Appendix E: Analysis of Impacts on Groundwater

Appendix E: Analysis of Impacts on Groundwater

E.1 Introduction

This Appendix was submitted to the Environment Agency for comment in September 2004. Initial comments were received on 3 November 2004. Following further comments by the Environment Agency at a meeting on 01 December 2004 an additional paper was prepared on the groundwater quality impact caused by dewatering of the deep aquifer. This has been incorporated into this document in Section E.4.3.

E.2 Scope

This appendix to the Assessment of Water Impacts Technical Report (the Main Report) summarises the investigations of how the impacts of Crossrail Line 1 on groundwater levels in the shallow and deep aquifer and on water quality were determined. The following are considered:

- Requirements for dewatering of the deep aquifer
- Impacts of dewatering the deep aquifer (both in terms of impacts on groundwater levels and groundwater quality)
- Impacts of discharge of dewatered effluent on surface water
- Impacts of dewatering the shallow aquifer
- Impacts of engineering structures within the shallow aquifer

It is stressed that the limitations and assumptions given elsewhere in the Assessment of Water Impacts Technical Report will also apply to this Appendix.

This Appendix does not describe disposal of the dewatering effluent or dewatering for utility diversions. In addition, this Appendix does not describe the impact of dewatering of sand lenses in the London Clay and Harwich Formation. The approaches to these two issues are described in the Main Report.

In addition, this appendix does not examine the impacts on groundwater levels within the Lambeth Group as:

- It is anticipated that any dewatering from the Lambeth Group would be undertaken by direct, local dewatering of the Lambeth Group itself, rather than by improving the gravity drainage from the Lambeth Group to the deep aquifer by connecting the Lambeth Group to the Thanet Sands and then pumping from the Thanet Sands or Chalk.

- Dewatering from the Lambeth Group will normally have no impact on groundwater levels in the deep aquifer, aside from potentially reducing the very small component of vertical throughflow.

- Exceptions may occur at scour hollows and would be evidenced by a fully hydrostatic gradient rather than an under-drainage profile.

E.3 Impacts on Water Levels in the Deep Aquifer

E.3.1 Introduction

The deep aquifer comprises the Chalk, Thanet Sands and the Upnor Formation (at the base of the Lambeth Group but hydrogeologically part of the deep aquifer). Recent geotechnical investigations undertaken for Crossrail have confirmed that the pore pressure profiles throughout these strata are often close to hydrostatic. Pumping from wells which are screened in the lower Thanet Sands or open holed through the uppermost layers of Chalk, can be used for dewatering the sequence. Dewatering has been previously undertaken in the general area of the Isle of Dogs for the construction of the Limehouse Link Tunnel, the Jubilee Line Extension (notably the Durands Wharf and Prestons Wharf shafts and for the Canary Wharf Station) and for construction of foundation piles of large office blocks. No permanent dewatering abstractions are proposed for Crossrail.

Altering groundwater levels during dewatering may have an impact on other groundwater abstractions and the associated source protection zones in this important aquifer. These impacts are considered under the assessment of impacts (Water). There may also be secondary impacts related to settlement of building foundations and buried services and lowering of water levels in areas of archaeological significance. No secondary impacts on designated ecological sites are expected to occur.

It is considered that Crossrail will not have any significant, permanent effect on groundwater levels and flows in the deep aquifer in any of the Crossrail Route Sections. Where works are constructed in the deep aquifer, they will obstruct transverse groundwater flows across the alignment by blocking off both fissures in the Chalk and porous flow through the Thanet Sands. There would be localised changes in the groundwater flow within these layers; however, the effective thickness of the Chalk is large enough to enable some flow to simply bypass the obstruction caused by the works. No significant overall permanent change in groundwater levels is expected. External grout and in situ concrete will prevent permeable, longitudinal pathways developing.

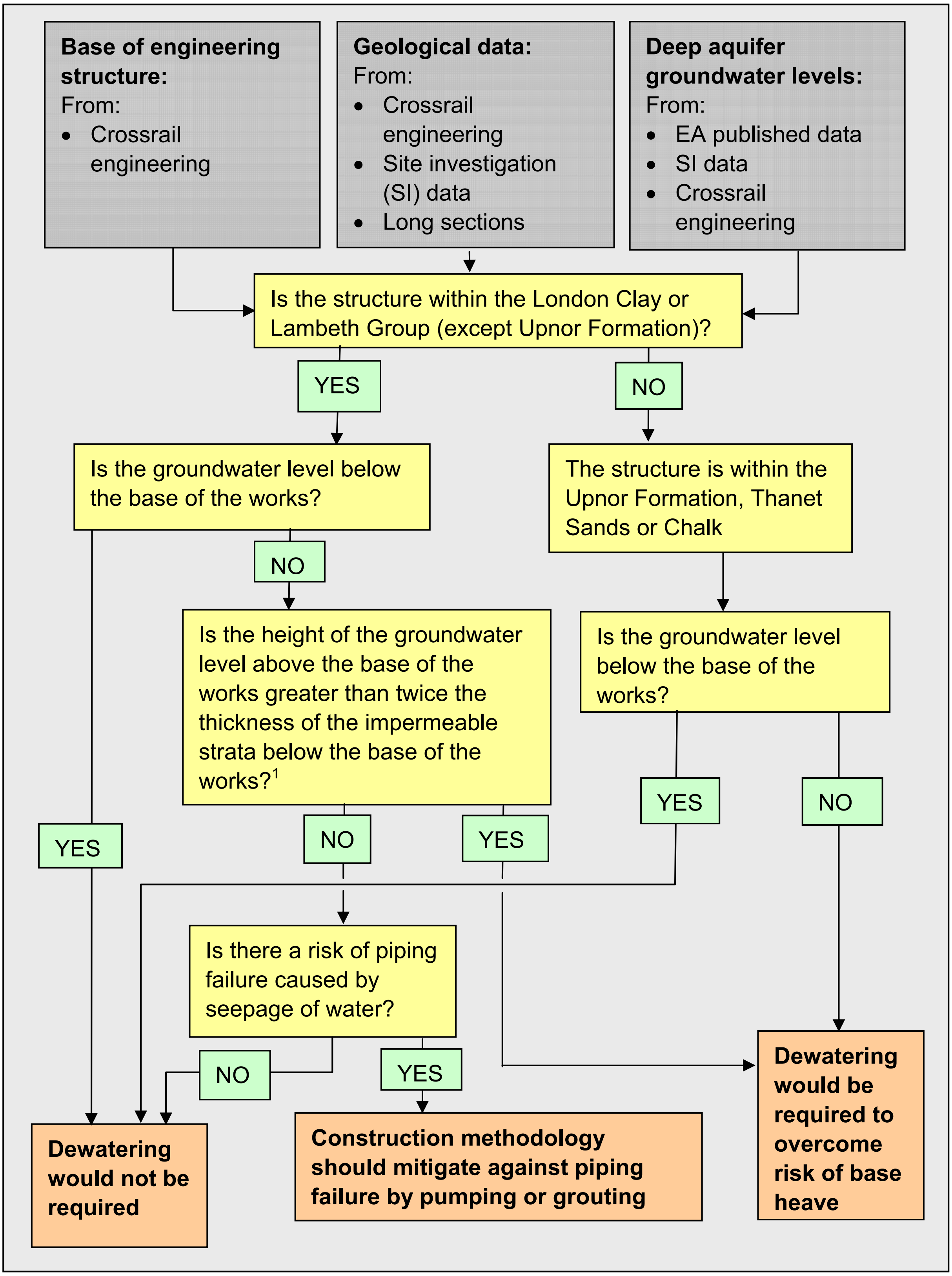
In the eastern part of the route at North Woolwich and Warren Lane and Arsenal Way Shafts the London Clay and the Lambeth Group (except at Arsenal Way Shaft) are absent and the shallow aquifer directly overlies the deep aquifer. At these locations the groundwater profile is hydrostatic. Tables E.1 and E.2 contain more details of the geology.

E.3.2 Methodology

Dewatering from the deep aquifer will only be required where manual excavation in saturated Upnor Formation, Thanet Sands or Chalk is needed, (such as at cross passages at vent shafts or stations), or where base heave, hydraulic fracture or ‘piping’ in excavations, especially in the lower Lambeth Group, are a concern.

Figure E.1 shows the initial conceptual methodology which has been used to assess whether dewatering would be required. This should only be used as a general guide.

Figure E.1: Conceptual Methodology – Deep Aquifer Dewatering



[1] This should only be used as a general 'first pass' assessment – further understanding of the individual situation is required to confirm whether or not dewatering would be required.

E.3.3 Results of Dewatering Assessment

The assumed requirements for dewatering are summarised in Tables E.1 to E.3. The Chalk groundwater levels, geology data and base levels of structures are those reported in the Assessment of Water Impacts Technical Report and are therefore based on current knowledge. Although minor changes in the data used to assess the requirements would be available in the future as additional site investigations and drilling for dewatering wells takes place, the overall assessment of need would apply even if there were changes of up to a few metres in the data at any site.

The following acronyms are used:

LC – London Clay

LG – Lambeth Group

TS – Thanet Sands

CK – Chalk

Table E.1: Central Route Section

Location	Base of Structure (mATD)	Geology	Chalk Ground Water Levels (mATD)[1]	Conclusion	Dewater - ing of Deep Aquifer Required?
Paddington Station	92.7-97.1	Base LC 61.8 - 66.2 mATD	65 to 70 (2003)	Base structure approx 26 to 31 m above base of LC	No
Hyde Park Shaft	81.0	Base LC 70.0 mATD	65 to 70 (2003)	Base structure approx 11 m above base of LC	No
Park Lane Shaft	94.4	Base LC 78.3 - 87.0 mATD	60 to 70 (2003)	Base structure approx 16 to 7 m above base of LC	No
Bond Street Station	95	Top LC 113 – 116	60 to 65 (2003)	Base structure approx 7 m above base LC. CK water levels 35 to 40 m below base of structure.	No
Tottenham Court Road Station	89.0-90.0	Base LC 90.0 - 94.0 mATD	60 - 65 (2003)	Base structure approx 5 m above base LC and well above Chalk water level.	No
Fisher Street Shaft	94	Top LC 118.7 Base of shaft in LG	65 (2002)	Base structure well above Chalk water level.	No
Farringdon Station	84.5	Station tunnel located mainly within the LG, except the western end where invert likely to encounter top of the TS	65 (2003)	Water level should be about 20 m below the base of the tunnel.	No

Location	Base of Structure (mATD)	Geology	Chalk Ground Water Levels (mATD)[1]	Conclusion	Dewater - ing of Deep Aquifer Required?
Liverpool Street Station	70	Station tunnels expected to be predominantly within the LC. The lower tunnel faces will intercept LG	65 to 70 (2003)	Tunnels constructed in LC and LG with minimal risk of high water pressures from deep aquifer.	No
Hanbury Street Shaft	80.5	Base LC 80 mATD Base LG 62 mATD	70 - 80 (2003)	Base of shaft at base of LC. Minimal risk from high water pressures from deep aquifer.	No
Whitechapel Station	82	Base LC 80 mATD Base LG 57 mATD	75 (2003)	Base of station at base of LC. Minimal risk from high water pressures from deep aquifer.	No
Pedley Street Shaft	77	Base LC 84 mATD	70 - 80 (2003)	Base of shaft above base of LC. Minimal risk from high water pressures from deep aquifer.	No
Stepney Green Shaft	75.4	Sand layer at base of LC ranging in thickness from 5.7 m to 1.3 m, with the top between 79.9 to 75.4 mATD. The top of the Thanet Sands lies between 68.1 mATD and 59.25 mATD	72 mATD (2003) Middle Aquifer (sand layer) – water level 90 mATD	Temporary dewatering of sand layer would be required unless groundwater can be controlled by grouting. No dewatering required from deep aquifer, unless underdrainage can be implemented.	No
Lowell Street Shaft	64	Base LC 88. Base LG 71	85 (2003)	Top of shaft box in LG, base in TS, CK water levels above base.	Yes, to approx 60 mATD
Hertsmere Road Shaft	72	Top LG 92.5 Top TS 79. Top CK 64	86 (2003)	Base of structure in TS, CK water levels above base.	Yes, to approx 68 mATD
Isle of Dogs Station	65.3	Base LG 74.3 - 81 Base TS61 - 65.5	90 (2003)	Tunnel would be in Thanet Sands and LG in east	Yes, to approx 60 to 65 mATD
Mile End Park Shaft	82	Base LC 80.8. Base LG 62.7	77.3 (2003)	Shaft probably constructed in LC, little risk of high water pressures from deep aquifer.	Low chance of being needed
Eleanor Street Shaft	73	Base LC 80.8. Base LG 62.7	85 to 90 (2003)	Shaft approx 8 to 10 m above top TS, risk of high groundwater pressures from deep aquifer	Yes, to approx 70 mATD

Location	Base of Structure (mATD)	Geology	Chalk Ground Water Levels (mATD)[1]	Conclusion	Dewater - ing of Deep Aquifer Required?
Pudding Mill Lane Portal	86 (tunnel eye)	Top LC 101.95 Top LG 89.15 Top TS 75.28 (tunnel eye)	85 (2003)	Base shaft in upper part of LG. Further site investigations required to confirm if dewatering required although the current data suggests that only a small water level reduction would be needed.	Pending further site investigation. Small flows and short term if required.

