and have levelled off in recent years. The 15 m may be an overestimate of recovery as this has been derived from

comparing historic record at Barrow Hill, which ceased in 2012 with its replacement site of Kilburn Grange, where monitoring started in March 2017, located approximately 2 km west of Barrow Hill.

- In southwest and south-central London, groundwater levels have fallen in the order of 2-5 m since 2000 as a result of increased abstraction.
- In east London groundwater levels have fallen in the order of 10 m since 2000 as a result of increased abstraction.

In east London, where the Chalk outcrops around the River Thames from Greenwich to Woolwich, there is a risk of saline intrusion (Chapter 1). As groundwater flows towards the North-West (Figure 11), abstractions could capture any saline waters that enter the aquifer. In response to this risk there are conditions attached to abstraction licences in this area, requiring regular water quality sampling. To date, sampling associated with Thames Water's Deptford licence has not indicated a clear trend in changes to groundwater salinity.

Legend

-  River Thames
-  Basin Study Area
-  Impermeable Chalk Faults
-  Jan 2000 Data (mAOD)
-  Contours Jan 2000 (mAOD)

Groundwater Levels Jan 2000 (mAOD)
 High : 80 mAOD

 Low : -50 mAOD

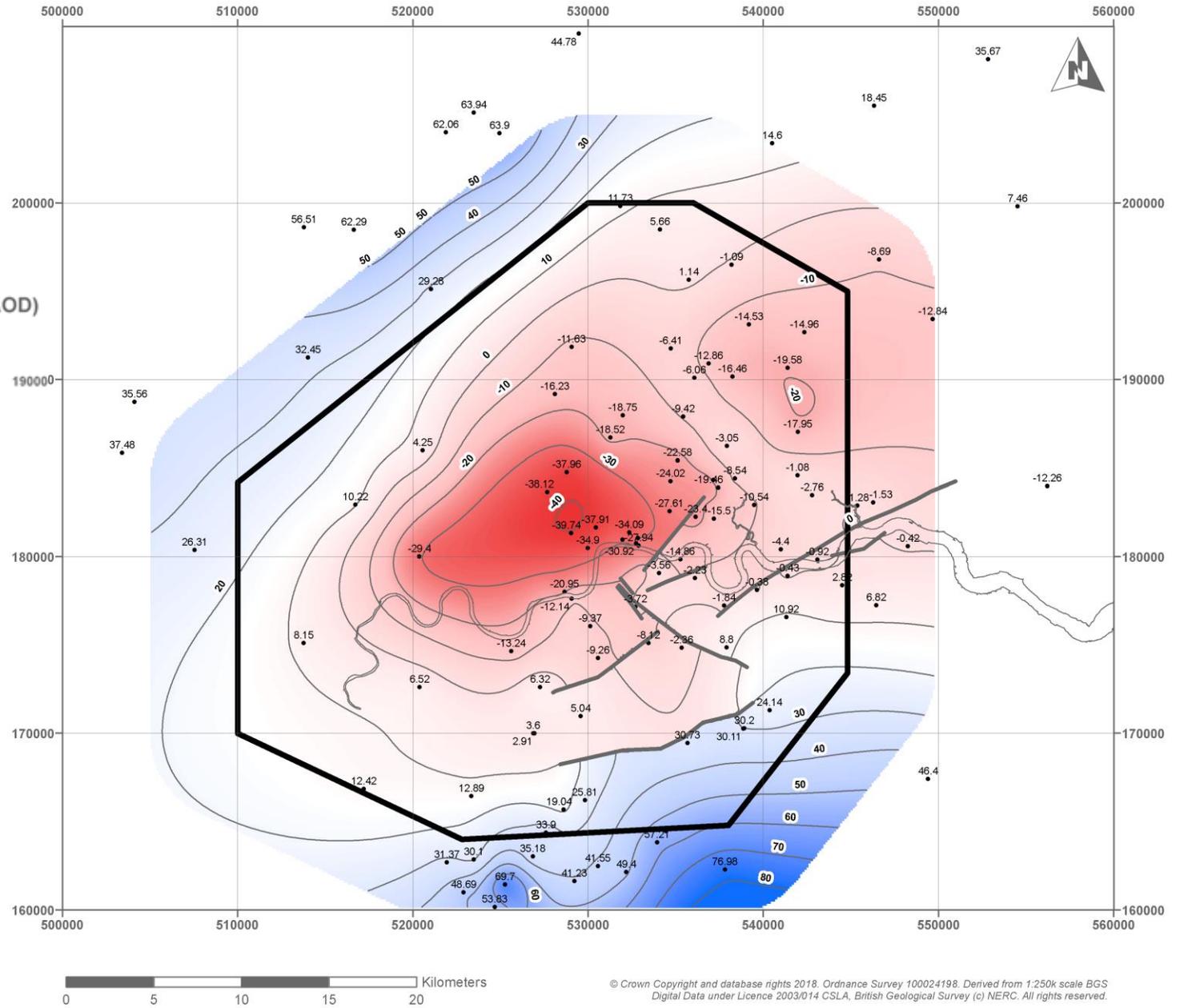


Figure 9 Monitored Groundwater Levels for January 2000

Legend

-  River Thames
-  Basin Study Area
- Impermeable Chalk Faults
-  Jan 2017 Data (mAOD)
- Contours Jan 2017 (mAOD)