1. Groundwater levels based on Environment Agency results and SI data where available. Actual levels could be different at time of construction and the dewatering need would be reassessed.

There are no locations in the North-East Route Section where dewatering of the deep aquifer would be required.

Since the majority of the South-East (SE RS) and Western (W RS) Route Sections are on the surface, in general the works would not impact on groundwater levels in the deep aquifer. Table E.2 summarises locations on the South-East and Western Route Sections where excavations may require dewatering.

Table E.2: South East and Western Route Sections

Location	Base of Structure (mATD)	Geology (mATD)	Chalk Ground Water Levels[1] (mATD)	Conclusion	Dewater - ing of Deep Aquifer Required?
Blackwall Way Vent Shaft	57.4	Base LC 84.1; top TS 67; top of CK 44	90 to 95 (2003)	Base of shaft within TS level. Risk of base heave and seepage due to high water levels	Yes to approx 50 mATD
Limmo Peninsula Vent Shaft (SE RS)	66	Base LC 65 and 58	90 to 95 (2003)	Base of shaft close to base of Lambeth Group. Top TS may be no more than 17 m below excavation level. Risk of base heave or seepage due to high water levels	Yes to approx 61 mATD
Victoria Dock Portal (SE RS)	85.3 (base diaphragm walls)	Base LC 84	90 to 100 (2003)	Diaphragm walls likely to terminate in the base of the LC or top of the LG depending on the stratigraphy. Assumed that there would be an adequate thickness of LC and LG to present a risk of base heave caused by the underlying GW pressure	Major flows considered unlikely on present data but stratigraphy uncertain
North Woolwich Portal (SE RS)	Track level approx 82.5 or 85	Superficial deposits overlying CK	103.5 to 106 (2003)	Base of structure uncertain, however high groundwater levels make it likely that some limited dewatering would be required	Yes some during construction of base slab

Location	Base of Structure (mATD)	Geology (mATD)	Chalk Ground Water Levels[1] (mATD)	Conclusion	Dewater - ing of Deep Aquifer Required?
Warren Lane Shaft (SE RS)	72	Superficial deposits overlying CK. Top of Chalk 94.96 – 90.92 TS may be present up to approx 1.4 m thick	100 to 105 (2003)	Groundwater levels well above base of shaft. Risk of base heave or seepage.	Yes, to approx 66 mATD
Arsenal Way Shaft	68	Superficial deposits overlying LG (may not be present), TS and CK	100 to 105 (2003)	Groundwater levels well above base of shaft. Risk of base heave or seepage.	Yes
Plumstead Portal (SE RS)	90	TS at surface	100 to 105 (2003)	Portal constructed within deep aquifer, below groundwater level. Would only be minor and short term before construction of the base slab between the diaphragm walls.	Yes, some during construction of base slab
Maidenhead Station (W RS)	Not much below GL at 130 mATD	CK at surface	120 to 130 (2002)	The high ground water level may create a risk of seepage during construction – SI would confirm groundwater levels.	Possibly, but would be highly localised and short term

1. Groundwater levels based on Environment Agency results and SI data where available.

Table E.3 below summarises the locations where dewatering of the deep aquifer is assumed to be required:

Table E.3: Summary of Dewatering Requirements

Location	Route Section	Description
Lowell Street Shaft	Central	Major
Hertsmere Road Shaft	Central	Major
Isle of Dogs Station	Central	Extremely Large
Eleanor Street Shaft	Central	Major
Pudding Mill Lane Portal[1]	Central	Minor
Blackwall Way Shaft	South-East	Major
Limmo Peninsula Shaft	South-East	Major
North Woolwich Portal	South-East	Some
Warren Lane Shaft	South-East	Major
Arsenal Way Shaft	South-East	Major
Plumstead Portal	South-East	Some
Maidenhead Station[1]	West	Possibly minor

1 Pending further site investigation to confirm groundwater levels at the time of construction

E.4 Deep Aquifer: Impact of Dewatering

E.4.1 Simulated Dewatering Impacts

(i) Introduction

The impact from dewatering on groundwater levels in the deep aquifer was assessed using the London Basin Groundwater Model (see Box 1) to simulate pumping from the following locations:

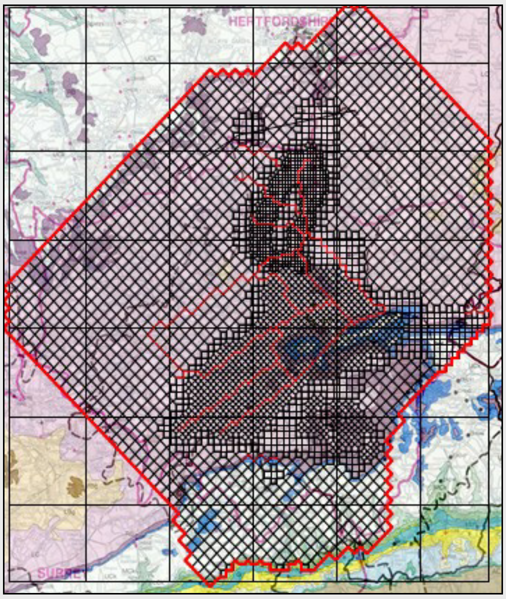
1. Isle of Dogs Station/Hertsmere Road Shaft
2. Lowell Street Shaft
3. Hertsmere Road Shaft
4. Eleanor Street Shaft
5. Blackwall Way Shaft
6. Limmo Street Shaft
7. Warren Lane Shaft
8. Arsenal Way Shaft

Dewatering at tunnel portal sites has not been simulated since the construction methodology would be significantly different to construction of shafts or stations. Pumping would be minor and of shorter duration since it would take place during phased construction of the base slab and following construction of the diaphragm walls. It is likely that groundwater ingress would be controlled where necessary using localised pumping and/or grouting which would not have a significant, long term impact on groundwater levels.

Box 1. London Basin Groundwater Model

The London Basin Groundwater Model (LBGM) was originally developed for Thames Water (TW) and the Environment Agency (EA) Thames Region during 1999. Since 1999 the model has undergone various upgrades and refinements. The model covers all of the confined Chalk in the Thames region and the unconfined Chalk of the North Downs to the south.

The model currently simulates groundwater levels between 1965 and 2003, and also can simulate future groundwater levels.



The model has five layers as follows:

- London Clay
- Woolwich and Reading Beds
- Basal Sands (Thanet Sands and Upnor Formation
- High Permeability Chalk
- Lower Permeability Chalk

The model is divided into 3732 grid cells.

(ii) Estimated Flow Rates Required for Dewatering

Initial estimates of the flow rates required for dewatering were made using the Thiem and Sichardt equations:

These equations apply to an idealised aquifer which is horizontal, confined above and below between impermeable formations, infinite in horizontal extent, of constant thickness and homogeneous and isotropic with respect to its hydrogeological parameters.

The equations also represent steady state conditions. Steady state conditions mean that the water level in the pumped well and the surrounding piezometers does not change with time.

$$Q = \frac{2\pi kD(H-h)}{\ln(R_o / \mathrm{R_e})}$$ Thiem equation for confined conditions

$$R_o = C(H-h)\sqrt{k}$$ Sichardt formula[1]

It is also assumed that the dewatering wells penetrate 20 m into the Chalk. The adjusted flow rate was calculated as follows:

$$Qpp = Q \times \frac{d}{D}$$

Where;

Q	=	flow rate (m^3/d)
Qpp	=	flow rate adjusted for partial penetrating wells
k	=	permeability (m/d)
D	=	thickness of the confined aquifer (m)
d	=	depth well penetrates into aquifer (m)
H	=	initial piezometric level in the aquifer (m)
h	=	target drawdown level in the equivalent well (m)
R_o	=	radius of influence (m)
R_e	=	effective radius of dewatering (m) (from engineering descriptions of the works)
C	=	empirical calculation factor (assumed to be 3000 when k in m/s)[2]

The values for permeability and thickness of the aquifer are those used in the LBGM for each of the dewatering sites.

The assumptions and resulting estimates of flow rate are summarised in Table E.4. The Isle of Dogs station and Hertsmere Road shaft have been treated as one location as they fall within the same model node in the LBGM. A large equivalent radius has been used in the calculation of flow rate for this combined site.

It should be noted that the required flow rates presented in Table E.4 are only rough estimates using very broad assumptions. In reality, as demonstrated during previous construction dewatering activities, the flow rates required to achieve the desired drawdown may vary significantly from that expected. The main sources of variation in the flow rate are the effective permeability and the effective partial penetration (assumed to be 20 m into the Chalk). However, the estimates of drawdown local to the abstraction points are quite robust. For example, if the flow rate required to achieve the target drawdown is found in practice to be 50% higher than the estimate, then the effective permeability must also be higher by 50%. The equations used above demonstrate that increasing these values in the same ratio will have no impact on the radius of influence and, consequently, little impact on the pattern of drawdown local to the wells.

[1] Groundwater Control: design and practice, CIRIA C515, 2000

[2] Groundwater Control: design and practice, CIRIA C515, 2000

Table E.4: Calculation of Indicative Flow Rates

Parameter	Location							Description
	Isle of Dogs / Hertsmere Road	**Lowell Street**	**Eleanor Street**	**Blackwall Way**	**Limmo Peninsula**	**Warren Lane**	**Arsenal Way**	
k (m/d)	5	5	5	5	5	5	5	Value of k in model node in upper layer of Chalk (from LBGM)
D (m)	67	65	64	65	66	76	72	Thickness of upper layer of Chalk (from LBGM)
H (mATD)	90	85	90	90	95	100	90	Predicted water level prior to dewatering
h (mATD)	60	59	68	40	61	67	63	Assumed target drawdown level
Drawdown (m)	30	26	22	30	34	33	27	H - h
C (dimensionless)	3000	3000	3000	3000	3000	3000	3000	Empirical calibration factor assuming H-h in metres and k in m/s.
R_o (m)	685	593	502	685	775	753	616	Calculated using Sichardt formula.
R_e (m)	250	25	25	25	25	25	25	Assumed radius of dewatering wells.
Q (m^3/d)	**18748.8**	**5184**	**4579.2**	**5702.4**	**6220.8**	**6134.4**	**5270.4**	**Calculated using Thiem equation. Assume well penetrates 20 m into Chalk**
Q (l/s)	**217**	**60**	**53**	**66**	**72**	**71**	**61**	

(iii) Historical Abstraction Rates

Dewatering has been undertaken in the past at a number of sites at and close to the Isle of Dogs. Table E.5 summarises the results.

Table E.5: Historic Dewatering Flow Rates

Location	Steady state discharge (l/s)	Approx drawdown achieved (m)	Specific Drawdown (m drawdown/l/s)
Limehouse Link	30	10	0.33
Druid Street Shaft	9.5	18.3	1.93
Ben Smith Way Shaft	2	6.5	3.25
Bermondsey Station	4	5.5	1.38
Culling Road Shaft	7	2.5	0.36
Canada Water	39	10.5	0.27
Downtown Road Shaft	33.2	4	0.12
Downtown Road Additional Measures	7	4	0.57
Durands Wharf initial Scheme	23	15	0.65
Durands Wharf additional measures	1.5	1.75	1.17
Durands Wharf additional measures 2	1	2.25	2.25
Canary Wharf station	35	21	0.60
Durands Wharf	1.5	1.5	1.00
Prestons Road	230	25	0.11

(iv) Modelled Abstraction Scenario

Two abstraction scenarios were modelled, firstly with a background abstraction series, and secondly with the addition of the estimated Crossrail dewatering flow rates to the background abstraction series.

Background Abstraction Series

The background abstraction series was taken as the historic, modelled values reported for January to December 2001 with the addition of average annual amounts from planned new sources. These new sources cover Thames Water licences determined in March 2003 (the application details were received from Thames Water Utilities on 3 October 2003) for a group of wells to form their ELRED[3] scheme and part of the GARDIT[4] strategy. A permanent

[3] ELRED: East London Resource Development Abstraction
[4] GARDIT: General Aquifer Research, Development and Investigation Team

licence for a group of wells that are required to stabilise CTRL's[5] Stratford Box had not been applied for by October 2003, however, following discussion with Rail Link Engineering, it was confirmed that an abstraction of up to about 8 000 m^3/d may be applied for in the future.

Although none of these new sources had operational values for 2001, the inclusion of additional abstractions in the model scenario has been undertaken since it results in a lowering of water levels towards 1990 levels.

Neither abstraction scenario includes other temporary abstractions for CTRL Stage 2. Other than at the Stratford Box, such temporary abstractions built up in the first quarter of 2002 and full recovery can be expected by 2006-2007. Thus, there will be some significant discrepancies between the simulation and observations in the period 2002-2005.