Groundwater Levels Jan 2017 (mAOD)
 High : 80 mAOD

 Low : -50 mAOD

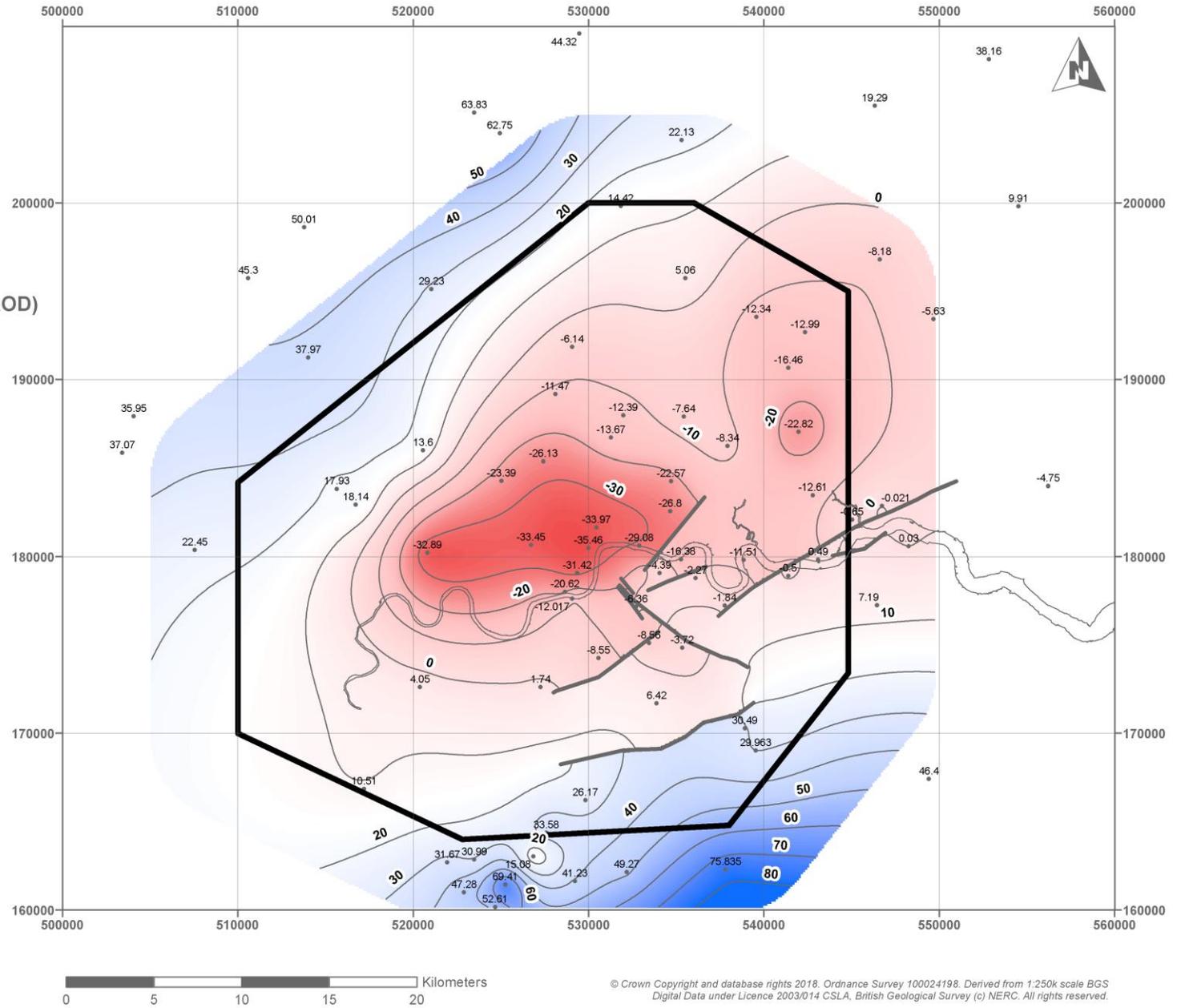


Figure 10 Monitored Groundwater levels in January 2017

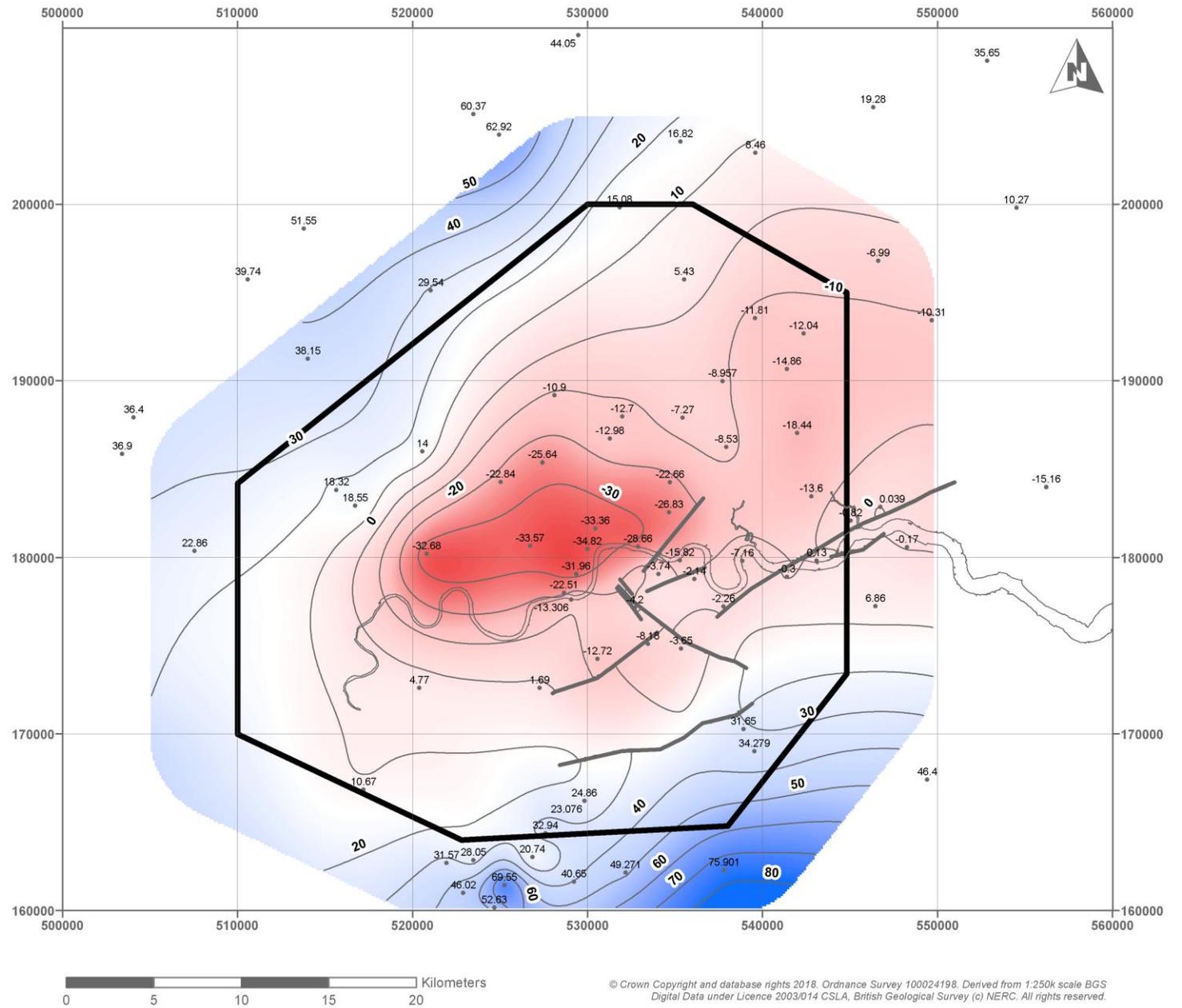
Legend

-  River Thames
-  Basin Study Area
-  Impermeable Chalk Faults
-  Jan 2018 Data (mAOD)
-  Contours Jan 2018 (mAOD)

Groundwater Levels Jan 2018

High : 80 mAOD

 Low : -50 mAOD



© Crown Copyright and database rights 2018. Ordnance Survey 100024198. Derived from 1:250k scale BGS Digital Data under Licence 2003/014 CSLA, British Geological Survey (c) NERC. All rights reserved.

Figure 11 Groundwater Level Contours for January 2018

Legend

-  River Thames
-  Basin Study Area
-  Impermeable Chalk Faults

Change in Levels 2018 - 2017 (m)

-  Rising Levels
-  Falling Levels

Difference Contour (m)

-  all other values
-  0 m

Change in Levels (m)