Crossrail Abstraction Series

The construction methodology reports have been reviewed to give an indication as to the duration of pumping. The following table lists the abstractions which were added to simulate dewatering for the Crossrail works:

Table E.6: Dewatering Simulation (Q in 1000 m^3/d)

Location	July 2007	Description	Jan 2008	Description	July 2008	Description	Jan 2009	Description
Isle of Dogs	18.7	Abstract for six months at full pumping rate	14.0	After six months reduce pumping rate by 25% to maintain level	14.0	After six months stop pumping at Limmo Peninsula, Blackwall Way and Arsenal Way Shafts	14.0	After further six months stop pumping everywhere except Isle of Dogs which continues until July 2010
Lowell Street	5.2		3.9		3.9		0.0	
Eleanor Street	4.6		3.1		3.1		0.0	
Limmo Peninsula	6.2		4.7		0.0		0.0	
Warren Lane	6.1		4.6		4.6		0.0	
Blackwall Way	5.7		4.3		0.0		0.0	
Arsenal Way	5.3		4.0		0.0		0.0	

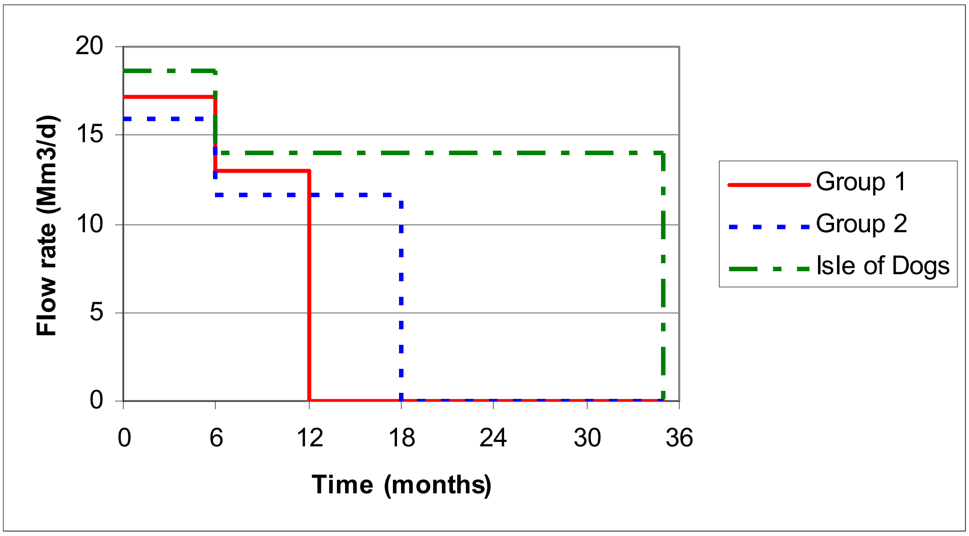
The dewatering scenario is illustrated in Figure E.2.

[5] CTRL: Channel Tunnel Rail Link

Figure E.2: Simulated Dewatering Scenario

Group 1: Limmo Peninsula, Blackwall Way and Arsenal Way Shafts

Group 2: Lowell Street, Eleanor Street and Warren Lane Shafts



(v) Simulated Drawdowns and Flows

Model results without and with the Crossrail dewatering in December 2007 can be seen in Section E.7, Figures E.3 and E.4 respectively. Figure E.5 shows the dewatering locations. The maximum drawdown is reached in December 2007. The resulting distribution of drawdown in December 2007 is shown in Figure E.6 (Section E.7). The overall pattern of drawdown shows some similarity to those observed previously during construction of the Jubilee Line Extension and during more recent dewatering at Canary Wharf.

The model also predicts that the impact of dewatering on the whole model water balance for December 2007, the last month of pumping at peak rates, is as shown in Table E.7.

Table E.7: December 2007 Water Balance

Values in 1000 m^3/d	Without Crossrail dewatering[1]	With Crossrail dewatering[2]	Change in %
Potential recharge	3 437	3 437	0
Abstraction	-411	-462	15
Flow across LBGM external boundaries	56	57	1.8
Flow from rivers	-9.7	-9.4	1
Rejected recharge (recharge that does not infiltrate into the model)	-2 615	-2 611	-0.15
Flow from River Thames to aquifer	5.7	13.7	42
Spring flow	-54	-53	-1.9
Storage changes	-404	-364	-11

1. Corresponds to model simulation run PiC7
2. Corresponds to model simulation run PiC10

The convention is that a positive flow represents a model inflow, while a negative flow represents an outflow.

The total maximum Crossrail dewatering flow rate of 51 744 m^3/d is largely balanced by an increase in storage (corresponding to a drop in the water level) and also by increased flow from the River Thames to the aquifer. The flow from the River Thames to the aquifer increases by about 8 000 m^3/d. There is also a slight change in rejected recharge, mainly from the Lambeth Group, also a result of the water level falling.

(vi) Simulated Impacts on Groundwater Abstractions

Figure E.7 (Section E.7) shows the licensed and planned groundwater abstractions and protected groundwater rights together with the distribution of drawdown in December 2007. The drawdown contours have been derived from the difference in simulated groundwater levels for each model grid cell for the two model runs. The contour plots show the regional values but do not show the local changes of drawdown for the 'near field', i.e. within about 200m of each dewatering point, since the model calculates an average value for an entire grid cell which covers an area of several hectares. However, this averaging does not affect the assessment of impacts at existing abstractions since they are more than 200 m away from dewatering points. Only existing licensed abstractions that fall within the 2 m drawdown contour are shown and, by inspection, there are 25 such wells. These are listed in Table E.8. The locations of fourteen Section 32 consents were provided by the Environment Agency on 14th November 2003. None of these consents fall within the 2 m drawdown contour. Additional wells that fall within the 0.5 m drawdown contour are listed in Table E.9 for completeness but such small drawdowns are not considered to be significant impacts.

Table E.8: Licensed and Planned Abstractions within the 2 m Drawdown Contour

Id Nr	Easting	Northing	Ref.	Licence Nr	Licensee	Annual Licence (m^3)	Daily Licence (m^3)	Modelled Drawdown (m)[1]
168	535540	179470	A	28/39/42/0048	LONDON BOROUGH OF SOUTHWARK	83804	229.6	6-8
169	533390	180180	B	28/39/42/0062	LONDON BRIDGE HOLDINGS LTD	270000	1400	2-4
170	538900	179830	C	28/39/44/0024	BLACKWALL AGGREGATES LIMITED	70000	400	12-14
171	540100	178700	D	28/39/44/0038	J SAINSBURY LTD	981266	2688	4-6
172	538550	177600	E	28/39/44/0039	TRUSTEES OF NATIONAL MARITIME MUSEUM	20000	86.4	2-4
173	539400	179300	F	28/39/44/0040	URBAN REGENERATION AGENCY	80000	600	8-10
174	538900	180050	G	28/39/44/0042	ENGLISH PARTNERSHIPS	315360	864	14-16
175	540550	178940	H	28/39/44/0043	UNITED MARINE AGGREGATES LTD	100000	400	4-6
176	539630	178090	I	28/39/44/0044	DEPT. OF HEALTH LONDON REGION	200000	548	2-4
177	538900	179830	J	28/39/44/0046	HANSON QUARRY PROD EUROPE LTD	20000	80	12-14
4	537300	183100	K	29/38/09/0142	RADIANT METAL FINISHING CO LTD	90920	545.52	4-6
5	537530	183420	L	29/38/09/0177	AGGREGATE INDUSTRIES UK LTD	30000	489	2-4
26	536500	182100	M	28/39/39/0191	THE MILE END PARK PARTNERSHIP	12330	48.2	8-10
29	537740	183700	N	29/38/09/0168	TARMAC HEAVY BUILDING MATERIALS UK LTD	15000	55	2-4
37	537900	183200	O	Proc_grw_r_1	BOW BACK RIVER		20	4-6
49	537400	183900	P	29/38/09/0113	THAMES WATER UTILITIES LTD	90921	2273.1	2-4
50	538900	183000	Q	29/38/09/0149	ANJUMAN-E-ISCAHUL-MUSLIMEEN OF UK	107000	1963.6	6-8
52	539130	181170	R	29/38/09/0162	LEE VALLEY REGIONAL PARK AUTH	30000	146.4	16-18
86	537350	179930	S	28/39/39/0179	BRITTANIA INTERNATIONAL HOTELS LTD	96624	264	18-20
87	534910	180540	T	28/39/39/0184	LONDON BOROUGH OF TOWER HAMLETS	966240	2640	6-8
97	542300	179800	U	Protected right	THAMES REFINERY, SILVERTOWN	1277500	3500	2-4
111	537583	183650	V	Section 32 Consent (111)	-	-	-	2-4

Id Nr	Easting	Northing	Ref.	Licence Nr	Licensee	Annual Licence (m^3)	Daily Licence (m^3)	Model-led Drawdown (m)[1]
113	536140	182260	W	Mile End (proposed site)	THAMES WATER UTILITIES LTD	-	2600	4-6
178	539300	180300	X	Protected right	HAVERING LOCAL AUTHORITY	-	-	16-18
179	539300	179400	Y	Protected right	GREENWICH LOCAL AUTHORITY	-	-	8-10

Table E.9: Additional Licensed and Planned Abstractions within the 0.5 m Drawdown Contour

Id Nr	Easting	Northing	Ref.	Licence Nr	Licensee	Annual Licence (m^3)	Daily Licence (m^3)	Model-led Draw-`down (m)
180	53480	18402		29/38/09/0171	OCS SMARTS GROUP LTD	175200	480	0.5-1
181	53616	18497		29/38/09/0178	METROPOLITAN WATER CO LTD	140000	3024	0.5-1
182	53730	18507		29/38/09/0086	FOXPACE LIMITED	4546	27.3	0.5-1
183	5371	1846		29/38/09/0160	DARO FACTORS LIMITED	68182	636	1-2
184	54136	18367		08/37/54/0055	B AND B'S SYCAMORE LAUNDRY	42500	178	0.5-1
185	54199	18335		08/37/54/0053	BP OIL UK LIMITED	21900	60	0.5-1
186	5419	1820		08/37/54/0042	LONDON BOROUGH OF NEWHAM	9092	45.5	1-2
187	54558	17928		28/37/44/0034	EUROPEAN COLOUR (PIGMENTS) LTD	325000	1080	0.5-1
188	53770	17654		28/39/43/0019	THAMES WATER UTILITIES LTD	12775000	37000	1-2
189	5355	1775		28/39/42/0043	NATIONAL GRID CO PLC	598980	1636.56	1-2
190	5340	1810		28/39/39/0048	NATIONAL WESTMINSTER BANK LIMITED	28217	148.2	1-2
191	5337	1809		28/39/39/0002	MARS PENSION TRUSTEES LIMITED	28185	90.9	0.5-1

1. Drawdown is for December 2007

(vii) Significance of Impacts

Since 1965 there has been a steady rise in groundwater levels in central London due to the regional reduction in abstraction. Since 1990, water levels in the area surrounding the Isle of Dogs have also been influenced by previous dewatering activities for construction of the

Limehouse Link (1990 to 1992), Jubilee Line Extension (1994 to 1997), at Canary Wharf (1999 – 2003) and for CTRL (from late 2002). The influence of these dewatering activities can be observed in the hydrographs shown in Section E.7 which also contains a location map for the observation points as Figure E.8. The observed data indicate that there was often up to a few metres rise in water level from 1990 to 2001 and that the majority of deep groundwater levels in the area have been highly modified and are not in a 'natural' condition.

The Environment Agency has advised by letter referenced NE/2003/009279-1/1 of 3 July 2003 that 'target' water levels for controlling rising water levels are those observed during 1990. This suggests that the possible aim of the GARDIT scheme within London is to return levels to near their 1990 values. This implies that any abstractors who have designed a well or chosen a pump setting depth assuming that levels would go on rising to a 'natural' level have done so at their own risk. It also implies that if dewatering lowered water levels to above the 1990 values, the EA would not consider that derogation had occurred. There is general agreement that all abstractors could reasonably anticipate that water levels would not return to their 1965 levels so the groundwater level at which derogation occurs is at or below the 1990 value. In this analysis, the 1990 Chalk groundwater levels are assumed to be the deepest water levels (below ground) at which the dewatering has 'no impact'.

The GARDIT (General Aquifer Research, Development and Investigation Team) five phase strategy to control London's rising groundwater was published in March 1999 and is now being implemented. Thames Water Utilities are managing the strategy to control the rising groundwater level by developing additional means of abstracting groundwater for public water supply. Except from an area in north-west London, where the water levels are still rising, a general fall in the groundwater levels is seen as a result of the pumping scheme. The fall is expected to stabilise within a few years (Environment Agency July 2004).