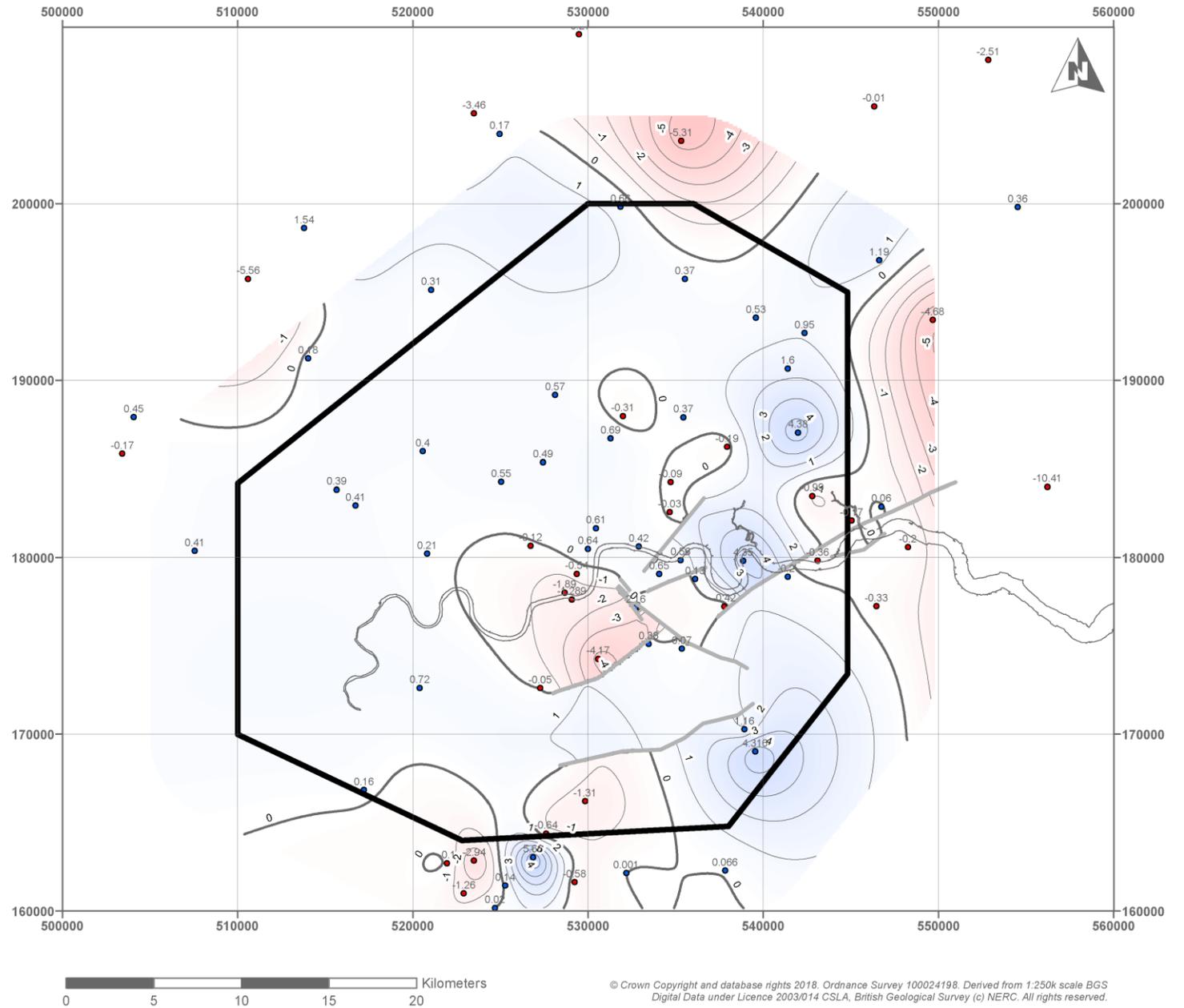


Figure 12 Change in Groundwater Levels between January 2018 and January 2017

Legend

-  River Thames
-  Basin Study Area
-  Impermeable Chalk Faults

Change in Levels 2018 - 2000 (m)

-  Rising Levels
-  Falling Levels

Difference Contours (m)

-  All other values
-  0 m

Change in Levels 2018-2000 (m)

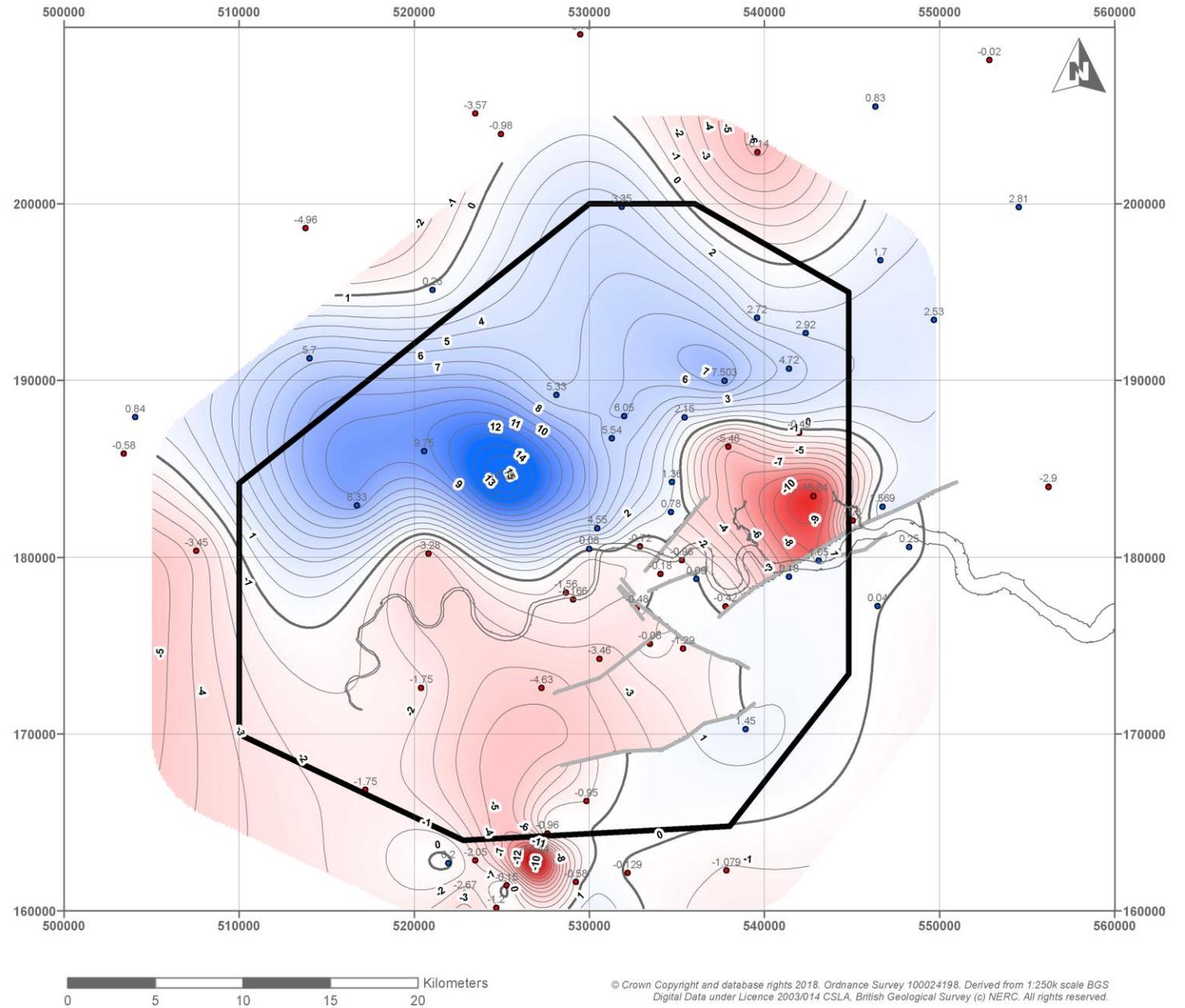


Figure 13 Change in Groundwater Levels between January 2018 and January 2000

6 Current licensing strategy

Our data show that piezometric levels of the Chalk aquifer vary significantly across the London Basin. The levels also respond more to changes in local abstraction intensity than the overall balance between abstraction and recharge, because of the distance and long travel time for the recharge to reach the centre of the Basin, and the level of abstraction which intercepts the recharge in its path. As such we need different policies for different areas of London to manage the available resource. The abstraction regime is also dynamic and changes year by year depending on the actual, rather than the licensed volume of abstraction, which means groundwater levels will never actually stabilise. Any strategy for the London Basin aquifer needs to be flexible, and regularly reviewed and updated.

The principle of the licensing strategy is to maintain groundwater levels below an upper level needed to protect underground structures, and above a lower level, which prevents the Chalk aquifer from being dewatered to an unacceptable level.

In 2006, we put into practice a principle to restrict further abstraction in areas that may be approaching their sustainable limit. It is considered that areas where there is a large volume of actual abstraction, or where groundwater levels are near the top of the Chalk, are unlikely to be able to support significant further abstraction. Three areas were defined where further consumptive abstraction needed to be restricted (Figure 15).

Model development for the London Basin Aquifer has enabled us to better interpret groundwater level changes with respect to the aquifer units. Since 2011, this report has included watertable geology maps (Figure 15), which are calculated by comparing each year's groundwater level contours against the elevation of aquifer units, using high resolution stratigraphic data from the BGS Geological Model (Royse, 2008; ESI, 2010 and 2013). These maps therefore estimate which geological unit the watertable or piezometric level resides in across the study area, to the resolution of the available monitoring data. When compared over the years (Figure 14), they provide clear visual displays of the extent of dewatering of the Chalk and Thanet Sand, as well as areas of water level recovery, for both the EA and the wider users of the report. As such we decided to adopt the watertable geology map method to guide the spatial application of the licensing strategy for the London Basin aquifer.

Where groundwater levels are below the top of the confined chalk, there is considered to be no water available as the aquifer is being dewatered. Similarly where Thanet Formation is being dewatered there will be no water available, as the objective for a sustainable resource is to have water levels at the top of these aquifer units. Where the pressure head of these aquifers is in the Lambeth Group there will be some water availability. Abstraction in these areas will cause drawdown that may start to dewater the Thanet Formation, and therefore water is available but the sustainable quantity to maintain water levels at the top of the aquifers may be restricted. Water is available where the aquifer pressure head is in the London Clay, and in order to protect infrastructure, the London Licensing Strategy encourages abstraction in these areas.

The watertable geology map method enables areas of different water availability status to be updated annually in this report. When dewatered areas become re-saturated they will change to the 'water availability restricted' status, and no new abstraction will be allowed in this area that may cause new dewatering. Renewals of licences in the 'No Water Available' area may need to include a 'hands-off groundwater level' to prevent further dewatering. Where possible we would like abstractions in this area to reduce to facilitate re-saturation of the aquifers.

There will be flexibility in the system. Potential applicants for a licence to abstract groundwater in the London Basin Aquifer are advised to look at the availability map (Figure 15) in the first instance. In the 'No Water Available' Areas, small abstractions may be allowed if the applicant can convincingly demonstrate that the drawdown caused by the abstracted volume does not jeopardise the long term water balance in London. In the 'Water Availability Restricted' Areas, applicants are encouraged to speak to Environment Agency hydrogeologists, who can review the current water level headroom down to the top of the Thanet Formation. This preliminary review will be used to inform the detail of the local assessment (see below) and potential viability of the proposal.

Local assessment are used to confirm if water is deemed to be available for licensing from the confined Chalk. These assessments take into account the local groundwater availability outcome maps and take into account the following bullet points:

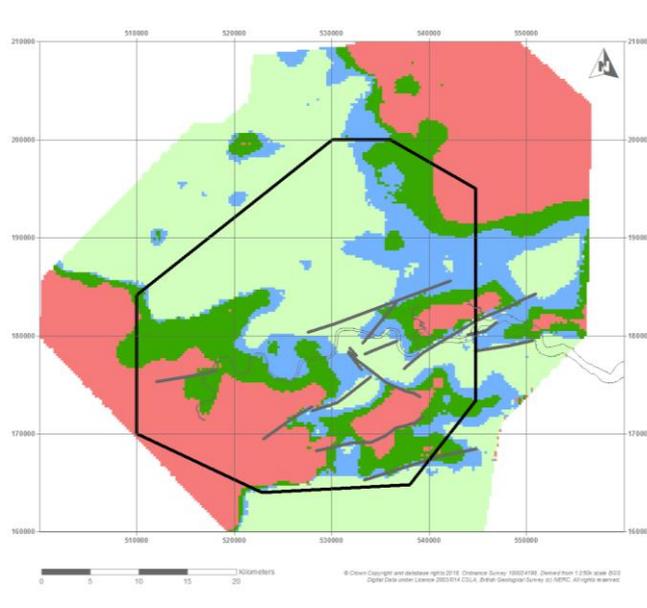
- Has there been any long-term (several years) downward trend in the groundwater level in the vicinity of the application?
- What are groundwater levels in relation to the base of the London Clay Formation? If the groundwater level is already below the base of the London Clay Formation, then it is likely that the licence application requires specific hydrogeological impact assessment to proceed. We will use discretion if there is a significant thickness of the Lambeth Group below the London Clay, but the aim is to manage abstraction to keep groundwater levels above the Thanet Formation.
- Is there any recent abstraction development in the same area? If groundwater levels have not yet responded to a recent change in abstraction, we may not grant further licences in that area.
- Are there other proposals in the area that have been refused for water resource reasons in the last five years?
- What is the proximity of the proposal to an existing or proposed Artificial Recharge Scheme? Artificial Recharge scheme proposals will be treated as a special case as they involve the management of groundwater levels to provide additional resource to the scheme operator.

The above criteria are used to carry out a local assessment of new and variation of existing abstraction proposals, using the monitoring data and interpretation described in previous chapters, to consider if the proposal is acceptable. All renewal applications will also need to consider these criteria, and the implications of changing conditions will be discussed with licence holders. Figure 14 shows watertable geology maps for what is considered the low point of water levels in the London Basin, 1965; the peak level in central London before GARDIT effects were measurable, 2000; and the latest water levels for January 2018 with a comparison to last year. It is worth noting that the change of watertable geology in a large area of east London between 2017 and 2018 is the result of a new observation borehole in Ilford installed by the EA, which improved the monitoring network and therefore the accuracy of the groundwater level contour in that area.

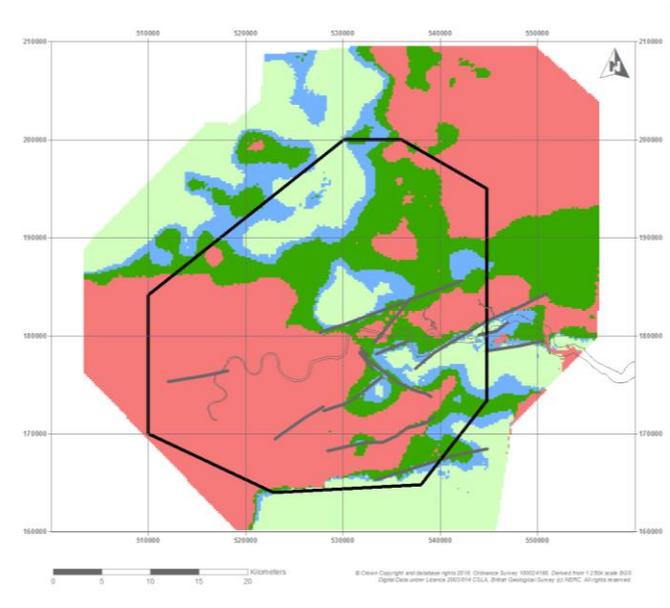
Legend

-  River Thames
-  Basin Study Area
-  Chalk Faults
- Water Table Geology**
-  London Clay
-  Lambeth Group
-  Thanet Sands
-  Chalk