The GARDIT/ELRED strategy modelled gives a predicted fall in water levels of between 3 to 10 m from 2003 to 2008 in some areas. Therefore, in 2008, even without any dewatering activities for Crossrail, the water levels in the area surrounding the Isle of Dogs would be at or up to 6 m below the levels in 1990. Therefore, on the premise that the GARDIT/ELRED strategy develops as modelled and 1990 levels are already achieved, it is assumed for assessment purposes that any drawdown from the Crossrail dewatering activities will be considered as having an impact.

However, it is also assumed that a drawdown of less than 2 m at an existing abstraction is insignificant, given the changes in water levels that have occurred historically and the normal design practice of setting well casing to the base of the Thanet Sands and setting pumps with a large margin of headroom below current dynamic water levels. These considerations result in a very low likelihood of a pump running dry or having a significant reduction in output if an additional drawdown of less than 2 m is imposed.

Table E.10 shows a comparison of the simulated 1990 water levels and December 2007 water levels with and without Crossrail dewatering at the identified sites. The maximum drawdown is reached in December 2007. The water level given in Table E.10 is the simulated average Chalk water level in the model grid cell in which the identified abstraction is situated.

Table E.10: Simulated Water Level Change 1990 to 2008

Id	Ref	Northing	Easting	Licence Nr	Licensee	Approx Dec 2007 Water Level			Simulat - ed Jan 1990 Water Level (mAOD)
						With De-watering (mAOD)	Without De-watering (mAOD)	Difference (m)	
168	A	535540	179470	28/39/42/0048	London Borough Of Southwark	-11.8	-6.3	5.5	-0.8
169	B	533390	180180	28/39/42/0062	London Bridge Holdings Ltd	-17.1	-12.8	4.3	-2.7
170	C	538900	179830	28/39/44/0024	Blackwall Aggregates Limited	-17.2	-5.8	11.5	-0.6
171	D	540100	178700	28/39/44/0038	J Sainsbury Ltd	-8.9	-4.9	4.0	1.8
172	E	538550	177600	28/39/44/0039	Trustees Of National Maritime Museum	-6.8	-4.7	2.0	0.5
173	F	539400	179300	28/39/44/0040	Urban Regeneration Agency	-12.8	-5.0	7.8	0.4
174	G	538900	180050	28/39/44/0042	English Partnerships	-25.0	-7.1	17.9	-1.9
175	H	540550	178940	28/39/44/0043	United Marine Aggregates Ltd	-7.9	-3.4	4.5	1.5
176	I	539630	178090	28/39/44/0044	Dept. Of Health London Region	-7.5	-4.1	3.4	1.8
177	J	538900	179830	28/39/44/0046	Hanson Quarry Prod Europe Ltd	-17.2	-5.8	11.5	-0.6
4	K	537300	183100	29/38/09/0142	Radiant Metal Finishing Co Ltd	-30.0	-26.7	3.3	-20.4
5	L	537530	183420	29/38/09/0177	Aggregate Industries UK Ltd	-30.0	-26.7	3.3	-20.4
26	M	536500	182100	28/39/39/0191	The Mile End Park Partnership	-28.9	-13.5	15.4	-7.8
29	N	537740	183700	29/38/09/0168	Tarmac Heavy Building Materials UK Ltd	-30.0	-27.5	2.6	-20.4
37	O	537900	183200	Protected right	Bow Back River	-29.6	-24.6	5.0	-18.8
49	P	537400	183900	29/38/09/0113	Thames Water Utilities Ltd	-32.9	-31.0	1.9	-21.5
50	Q	538900	183000	29/38/09/0149	Anjuman-E-Iscahul-Muslimeen of UK	-24.8	-19.7	5.1	-14.3
52	R	539130	181170	29/38/09/0162	Lee Valley Regional Park Auth	-27.8	-8.3	19.5	-3.3
86	S	537350	179930	28/39/39/0179	Brittania International Hotels Ltd	-20.0	-6.2	13.8	-1.4
87	T	534910	180540	28/39/39/0184	London Borough Of Tower Hamlets	-17.8	-9.6	8.2	-3.3
97	U	542300	179800	Protected right	Thames Refinery, Silvertown	-4.7	-1.9	2.8	0.6
111	V	537583	183650	Section 32 Consent (111)	-	-30.0	-27.5	2.6	-20.4
113	W	536140	182260	Mile End (proposed site)	Thames Water Utilities Ltd	-32.2	-27.6	4.7	-19.9
178	X	539300	180300	Protected right	Havering Local Authority	-18.8	-6.1	12.7	-0.9
179	Y	539300	179400	Protected right	Greenwich Local Authority	-12.8	-5.0	7.8	0.4

E.4.2 Implications for Crossrail

The impact of dewatering the deep aquifer at Lowell Street, Hertsmere Road, Eleanor Street, Limmo Peninsula, Warren Lane, Blackwall Way and Arsenal Way Shafts and the Isle of Dogs Station has been predicted using the London Basin Groundwater Model.

Table E.11 lists the locations where deep aquifer dewatering is likely to be required, and highlights the locations where a lowering of groundwater levels caused by Crossrail dewatering would have an impact on groundwater abstractions.

Table E.11: Summary of Potential Impacts

Location	Impacts on water levels?
Lowell Street Shaft	Yes
Hertsmere Road Shaft	Yes
Isle of Dogs Station	Yes
Eleanor Street Shaft	Yes
Pudding Mill Lane	Unlikely to be significant
Limmo Peninsula Shaft	Yes
North Woolwich Portal	Unlikely to be significant
Warren Lane Shaft	Yes
Blackwall Way Shaft	Yes
Arsenal Way Shaft	Yes
Plumstead Portal	Unlikely to be significant
Arsenal Way Shaft	Yes
Maidenhead	Unlikely to be significant

1. 25 abstractions are located in areas where the predicted drawdown exceeds 2 m.
2. Of these, seven abstractions have a predicted drawdown of 10 m or more.
3. The practical significance of the drawdown impact at individual abstraction wells will vary, depending on well design and pump configuration, and the fact that water levels in this area have been lowered a number of times in recent years for other dewatering activities.
4. During dewatering, water levels should be monitored in selected EA observation wells and also at some monitoring points at the dewatering sites in order to record the impacts. There may be a need for a few additional monitoring points between the main area of drawdown and some of the potentially affected abstraction sources. These points could be either at the existing wells, or at new sites. The main gap in the observations would be around 1 to 1.5 km north east of the Isle of Dogs station.
5. Crossrail will not have any significant, permanent effect on groundwater levels and flows in the deep aquifer.
6. Initial consultation with the Environment Agency and the well owners has taken place.

E.4.3 Impact of Dewatering on Water Quality

(i) Introduction

Lowering the groundwater levels is expected to increase the saline inflow from the River Thames into the aquifer. Although the London Basin Groundwater Model does not directly simulate water quality, an assessment of the change in flow from the River Thames has been undertaken to assess the potential impact on water quality at wells located within the zone where predicted drawdown is two metres or more.

(ii) Overall Water Balance

Figure E.9 (Section E.7) shows the major water balance components through time. The main features are as follows:

- The abstraction series is balanced by a rapid increase in water being taken from groundwater storage as the water level decreases. After the end of pumping the groundwater storage is replenished as the water levels recover.
- The figure also shows an increase in total flow from the River Thames into the aquifer, the flow increases rapidly in response to abstraction and subsequently, when abstraction rates decline, reduces gradually through time.
- Around 50% of the abstraction is balanced by an increased inflow from the River Thames into the aquifer.

During winter periods, there are some minor fluctuations in rejected recharge (recharge that does not infiltrate into the model) and these are balanced by changes in storage. These variations are caused by variations in the simulated groundwater level in areas of the model where the Woolwich and Reading Beds are the uppermost geological layer. In the non dewatering case, the water level is close to the surface, and the full volume of recharge may not be able to infiltrate into the aquifer, thus resulting in flow being rejected from the model. In the dewatering case, the water level is lower, and the recharge can infiltrate to fill up the aquifer. Less recharge is rejected.

(iii) Flow Direction and Magnitude

Figure E.10 (Section E.7) illustrates the direction and magnitude of groundwater flow in the upper Chalk layer for December 2007. The black arrows represent the non pumping case, while the red arrows represent the pumping case. Where the flow arrows are a similar size the red arrows are hidden behind the black arrows and this indicates no impact of pumping on flow magnitude and direction. The main features are highlighted on the figure and are summarised as follows:

- The baseline pattern of flow is from south to north under the Thames as recharge from the Chalk outcrop of the North Downs flows towards central and east London.
- The main changes to the flow due to dewatering occur in a narrow zone around the Isle of Dogs, with small changes also occurring around Eleanor Street, Warren Lane and Arsenal Way shafts.

- The flows in the Isle of Dogs area increase in magnitude and the direction of flow shifts towards the dewatering locations, largely due to enhanced flows from the River Thames into the aquifer.

Low permeability barriers restrict northward flow towards the NLARS (North London Artificial Recharge Scheme) and ELRED (East London Resource Development Abstraction) areas of London. These barriers are shown in red in Figure E.10 (Section E.7).

(iv) Interaction between the Aquifer and the River Thames (Impacts on the Aquifer)

The critical influence on potential changes in water quality in the aquifer is the interaction between the aquifer and the River Thames. Where the London Clay is absent, the saline river water is able to infiltrate into the underlying aquifer. Historical abstractions have drawn down the water levels in central London, increasing the infiltration from the river, and thus the salinity of the groundwater. The groundwater in the Isle of Dogs area is saline due to historical infiltration. This is discussed in more detail in the main text of this Crossrail Water Specialists Technical Report.

During construction dewatering for Crossrail, the groundwater levels would be temporarily lowered. As shown in Figure E.9 (Section E.7) this results in an overall increase in flows from the River Thames into the aquifer. Figure E.11 (Section E.7) shows the simulated increase in flows from the river into the aquifer caused by the dewatering (December 2007). The figure shows that the flow from the river is not uniform, but that the increased flows are concentrated around two main areas: south of the Isle of Dogs and along the Woolwich Reach. This is because in these areas the London Clay is absent and the river is thus in hydraulic continuity with the aquifer. These areas are also located close to the areas of dewatering.

Figures E.12 (Section E.7) and E.13 (Section E.7) show the components of the water balance in more detail. These indicate that lateral flow also increases greatly in the pumping scenario, as well as inflow from the River Thames. The figures show that cross sections marked five and seven (south of the Isle of Dogs and the Woolwich Reach) show the biggest increase in river inflow. In contrast, in cross section six there is a big increase in horizontal flow, although only a minor part is attributed to increase in river inflow. Along the reach of the Thames shown in cross section six, the lower permeability Woolwich and Reading Beds are present at the surface, preventing vertical throughflow from the river. The dewatering abstraction is balanced by an increase in horizontal underflow within the Chalk, rather than vertical flow from the river. The flow components in the cross sections do not always sum to zero. This is because abstractions and flow along the direction of the river are not taken into consideration.

(v) Impact of Effluent Discharge on the River Thames

The majority of the effluent from dewatering of the deep aquifer will be discharged into the River Thames near to the locations listed in Table E.4. The effect of the discharge of dewatering effluent on the Thames water quality has been examined as discussed below.

The quantity of dewatered effluent to be added to the Thames was assumed to be 0.6 m^3/s (600 l/s) based on the sum of the indicative flow rates outlined in Table E.4. This is a relatively small discharge rate compared to that of the Thames. The freshwater input to the River Thames at Teddington Weir, Kingston, i.e. ignoring downstream rivers such as the Wandle and the Lea, ranges from a 95% low value of around 8 m^3/s to a 10% high value of 162 m^3/s. EA data for the River Thames in Appendix C show that the chloride concentration in river water (measured at Woolwich) varied from around 30 to over 3000 mg/l in 2001-2002 and may vary by around 345% daily between high and low tide. This appears to be a result of the varying amount of dilution of the saline tidal inflow by freshwater outflow.

The dewatering effluent is expected to have a chloride content of the order of 1000 mg/l. The chloride concentrations and flow data in the Thames are values observed on selected dates in 2001-2002.

As shown in Table E.12, the potential changes in salinity of the Thames due to dewatering effluent were calculated to be in the range -29 to +16 mg/l. In all cases, the changes narrow, rather than widen, the variation in river salinity. River water and groundwater are sometimes similar; there was virtually no difference in water quality at all on 30/05/02.

The calculations are conservative in that inflows below Teddington are ignored and these will further reduce the impact of the effluent discharge.

Table E.12: Potential Change in Chloride Concentration of the Thames as a Result of Discharge of Dewatered Effluent

Date	Assumed Thames Flow (m^3/s)[1]	Observed River Chloride Concentration (mg/l)[2]	Observed Chloride Concentration in groundwater from dewatering (mg/l)[3]	Calculated Chloride Concentration (mg/l) after addition of groundwater from dewatering	Change in River Chloride concentration (mg/l)
01/11/01	55	42	1070	52	+10
05/12/01	114	67	1118	73	+6
28/02/02	210	83	1050	86	+3
30/05/02	33	1000	910	998	-2
11/07/02	38	386	1100	397	+11
31/07/02	32	2900	1300	2871	-29
25/10/02	50	30	1400	46	+16

[1]Thames flow for each of the dates mentioned was taken from the NRFA homepage. The flow rate was assumed to be equal to that measured at Teddington Weir (Thames at Kingston, ref. 39001).