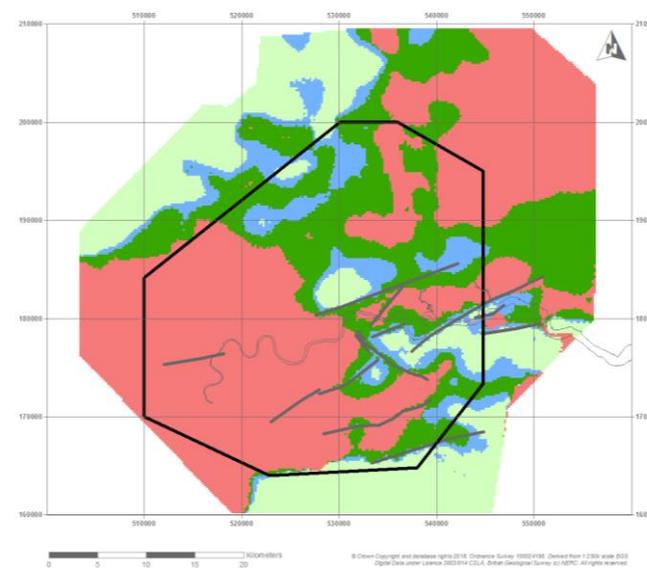
1965



2000



2017



2018

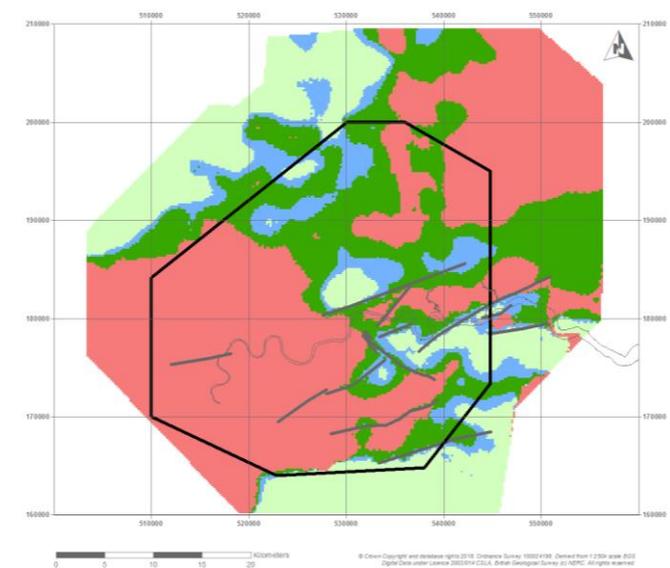


Figure 14 Watertable Geology Maps for 1965, 2000, 2017 and 2018

Legend

-  River Thames
-  Basin Study Area
- Key Wells 2018**
-  Replacement Key Well
-  Active Key Well
-  Lost Key Well
-  Old London Licencing Policy Areas
- London Licencing Policy 2018**
-  Water Available
-  Water Availability Restricted
-  No Water Available
-  Basin Study Area

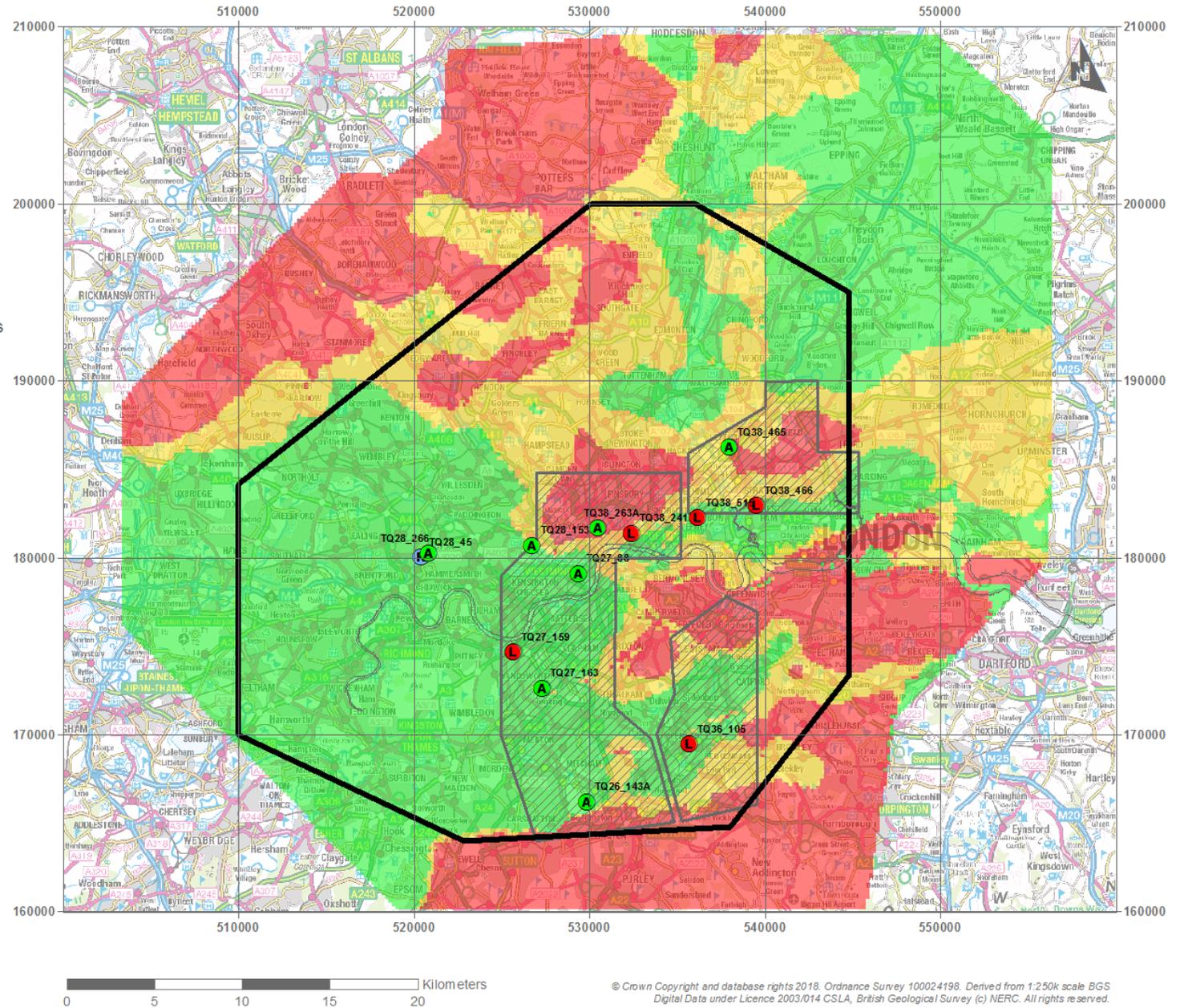


Figure 15 London Licencing Policy Map 2018

Locations of key wells are included to reference the groundwater Hydrographs in Figure 16.