[2] from Figure C.1

[3] from Figure C.2

(vi) Conclusion

The results from Section E.4.3 have been analysed to assess the impacts on groundwater abstractions located within the two metre drawdown zone (March 2008). Figure E.14 (Section E.7) summarises the predicted impact. The increased flow of water from the River

Thames is only expected to have any water quality impact at wells T, S, R, U and X (marked by red circles in Figure E.14). These are all located to the north of the River Thames, and are impacted by the pumping at the Isle of Dogs.

However, the water quality at these wells is already poor (see Appendix C), with high salinity originating from historical infiltration. There are no groundwater abstractions for potable supply in this area other than where a desalination plant has been installed. The change in water quality due to temporary dewatering for construction of Crossrail may be significant, but the severity of the impact would be minor.

The model shows that there is very little impact from pumping to the north of the low permeability barrier directly to the north of abstractions S and R. However, further monitoring of groundwater levels and quality would be required to confirm the impacts of dewatering in this area.

It is planned that the water quality be monitored during the construction period to quantify any changes. The local baseline water quality and groundwater levels should be confirmed at monitoring locations (to be proposed and agreed with the Environment Agency during the detailed design phase) prior to works commencing. The monitoring would be similar to that carried out in previous phases of dewatering. Further consultation with well owners and the Environment Agency will take place.

E.5 Dewatering: Shallow Aquifer

E.5.1 Introduction

The surface geology along the Crossrail route comprises unconsolidated deposits commonly grouped as ‘drift’ which include artificial ‘Made Ground’, alluvium, assorted sands and gravels. The highly permeable sands and gravels dominate the hydrogeological properties of the drift, and, as such, this geological unit is considered to form an upper, shallow aquifer.

All construction sites are likely to involve some ground break and excavation through the drift deposits, especially where shallow foundations are being constructed. Minor local dewatering of the shallow aquifer would be required.

E.5.2 Estimated Flow Rates Required for De-watering

An assessment of the impact of dewatering of the shallow aquifer has been made based on a standard formula quoted in many hydrogeological textbooks.

Using the Cooper Jacob equation for non-steady conditions the drawdown, s at a distance, r from the borehole, can be calculated as:

$$s = \frac{2.303 * Q * Log10(2.25 * kD * t / (r2 * S))}{4 * \pi * kD}$$

(Semi confined conditions assumed)

Where

Q = flow rate from well (m^3/s)

k = permeability of surface aquifer (m/s)

D = Saturated thickness of the surface aquifer (m)

r = radius of interest (m)

s = drawdown (m)

S = specific yield of surface aquifer

Firstly, the flow rate Q was determined which, with a permeability of 100 m/d, would achieve:

- Scenario 1A where s = 2.5 m at r = 2.5 m after 10 days, representing dewatering around a manhole or pit (see Table E.13, Id A1.0)
- Scenario 1B where s = 2.5 m at r = 12.5 m after 50 days, representing dewatering around a shaft (see Table E.13, Id B1.0)

Then, the radius, r was determined from the equation using these flowrates and different values of drawdown. The calculations are shown in Tables E.13 and E.14 for both Scenarios: Id A1.1, A1.2, B1.1 and B1.2.

Table E.13: Drawdown Calculations, Scenario 1

Aquifer thickness D = 5 m (Medium-Thin aquifer) S=0.05						
	Scenario A - Manhole			**Scenario B - Shaft**		
Id	A1.0	A1.1	A1.2	B1.0	B1.1	B1.2
Q(l/s)	**17.4**	17.4	17.4	**20.5**	20.5	20.5
kD (m^2/d)	500	500	500	500	500	500
t (days)	10	10	10	50	50	50
r (m)	2.5	**7.2**	**166.5**	12.5	**30.7**	**437**
s (m)	2.5(design)	2.0	0.5	2.5(design)	2.0	0.5

Similarly, the equation was used with s = 5 m as starting point (Scenario 2). The calculations are shown in Table E.14.

Table E.14: Drawdown Calculations, Scenario 2

Aquifer thickness D = 10 m (Thick aquifer) S=0.05						
	Scenario A - Manhole			**Scenario B - Shaft**		
Id	A2.0	A2.1	A2.2	B2.0	B2.1	B2.2
Q(l/s)	**65.0**	65.0	65.0	**75.2**	75.2	75.2
kD (m^2/d)	1000	1000	1000	1000	1000	1000
t (days)	10	10	10	50	50	50
r (m)	2.5	**72**	**383**	12.5	**217**	**925**
s (m)	5.0(design)	2.0	0.5	5.0(design)	2.0	0.5

A steady state analysis (i.e. based on an infinite duration of pumping) was undertaken but disregarded since it appeared to overestimate the required Q for the medium-thin aquifer.

The results show that initial saturated thickness has a strong influence on the discharge required to achieve a drawdown of 50% of the thickness. The radii of influence at 0.5 and 2 m drawdown have been calculated since beyond this point the drawdown would be difficult to detect in view of the natural fluctuations in groundwater levels.

E.5.3 Implications for Crossrail

Trial calculations of drawdowns due to dewatering in the shallow aquifer are presented above using a high value of permeability of 100 m/d to represent maximum impact. The radii of influence at 0.5 and 2 m drawdown have been calculated. These calculations show that short term dewatering would produce drawdowns >0.5 m over an area of radius 166 m and >2 m over a radius of 7 m assuming 50 % dewatering of an aquifer of thickness 5 m for 10 days in order to construct a manhole or pit of diameter less than 5 m. The indicative flow rate would be less than 20 l/s.

Full scale dewatering over 50 days to assist construction of a shaft of diameter less than 25 m and lacking a cutoff wall, increases the calculated radii of influence to 437 and 30.7 m respectively. The indicative flow rate would be less than around 75 l/s. In reality these figures are only broad guides since the results are sensitive to the assumed parameters, especially the values taken for the initial saturated thickness and permeability. Values for a thick aquifer are more severe and the radii of the cones of depressions are larger as shown in Table E.14.

E.6 Shallow Aquifer: Impacts of New Structures

E.6.1 Introduction

Construction of structures such as vent shafts and station ticket hall boxes would provide a total barrier to flow in the shallow aquifer. In a few cases, long wall structures such as portal ramps or complete stations (such as Paddington) would provide longer barriers several hundred metres in width. Construction of such a barrier causes groundwater levels to rise above existing levels on the upgradient face (with a corresponding drop on the downgradient face) until the existing regional groundwater flow is redistributed around the barrier. Although the downgradient effect may be numerically more severe, the upgradient rises in groundwater levels are normally of greatest concern to buildings, utilities etc.

A simple groundwater model has been used to calculate the likely impacts on groundwater levels from a new structure acting as a barrier to groundwater flow in the shallow aquifer. The aim is to investigate the water level change as a function of the width of the structure (across the direction of groundwater flow) and of the hydraulic properties of the aquifer.

From first principles, it could be expected that the structure simply introduces a new component of hydraulic gradient perpendicular to the regional flow with the result that:

- Wider structures would lead to a greater effect on the water table and the relationship might be linear.
- The amount of rise in water levels upgradient would reduce with distance from the face of the structure as well as with offset from the centreline of the structure.
- The amount of rise in water levels on the centreline on the upgradient face would depend on the original hydraulic gradient and the relationship would be near linear.
- The structure's length, i.e. dimension in the direction of the original hydraulic gradient would have less impact on water levels than the width.

E.6.2 Groundwater Modelling

A Modflow model has been set up based on the conceptual model described in the box below. Figure E.15 shows the basic model setup.

An initial regional gradient of the water table of 0.012 (1.2%) was selected based on the closer of the contour spacings shown in the CIRIA (1993) study of the Thames Gravels and in the draft report for Crossrail on the shallow aquifer between Liverpool Street and the Isle of Dogs (Entec 2003).

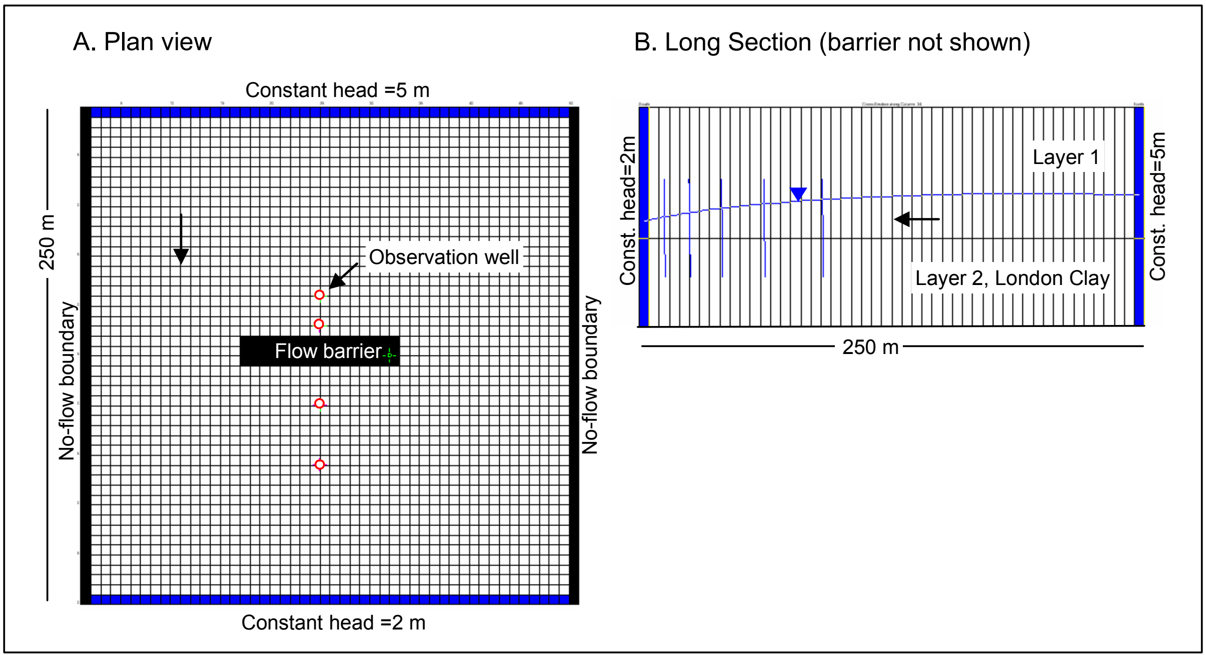
Model Description

- 250 x 250 m area divided into 5 x 5 m grid cells.
- 2 model layers:

  Upper (layer 1): Superficial deposits with a high permeability. This layer is 15 m thick and horizontal. The saturated thickness is less than 5 metres.

  Lower (layer 2): London Clay with a low permeability of $1x10^{-12}$ m/s. This layer is 10 m thick and horizontal.
- The model boundaries to the north and south are specified as constant head cells with values of 5 m and 2 m respectively. The flow is, therefore, driven by the head difference between the boundaries, which results in an average gradient of 0.012. The two remaining other boundaries are specified as no-flow cells.
- The recharge into the superficial deposits is assumed to be 200 mm/yr equal to $6.3x10^{-9}$ m/s.
- An engineered structure is represented in the model as a no-flow internal barrier in the upper layer. It has a length parallel to the groundwater flow of 15 metres and the width across the regional flow is varied.
- Water level changes are reported at notional ‘observation wells’ located around the structure.

Figure E.15: Model Set-up



A series of four ‘base case’ scenarios without a structure are used as the reference cases. Each scenario represents a different flow situation resulting from use of one of a range of permeability values. Table E.15 gives the values used for the selected scenarios (in order of decreasing permeability) and Figure E.16 shows the water table across the model for these cases. In general, it is assumed that the vertical permeability is 10% of the vertical. It can be seen that for high hydraulic conductivities the water table would approach a straight line with a gradient of 0.012. Higher conductivities would, therefore, be close to the result of Scenario A1 and have not been investigated further. Scenario A4 was deemed to be so close to A1 and A2 that it was also dropped from further investigations. For low hydraulic conductivities (A5), the water table becomes distinctly curved as the saturated thickness reduces towards the downgradient end of the model.

For each of the Scenarios A1, A2, A4 and A5, the flow around the structure was simulated in a series of runs with different widths of the barrier. Water levels at the observations points in each run are then compared with the ‘base case’ scenario and the drawdowns on the downgradient side and rise on the upgradient side calculated (as positive and negative changes respectively).