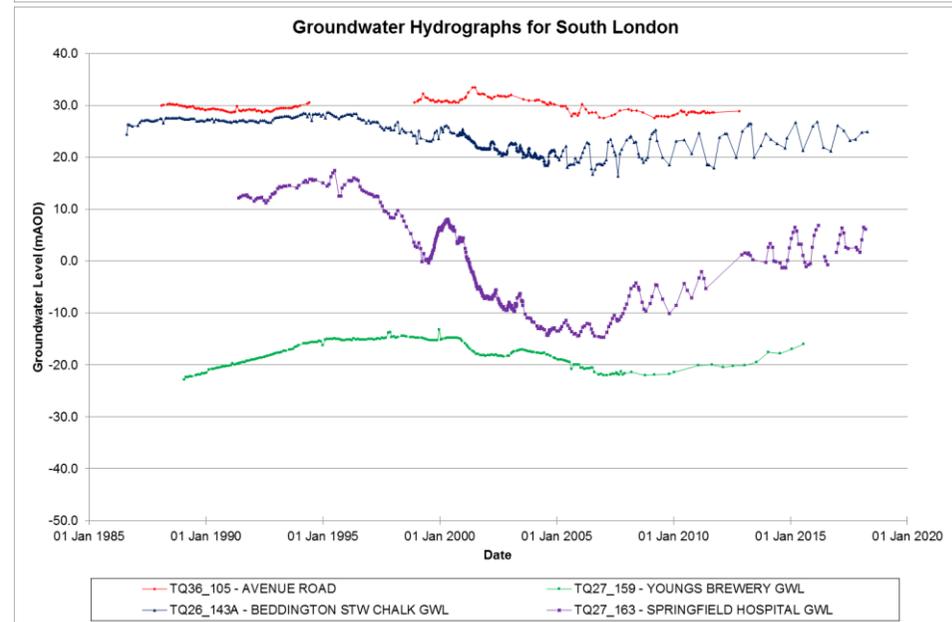
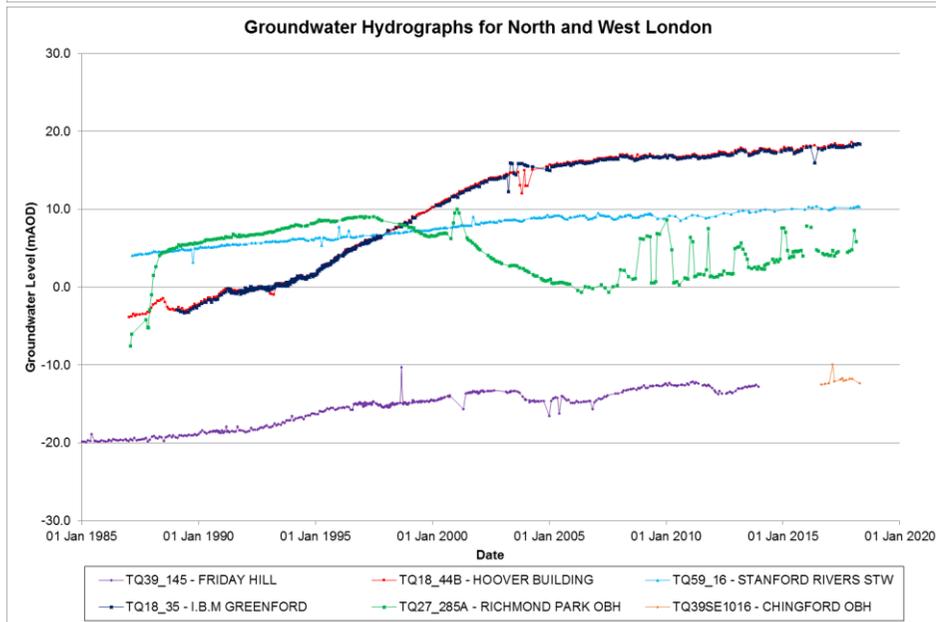
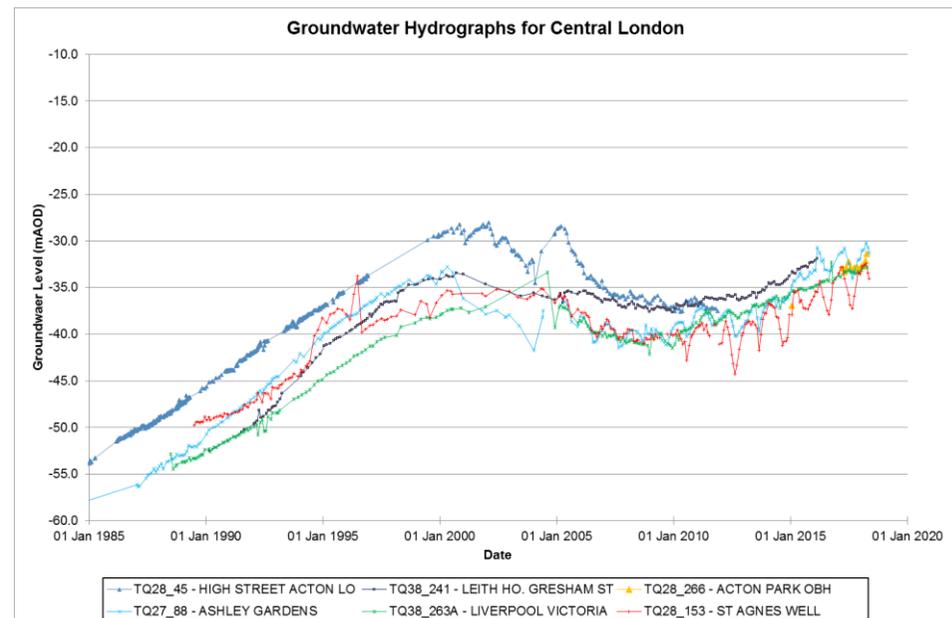
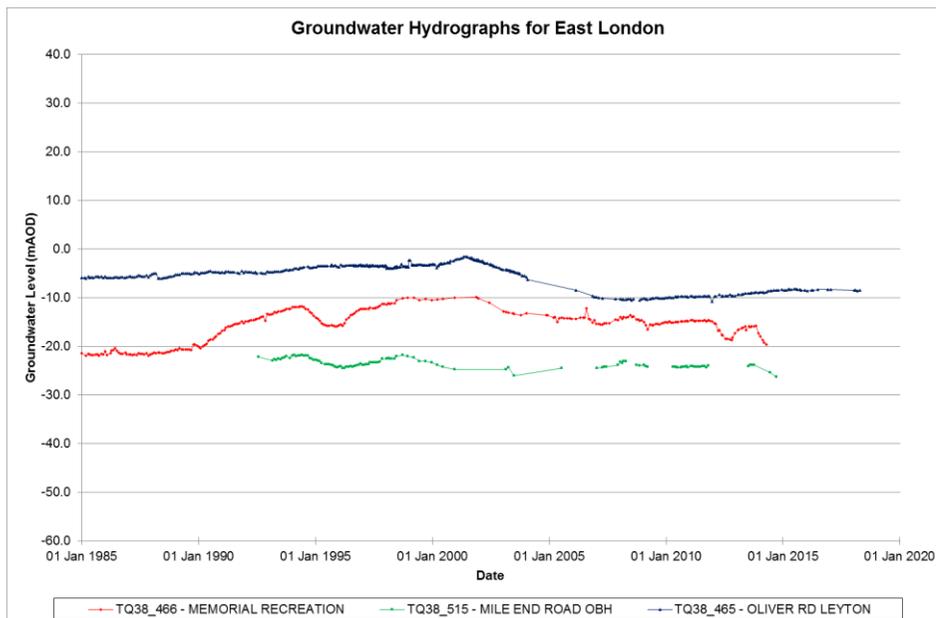


Figure 16 Hydrographs from Key Wells at different Areas in London. For distribution of key wells please refer to Figure 15. The hydrographs include lost key wells to show long term water level changes.

7 Open loop ground source heating and cooling (GSHC) schemes status

In 2016, there were 2 new proposals recorded for open loop GSHC systems in central London and 1 scheme became active. If you are considering a GSHC scheme you should contact us as there may be additional sites on our records since this report was published.

It can be seen that GSHC schemes can take several years to set up, reflected by the number of proposal and investigation sites being significantly larger than the number of schemes that become active. Figure 17 shows the trends in applications, investigations and active schemes, and the locations of schemes proposed, investigative and becoming active in 2016 in relation to existing schemes (active, investigative, or proposed).

Abstractions for GSHC are subject to the London Licensing Strategy. Overall, only non-consumptive schemes will be licensed in an area with “No water available” status. We will also only consider non-consumptive schemes in central London to the North of the River Thames, because of the particular concentration of open loop GSHC schemes in this area, and the potential impact on the recovery of the central London groundwater depression.

For GSHC to function effectively, groundwater temperatures need to be kept inside practical limits. We have received reports of active schemes that have been experiencing increased abstraction temperatures, making their schemes less efficient, or inoperable. The Environment Agency continues to raise these concerns to operators, that for sustainable operation they should seek to balance heating and cooling, or design the scheme to remove excess heat before discharge back to the aquifer.

A further complication is that groundwater in the London Basin has no natural outlet, with flow inward to the centre of the depression, and removed by abstraction. This means within the area of approximately the -30 mAOD contour on Figure 11, there is little groundwater through-flow to allow heat to quickly dissipate away from the aquifer mass immediately around GSHC schemes, thus increasing the probability of higher than designed abstraction temperatures in this area. Applicants need to carefully assess the risks and long term sustainability of installing GSHC schemes in areas where groundwater temperatures may be rising, or where there is a high concentration of existing schemes.