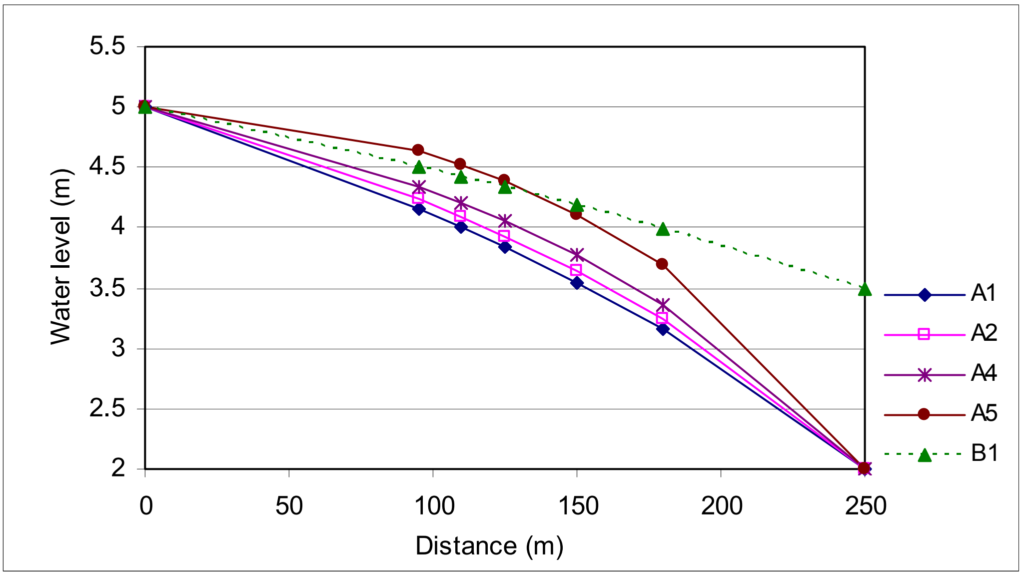
Table E.15: Hydraulic Parameters used in Model Runs

Scenario	A1	A2	A4	A5
Horizontal permeability (m/s)	$5x10^{-4}$ m/s (43.2 m/d)	$1x10^{-4}$ m/s (8.6 m/d)	$5x10^{-5}$ m/s (4.3 m/d)	$2x10^{-5}$ m/s (1.7 m/d)
Vertical permeability (m/s)	$5x10^{-5}$ m/s 4.3 m/d	$1x10^{-5}$ m/s (0.86m/d)	$5x10^{-6}$ m/s (0.43 m/d)	$2x10^{-6}$ m/s (0.17 m/d)

Note: Scenario A3 is intentionally left out

One additional scenario (**B1**) was run with the hydraulic parameters as in **A1** and a structure width of 80 m but assuming the initial hydraulic gradient was only 0.006 ie 50% of that used in **A1** to **A5**.

Figure E.16: 'Base Case' Water Levels



E.6.3 Results

The model was run with different widths of the barrier for Scenarios A1, A2 and A5. The effects on the groundwater levels are shown in Figure E.17 as predicted from the runs for an 80 m long structure in three scenarios (A1, A2 and A5). Figure E.18 shows a typical plan view of the modelling results, with the flow vectors shown as red arrows. This shows how the groundwater flows will redistribute around the structure.

The water level is reported for 'observation wells' located 20 m and 5 m upgradient of the structure and 20 m and 50 m downgradient. The greatest rise in water level is caused by the highest permeability (A1) and would be approximately 0.4 m, at a distance 5 m from the structure reducing to 0.15 m at a distance of 20 m. At a location 50 m downgradient of the structure, the water table would be around 0.2 m lower than the base case situation.

Figure E.17: Impacts on Water Levels from an 80m-wide Structure

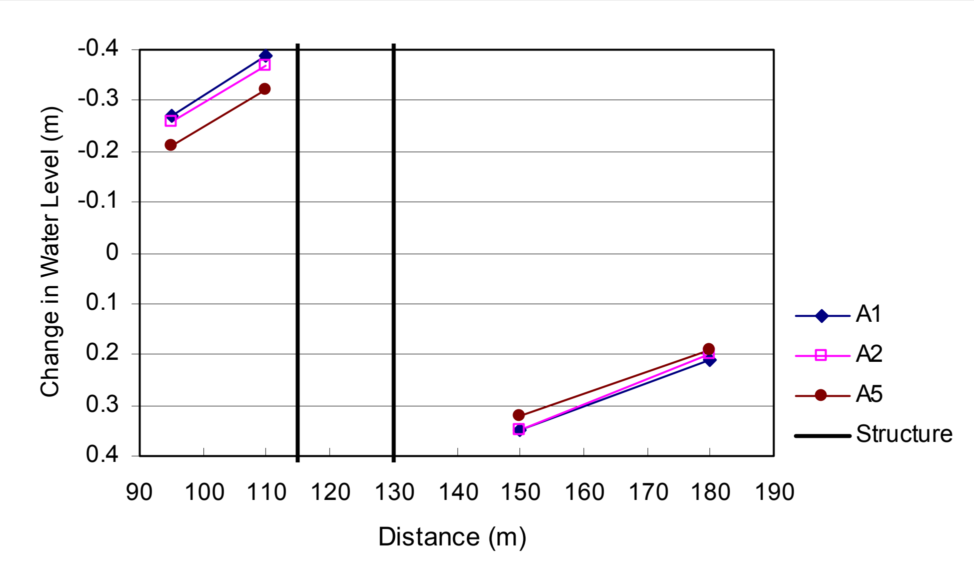
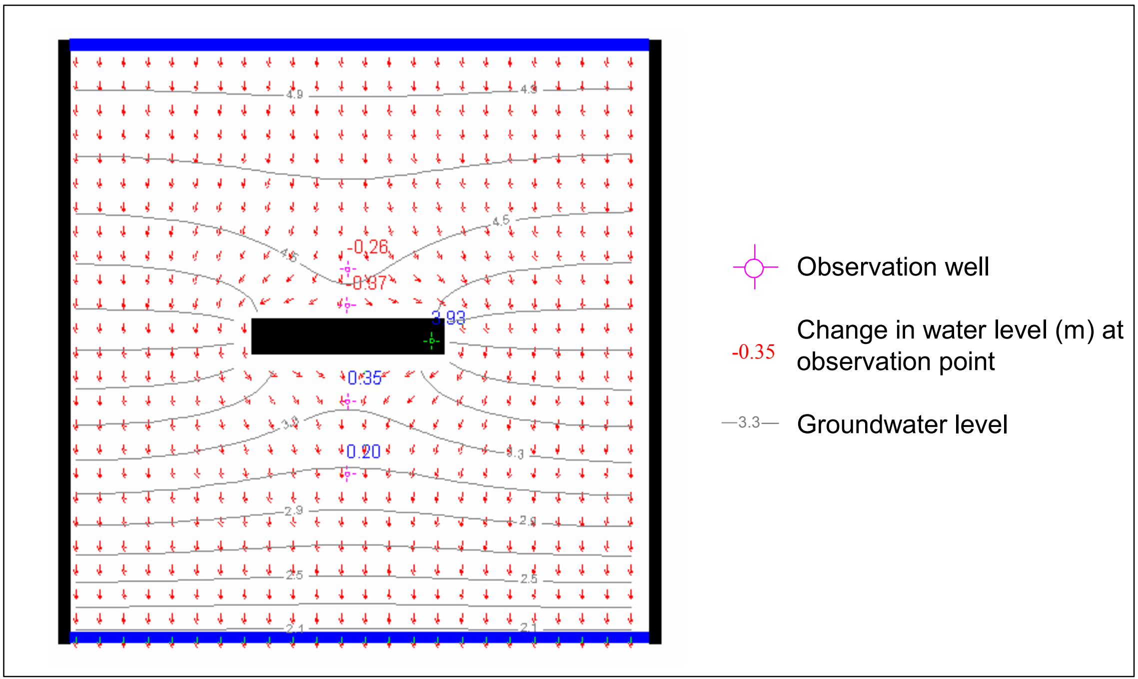


Figure E.18: Model Results (Plan View)



The results from the modelling of all runs and scenarios are presented in Table E.16 and Figure E.19 shows a graphical comparison of most results.

Table E.16: Model Results

Scenario	Width of Structure	Change in Water Level from Base Case Scenario (m)			
		Upgradient		Downgradient	
		20 m	5 m	20 m	50 m
A1	40	-0.12	-0.2	0.14	0.08
A1	60	-0.2	-0.3	0.24	0.14
A1	80	-0.27	-0.39	0.35	0.21
A2	30	-0.07	-0.15	0.1	0.05
A2	40	-0.11	-0.2	0.15	0.07
A2	60	-0.18	-0.29	0.25	0.13
A2	80	-0.26	-0.37	0.35	0.2
A2	120	-0.39	-0.52	0.56	0.35
A5	40	-0.09	-0.16	0.13	0.07
A5	60	-0.15	-0.24	0.22	0.13
A5	80	-0.21	-0.32	0.32	0.19
B1	80	-0.15	-0.21	0.18	0.1

Figure E.19 confirms that the change in water level at a given point offset along the centreline of the structure can be approximated to a linear function of the width of the structure. Since the graphs for a point on the upgradient face of the structure should all pass through the point 0,0 the function can be written as:

$$\frac{\text{Water level change}}{\text{Width}} = R \qquad \text{(constant hydraulic settings)}$$

The constant ratio (R) is unique to each hydraulic scenario and location but is very similar for A1 and A2; the high conductivity scenarios and the following was determined for the A1 case:

5 m upgradient: $R_{US5} = -0.0049$

The run for an 80 m structure under Scenario B1 (lower hydraulic gradient) gives:

5 m upgradient: $R_{US5} = -0.0026$

This confirms that, as expected, the ratio (R) is itself approximately proportional to the original hydraulic gradient (i) since this was halved from 0.012 in scenario A to 0.006 in scenario B.

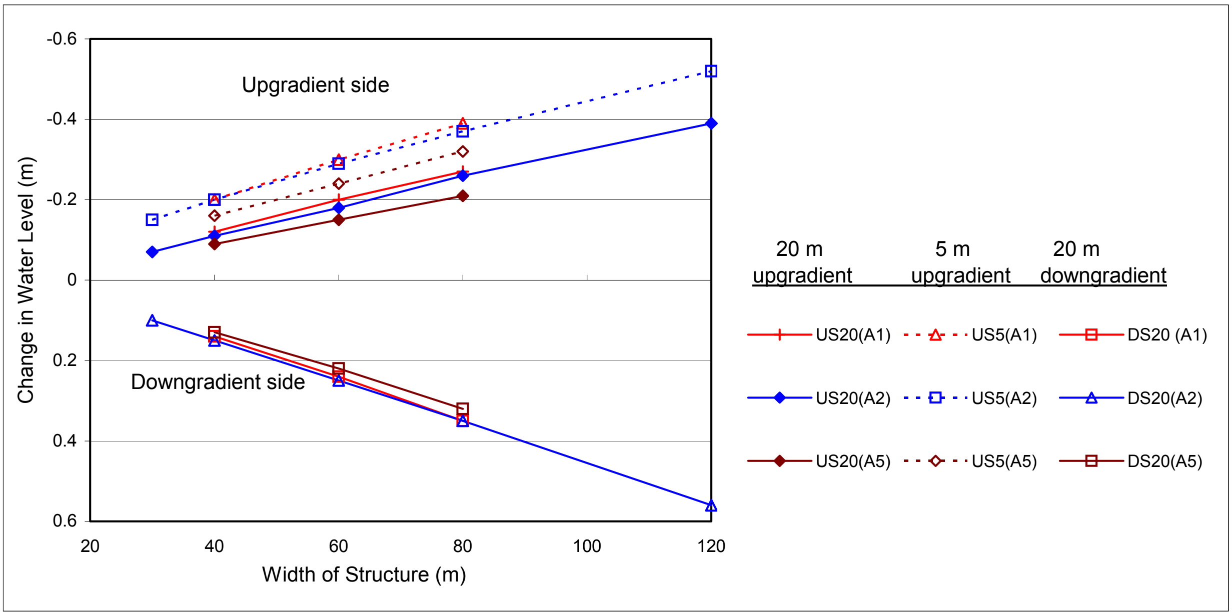
For locations further away from the structure, the linear relationship does not go through the origin 0,0 when fitted to the results over the structure widths of interest. This occurs because the zone of influence of the structure expands as the width increases so a distant location is not influenced by a small structure. The best fit lines derived for Scenario A1 are:

20 m upgradient: $s_{US20} = -0.00375 \times W + 0.028$

20 m downgradient: $s_{US20} = 0.00525 \times W - 0.072$

Where s = water level change and W = width of structure

Figure E.19: Impacts on Water Levels from a Structure



The model set-up used for this study is considered to be applicable for most cases along the Central and Eastern route section where a structure is proposed in the shallow aquifer.

E.6.4 Main Findings

- The water level change at a given point offset along the centreline is approximately a linear function of the width of the structure and the original hydraulic gradient.
- Permeability values greater than those explored in Scenario A1 would only lead to a slightly greater effect on the water levels.
- The water level change can be expressed as a function of the structure width and the hydraulic properties of the aquifer and the original hydraulic gradient. Modelling has allowed the relationships to be explored for the hydraulic conductivities and gradients expected in the shallow aquifer and for a range of structure widths at shafts and stations that would be constructed for Crossrail.