As part of the licence provisions, all new GSHC schemes are advised to monitor water temperature at the point of abstraction, and at the point of discharge before the spent water is returned to the aquifer. As a guideline, temperature of the discharge water should not be higher than 25 degrees Celsius, or be more than 10 degrees Celsius different (either higher or lower) to that measured at the point of abstraction. Operators that consider their schemes at risk of breaching these guidelines

are encouraged to contact the Environment Agency at an early opportunity to discuss possible mitigating options.

Groundwater temperature data has been gathered at several central London observation boreholes in recent years. We aim to create a dataset of baseline groundwater temperature so that long term trends can be observed. Temperatures have risen approximately 3 degrees Celsius from 2005 to 2009 in central London. Since 2010 the rate of increasing temperature has slowed, with temperatures currently at around 2 degrees higher than the pre-2005 level.

Figure 18 presents temperature monitoring within the Chalk of central London as collected by the Tideway Project. It is observed that near Battersea, temperatures have experienced a slight fall in 2016 (of less than 1 degree Celsius). Local variations will reflect local groundwater fluxes, proximity of GSHC to monitoring points, and whether these schemes are balanced or predominantly re-injecting warmer water.

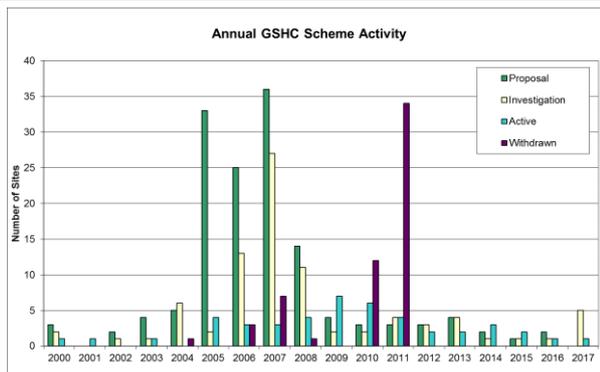
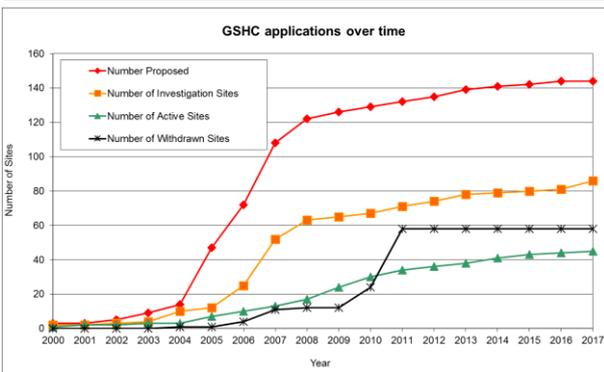
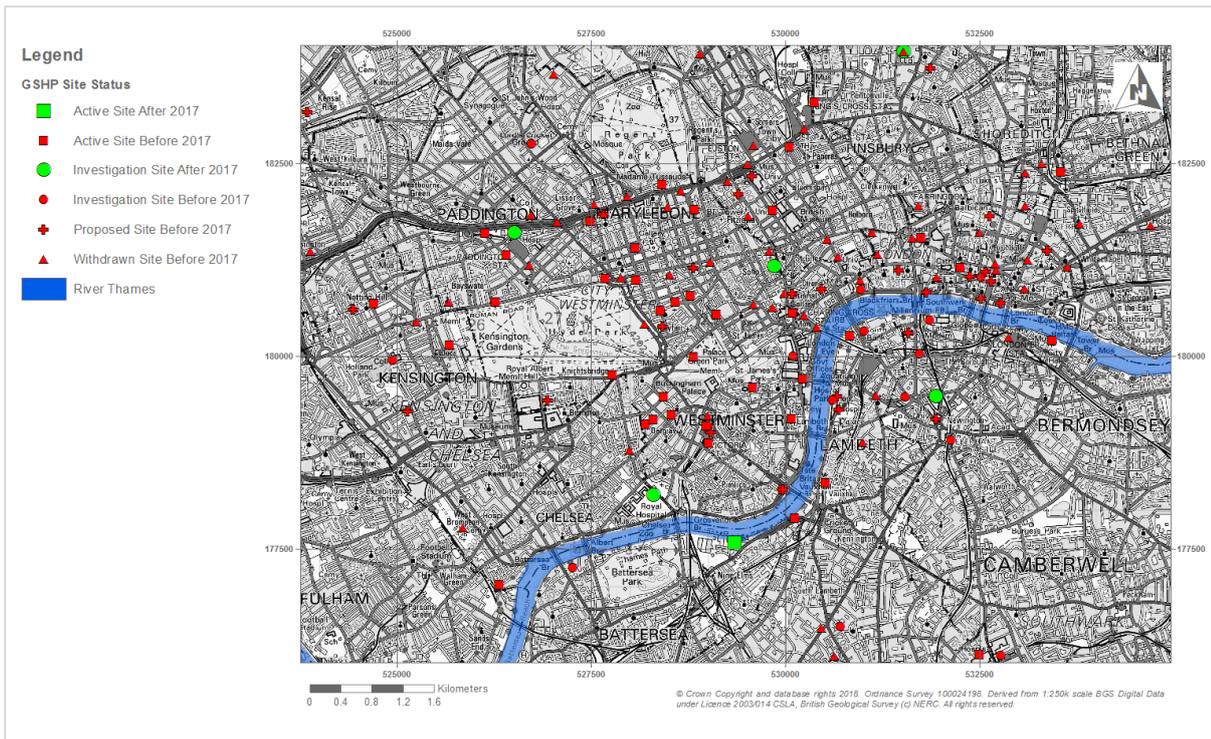


Figure 17 London Open-loop Ground Source Heating and Cooling Systems Status 2017

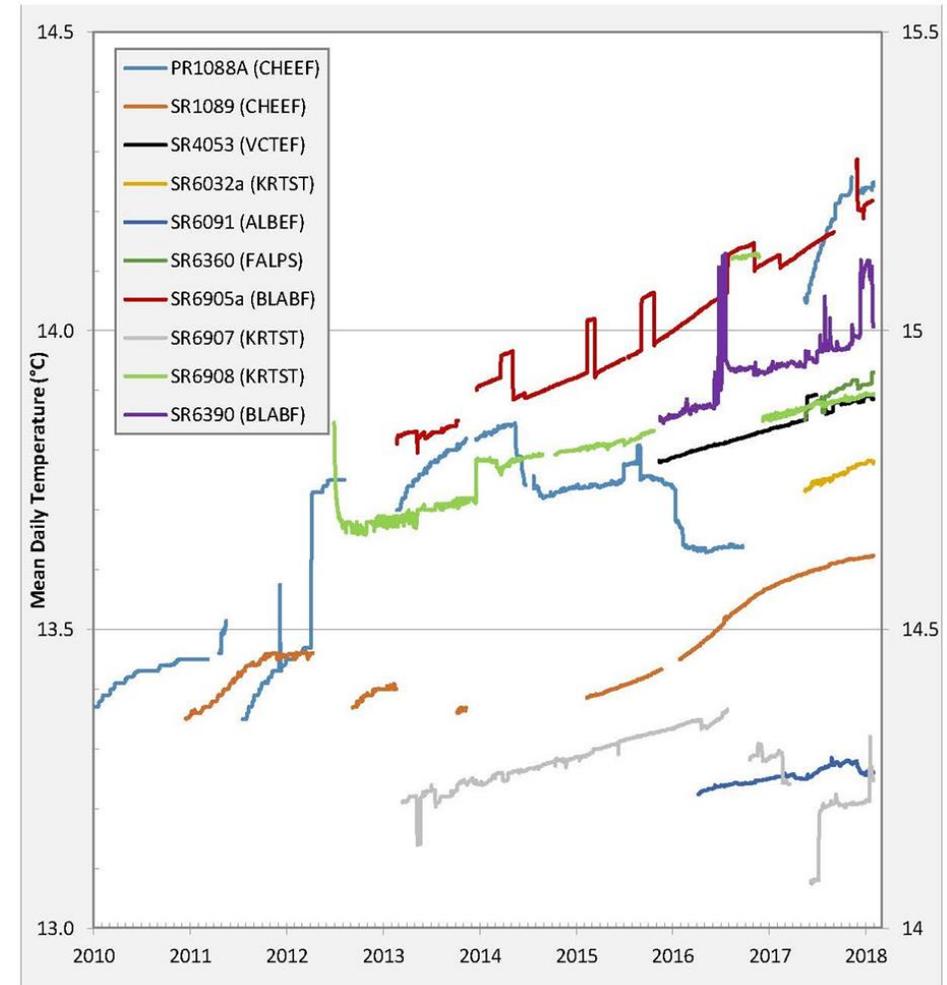
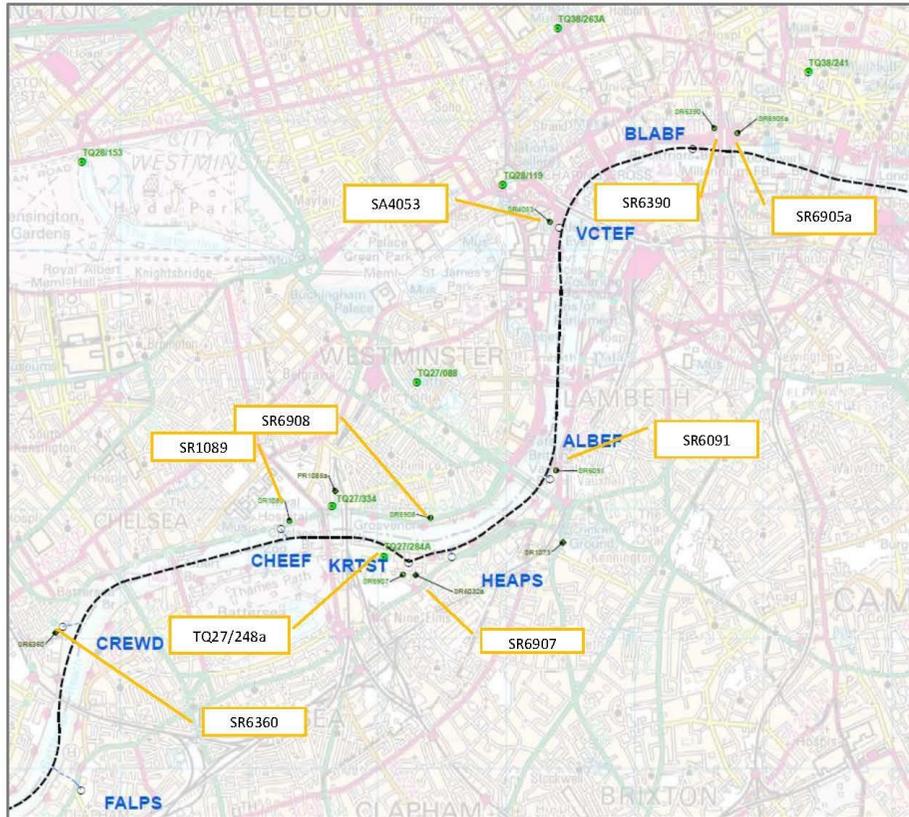


Figure 18 Temperature Monitoring within the Chalk of Central London from 2010 to 2017

Reproduced with permission of Tideway and is taken from the Ferrovial Laing O'Rourke (joint venture) Annual Interpretive Report 2017 and produced by AECOM

8 Conclusions

Between 2016 and 2017 the volume of licensed groundwater abstraction for water companies in the London Basin was unchanged, while actual abstraction decreased by 5.5%. Increases in abstraction occurred in East and South London and decreases were mostly concentrated along the Lower Lee corridor and at Shortlands.

NLARS abstraction in 2017 was 49% less than that in 2016, with re-injection for storage at 28% of abstraction. In south London, WARS abstraction has increased since 2016, and re-injection has decreased by 51% to a historically low level.

The shape of the central London groundwater depression has not changed significantly between 2017 and 2018. In east London, the -10 mAOD contour has retreated westward, and a small -20 mAOD contour which appeared in 2014 has now disappeared.

In 2017, 1 new GSHC scheme became active and 2 new schemes were proposed.

The area of dewatered aquifer in central and east London, as well as in south London is little changed from last year. Consequently, the areas of aquifer with water available for licensing continue to be in west, southwest and northeast London.

The watertable geology map will continue to be used as the basis for the Licensing Strategy for the London Basin Chalk Aquifer.

9 References

A summary of the development of London groundwater level management:

http://www.groundwateruk.org/Rising_Groundwater_in_Central_London.aspx (Accessed August 2017)

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

Allen, D.J., Brewerton, L., Bloomfield, J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., MacDonald, A.M., Wagstaff, S.J., Williams, A.T.P. and Robinson, V.K., 1997. The Physical Properties of Major Aquifers in England and Wales. *British Geological Survey Technical Report WD/97/24. Environment Agency R&D Publication 834*.

Bierens de Haan, S., Rae, J.E. and Parker, A., 1994. Pyrite oxidation in the tertiary sands of the London Basin aquifer. *Applied Geochemistry* 9, 161-173

Chandler, R.J. and Apted, J.P., 1988. The effect of weathering on the strength of London Clay. *Quarterly Journal of Engineering Geology and Hydrogeology* 21, 59-68.

Construction Industry Research and Information Association, 1989. The Engineering Implications of Rising Groundwater Levels in the Deep Aquifer Beneath London, Special Publication 69, CIRIA, London, UK.

Ellison, R.A., Woods, M.A., Allen, D.J., Forster, A., Pharaoh, T.C. and King, C., 2004. Geology of London. *Memoir of the British Geological Survey*, Sheets 256 (North London), 257 (Romford), 270 (South London), 271 (Dartford) (England and Wales).

ESI, 2010. London Basin Aquifer: Conceptual Model Report. Report reference 60121R1.

ESI, 2013. London Basin Aquifer: Numerical Model Report. Report reference 60121R2.

Fry, V., 2009. Lessons from London: regulation of open-loop ground source heat pumps in central London. *Quarterly Journal of Engineering Geology and Hydrogeology* 42, 325-334.

Hamilton, A., Riches, J., Realey, G. and Thomas, H., 2008. 'ELRED': New water for London from old assets. *Proceedings of ICE, Civil Engineering* 161, 26-34.

Hargreaves, T.R (AECOM), Tideway, Contractor's Annual Interpretative Report 2017, *Report Reference 4602-FLOJV-TTCEN-491-NZ-RG-010017*, 08 May 2018

Harris, S.J., Adams, M. & Jones, M.A., 2005. NLARS: Evolution of an artificial recharge scheme. In: "Recharge systems for protecting and enhancing groundwater resources". *Proceedings of the 5th International Symposium on Management of Aquifer Recharge*, ISMAR5, Berlin, Germany, 11-16 June 2005.

Kinniburgh, D.G., Gale, I.N., Smedley, P.L., Darling, W.G., West, J.M., Kimblin, R.T., Parker, A., Rae, J.E., Aldous, P.J. and O'Shea, M.J., 1994. The effects of historic abstraction of groundwater from the London Basin aquifers on groundwater quality. *Applied Geochemistry* 9, 175-195

Rainey, T.P., and Rosenbaum, M.S., 1989. The adverse influence of geology and groundwater on the behavior of London Underground railway tunnels near Old Street Station. *Proceedings of the Geologists' Association* 100, 123-134

Royse, K.R., 2008. The London Chalk model. British Geological Survey. *Commissioned Report CR/08/125*.