The findings relevant to the assessment of Crossrail structures that fully penetrate the shallow aquifer are:

- A scenario with high flows and a long structure will lead to the greatest impacts.
- For Scenario A1 (worst case), the change in water level (s) for different structure widths (W) can be calculated as:

5 m upgradient: $s_{US5} = -0.0049 \times W$

20 m upgradient: $s_{US20} = -0.00375 \times W + 0.028$

20 m downgradient: $s_{US20} = 0.00525 \times W - 0.072$

- The modelling shows that for the worst case scenario, examined with an 80 m long structure located perpendicular to the groundwater flow, the rise in groundwater levels on the upgradient side of the structure is likely to be less than 0.4 m. It would be less than 0.3 m 20 m away. The situation, with an 80 m wide structure, applies at Cowcross Hall at Farringdon Station and at the Intermediate Concourse at Whitechapel Station. The longest dimensions at Bond Street, Tottenham Court Road and Liverpool Street and the other structures at Farringdon and Whitechapel are around 40 m and so the rises would be less than 0.2 m.

- The fall in the water levels on the downgradient side of an 80 m long structure would be up to 0.35 m at a location 20 away. It would be greater closer to the structure.

- For original hydraulic gradients that are flatter than 1.2 %, the impacts reduce pro rata.

- For a typical intervention shaft with a maximum width of around 20 m, the rise in groundwater levels on the upgradient side of the structure is likely to be less than 0.1 m.

- Although not considered in detail, it appears that the zone of influence of the structure may extend upgradient by a distance similar to the structure's width perpendicular to the direction of flow.

- Longer structures that would block the flow in the shallow aquifer are planned at diveunders and track lowering schemes on the western routes, the portals for the tunnels and at Paddington and Isle of Dogs Stations. Extrapolation of the model results suggests that a rise in water levels of around 1 m could occur at Paddington assuming a total width between the two shafts of around 200 m, although this has not been modelled explicitly.

These findings should be used with care as they are based on a fairly simple model study. However, they have been used to inform the assessment of impacts related to water levels in the shallow aquifer.

E.6.5 Summary of the Predicted Impacts of Works in the Shallow Aquifer

The more detailed assessments carried out for each work site have been summarised as shown in Tables E.17 and E.18. The term 'Generic' dewatering refers to the <20 l/s and <2.5 m drawdown case which is assumed to be applicable at all sites where there are groundworks since manhole and other service connections are also likely to be needed.

Table E.17: Summary of Groundwater Level Impacts in Shallow Aquifer in Central Route Section

Location	Maximum Dimension of the Structure (m)[1]	Ground Level[2] (mATD)	Top of River Terrace Deposits[2] (mATD)	Top of London Clay[2] unless otherwise stated (mATD)	Shallow Aquifer Ground Water Levels (mATD)[3]	De-watering Requirements in Shallow Aquifer	Possible Impacts in Shallow Aquifer
Royal Oak Portal	310 m ramp, 280 cut and cover box, 8 m^2 area vent shaft	121.9	Absent	119.7	Isolated pockets only due to limited thickness	Generic only	Rise of < 1.6 m due to cutoff effect; rise will be curtailed by existing drains
Paddington Station	325 m cut and cover box	122.65-127.1	122.4	120.1	119-120 (1992)	Generic only	Rise of < 1.3 m due to cutoff effect; rise likely to be curtailed by any existing drains and foundations
Hyde Park Shaft	200 m cut and cover, 13 m internal diameter vent	124.5	122.5	120	120-120.5 (1992)	Generic only	Rise of < 1.1 m due to cutoff effect; rise will be curtailed by drainage layer above cover slab
Park Lane Shaft	12.5 m internal diameter vent	127	124.7	118.3	119.5 (1992)	Generic only	Insignificant rise; < 0.1 m due to cutoff effect
Bond Street Station	40 m hall < 20 m temp shaft	119-123.5	118.7	113-116	119-119.5 in west; 116-117 at Bond Street; 119 at Hanover Gardens (1992-1993)	Generic only	Rise of < 0.2 m at hall due to cutoff effect Insignificant rise at shaft; < 0.1 m
Tottenham Court Road Station	40 m halls	124.8	122	118	118-120, a few up to 125 (1992-1993)	Generic only	Rise of < 0.2 m at hall due to cutoff effect
Fisher Street Shaft	< 20 m shaft	126	119.3	118.7	120 (1997)	Generic only	Insignificant rise at shaft; << 0.1 m
Farringdon Station	40 m halls	114-118	112-113.4	108-112	Currently unknown	Generic only	To be completed
Liverpool Street Station	40 m halls	113-114	108.6	102-107	106.23-107.3, or dry (all 1992-1993). 106.3 (2004)	Generic only	Rise of < 0.2 m at halls due to cutoff effect
Hanbury Street Shaft	14 x 32 m shaft	112.7	108.8	105	107.4 (2004)	Generic only	Insignificant rise at shaft; < 0.1 m
Whitechapel Station	80 m concourse	112-113	108.8	108	107.5-108.1 (1992-1993), or 106.3 (2003)	Generic only	Rise of < 0.4 m at concourse due to cutoff effect but influenced by any existing drains and foundations

Location	Maximum Dimension of the Structure (m)[1]	Ground Level[2] (mATD)	Top of River Terrace Deposits[2] (mATD)	Top of London Clay[2] unless otherwise stated (mATD)	Shallow Aquifer Ground Water Levels (mATD)[3]	De-watering Requirements in Shallow Aquifer	Possible Impacts in Shallow Aquifer
Pedley Street Shaft	< 20 m shaft; shotcreted temporary tunnel	112-113.7	108.8	104.4	107.5-108.1; 4 Boreholes were dry (1992)	Generic and also pumping of tunnel seepage	Insignificant rise at shaft; < 0.1 m
Stepney Green Shaft	62 m long basement	110	107.4	104	106.5 (2003)	Generic only	Rise of 0.3 m at halls due to cutoff effect; rise will be curtailed by drainage layer above cover slab
Lowell Street Shaft	18.8 m diameter shaft	109.4	106.2	103.4	104.5 (2004). Probably linked to Limehouse Basin	Generic plus 50 l/s from deep aquifer. The caisson will be sunk inside the pile cut off for the basement	Insignificant rise at shaft; < 0.1 m
Hertsmere Road Shaft	9 m diameter shaft	104.5	99.5	Absent – 93.9 to top of HF	101.2 (2004). Probably linked to Thames	Generic plus 50 l/s from deep aquifer. The caisson will be sunk inside the pile cut off for the basement	Insignificant rise at shaft; < 0.1 m
Isle of Dogs Station	475 m long box	95 base of dock level, 106 for ground around dock	94.8	Absent – 92 to top of LG	104.3 average dock level (2004)	Generic only from shallow aquifer plus 200 l/s from deep aquifer	Changes probably undetectable due to influence from tidal Thames
Mile End Park Shaft	16 m diameter shaft	109.5	104.8	103.8	106.5 (2004)	Generic only	Insignificant rise at shaft; < 0.1 m
Eleanor Street Shaft	15 m diameter shaft	110	107.8	104.05-106.76	107.1 (2004)	Generic only from shallow aquifer plus 50 l/s from deep aquifer	Insignificant rise at shaft; < 0.1 m
Pudding Mill Lane Portal	165 m long portal	105-110	101	96 east of River Lea. LC thins to the east	104 (historic)	Generic only from shallow aquifer plus small flows from deep aquifer	Possibly temporary drop due to dewatering as base slab is cast. Rise of < 0.3 m at 20 m away due to cutoff effect; rise likely to be curtailed by any existing drains

1. Lengths of structure are approximate.
2. All geological levels are approximate only.
3. Groundwater levels based on Crossrail SI data where available.
4. Young and Rutty (1991). Proc. ICE Part 1 1991 90

Key: GL- Ground Level; LC – London Clay; HF – Harwich Formation, LG – Lambeth Group; TS – Thanet Sands; CK - Chalk

Table E.18: Summary of Groundwater Level Impacts in Shallow Aquifer in South-East Route Sections

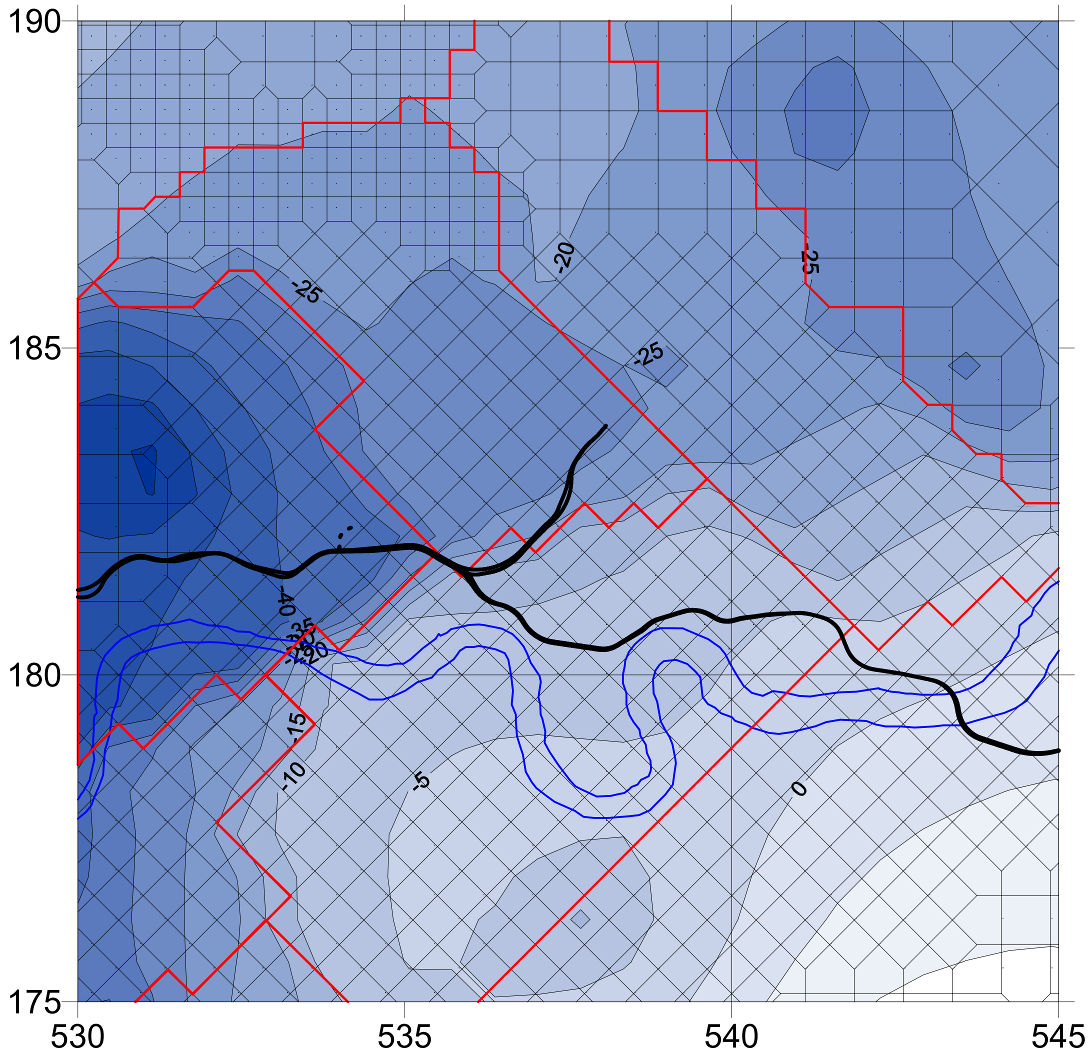
Location	Maximum Dimension of the Structure (m)[1]	Ground Level[2] (mATD)	Top of River Terrace Deposits[2] (mATD)	Top of London Clay[2] unless otherwise stated (mATD)	Shallow Aquifer Ground Water Levels (mATD)[3]	De-watering Requirements in Shallow Aquifer	Possible Impacts in Shallow Aquifer
Limmo Peninsula Vent Shaft (SE RS)	25 m diameter shaft	107.5	96	93	100 (2004)	Possible temporary > 2m drop up to 217 m away, 0.5 m drop to 925 m away due dewatering; Insignificant rise at shaft; < 0.1m	Generic plus <75 l/s from shallow aquifer if caissons give problems or unless pile cutoff used plus nominal 70 l/s from deep aquifer
Victoria Dock Portal (SE RS)	22 m diameter shaft, 60 m cut and cover, 520 m retained cut (580 m total)	102.5	97.4	90.5	98.5-99.6 (2004)	Possibly temporary drop due to dewatering as base slab is cast. Rates depend on amount of grouting and water levels. Rise of 1-2 m at 20 m away due to cutoff effect; rise likely to be curtailed by any existing drains.	Generic plus medium flows from shallow aquifer as base slab is cast
North Woolwich Portal (SE RS)	20 m shaft, 160 m cut and cover, 290 m retained cut (450 m total	102.7	96.1	Absent – 89.9 to top of CK	100 (2004)	Possibly temporary drop due to dewatering as base slab is cast. Rates depend on amount of grouting and water levels. Rise of 1-2 m at 20 m away due to cutoff effect; rise likely to be curtailed by any existing drains.	Generic plus medium flows from shallow and deep aquifer as base slab is cast
Warren Lane Shaft (SE RS)	13.5 m diameter shaft	105.26	102	Absent – 100 to top of TS	100 to 105 (2003, EA)	Insignificant rise at shaft; < 0.1 m	Generic only from shallow aquifer plus nominal 70 l/s from deep aquifer
Arsenal Way (formerly Sydney Street) Shaft	16 m diameter shaft	107.5	104.8	Absent – 102.7 to top of LG	100 to 105 (2003, EA)	Insignificant rise at shaft; < 0.1m	Generic only from shallow aquifer plus nominal 60 l/s from deep aquifer

1. Lengths of structure are approximate.
2. All geological levels are approximate only.
3. Groundwater levels based on Crossrail SI data where available.

Key: GL- Ground Level; LC – London Clay; HF – Harwich Formation, LG – Lambeth Group; TS – Thanet Sands; CK - Chalk

E.7 Figures E.3 to E.14

FIGURE E.3
December 2007 Chalk Water Levels: Without Crossrail Dewatering



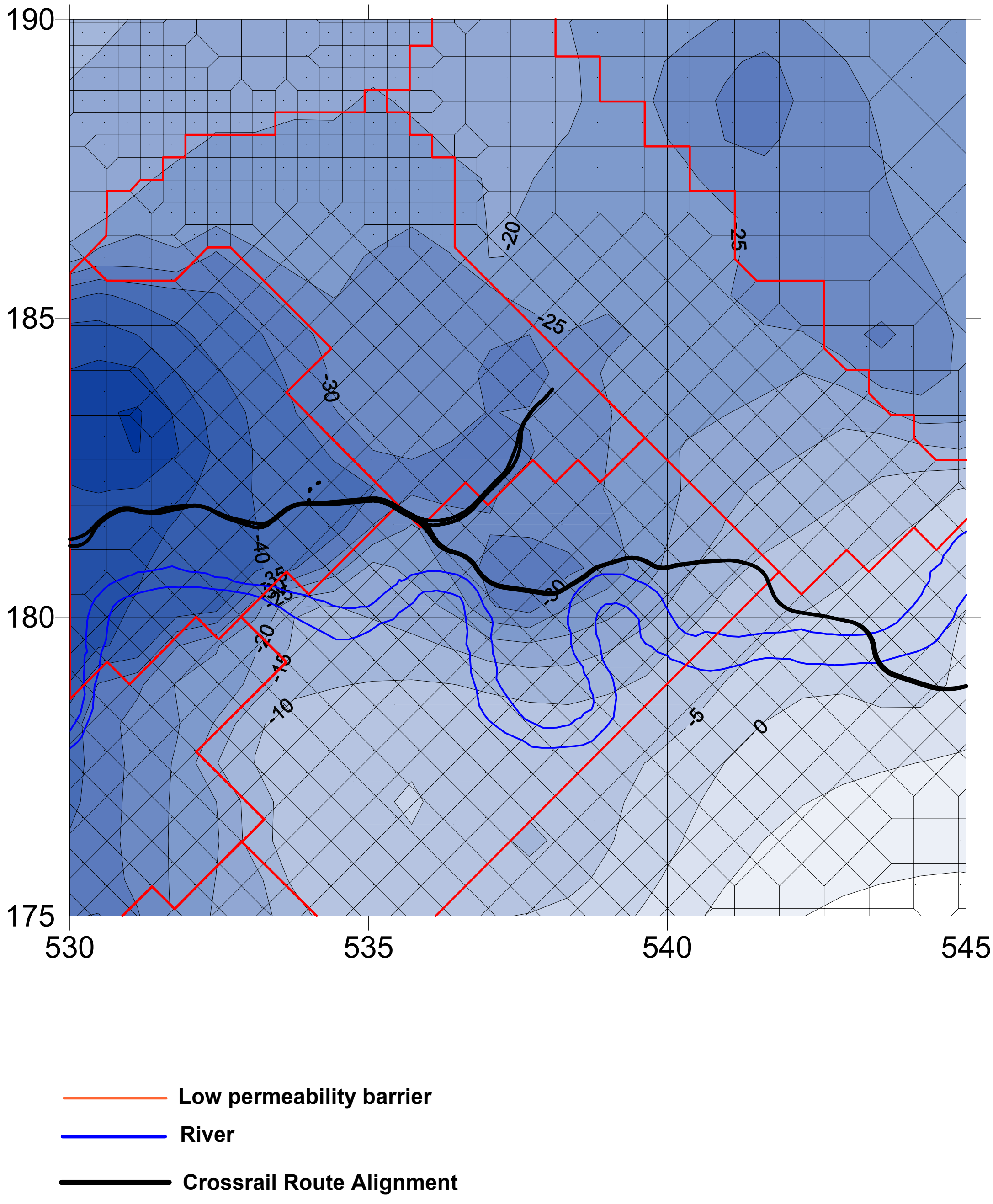
Low permeability barrier

River

Crossrail Route Alignment

Mott MacDonald

FIGURE E.4
December 2007 Chalk Water Levels: With Crossrail Dewatering



Mott MacDonald

FIGURE E.5
Crossrail Dewatering Locations

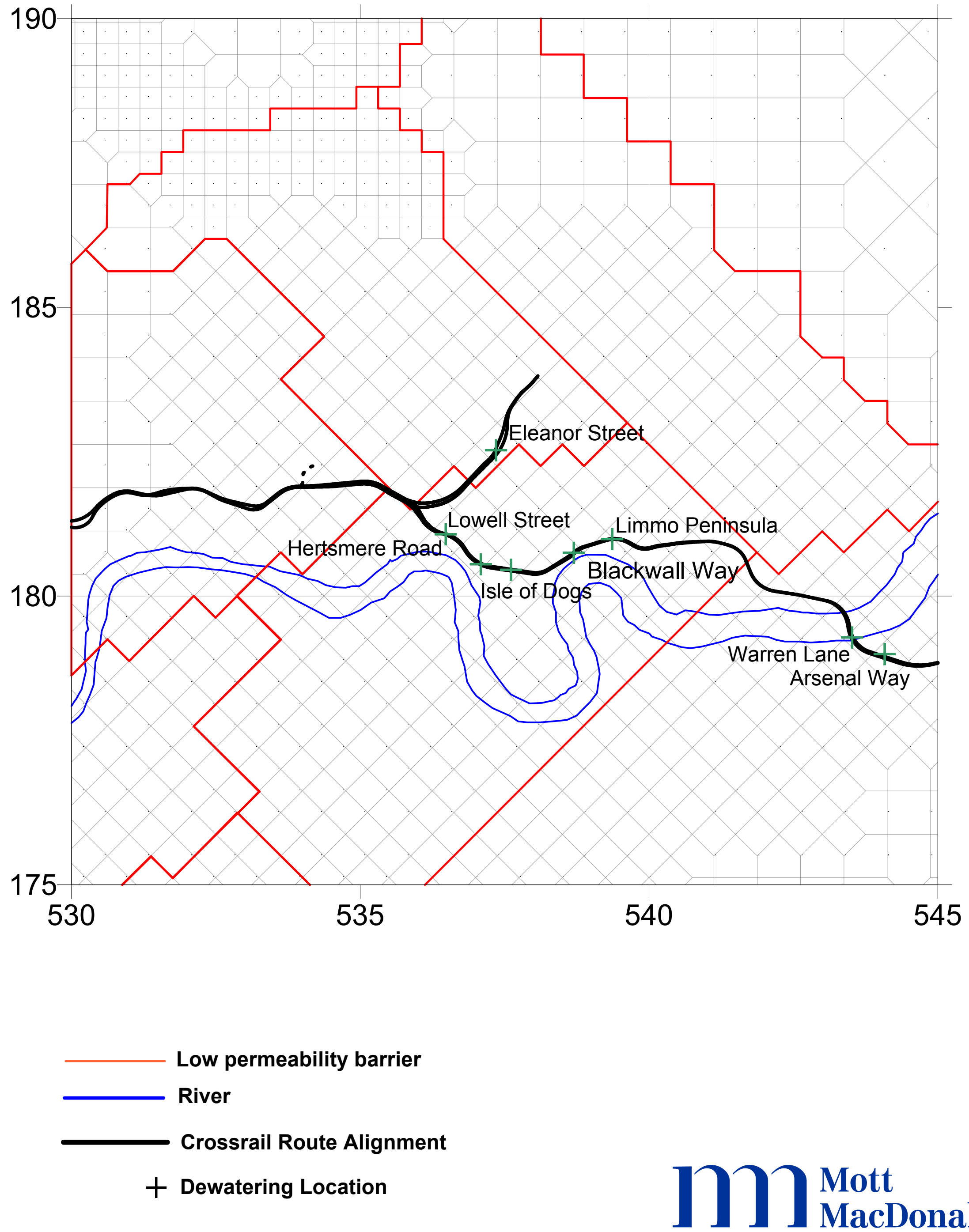
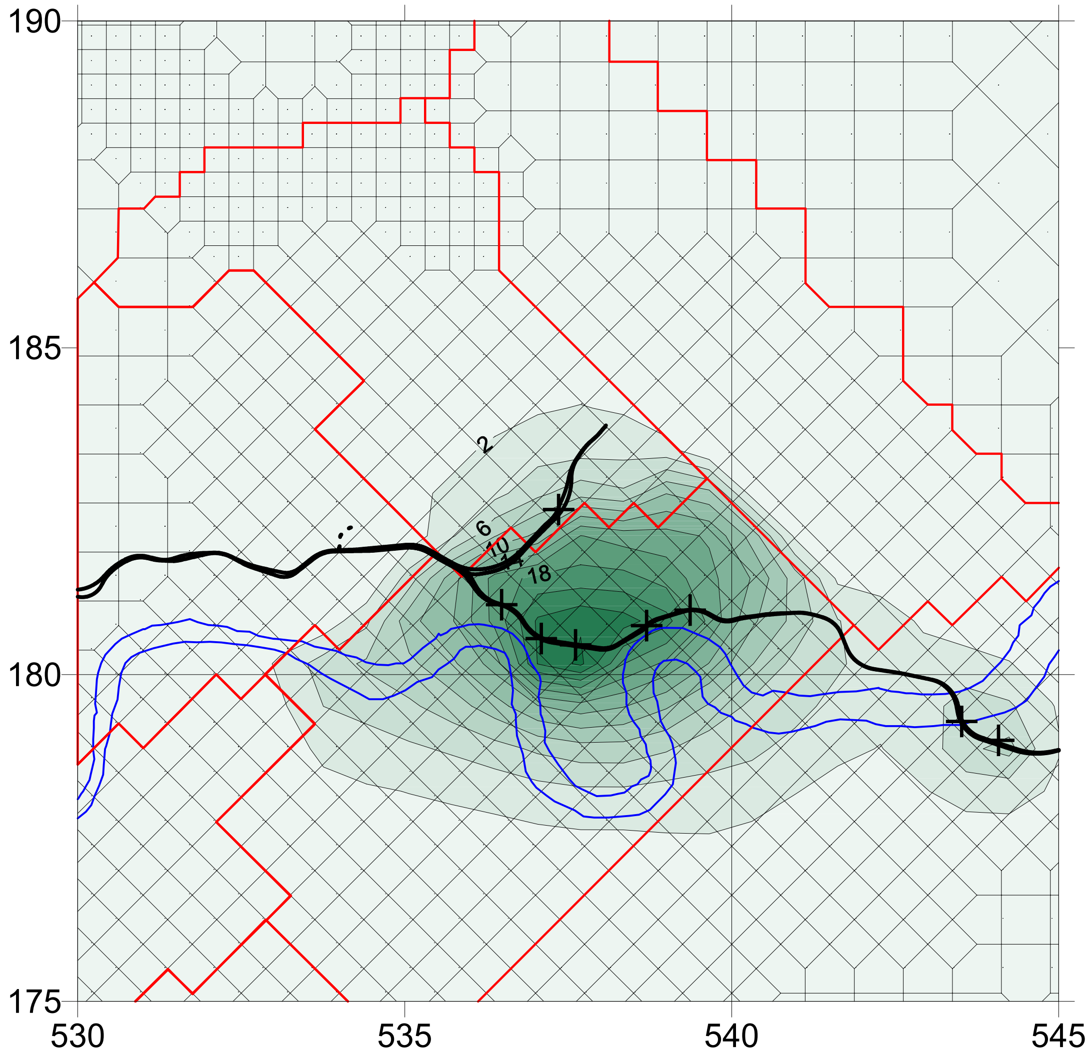


FIGURE E.6
Predicted Drawdown: December 2007



Low permeability barrier

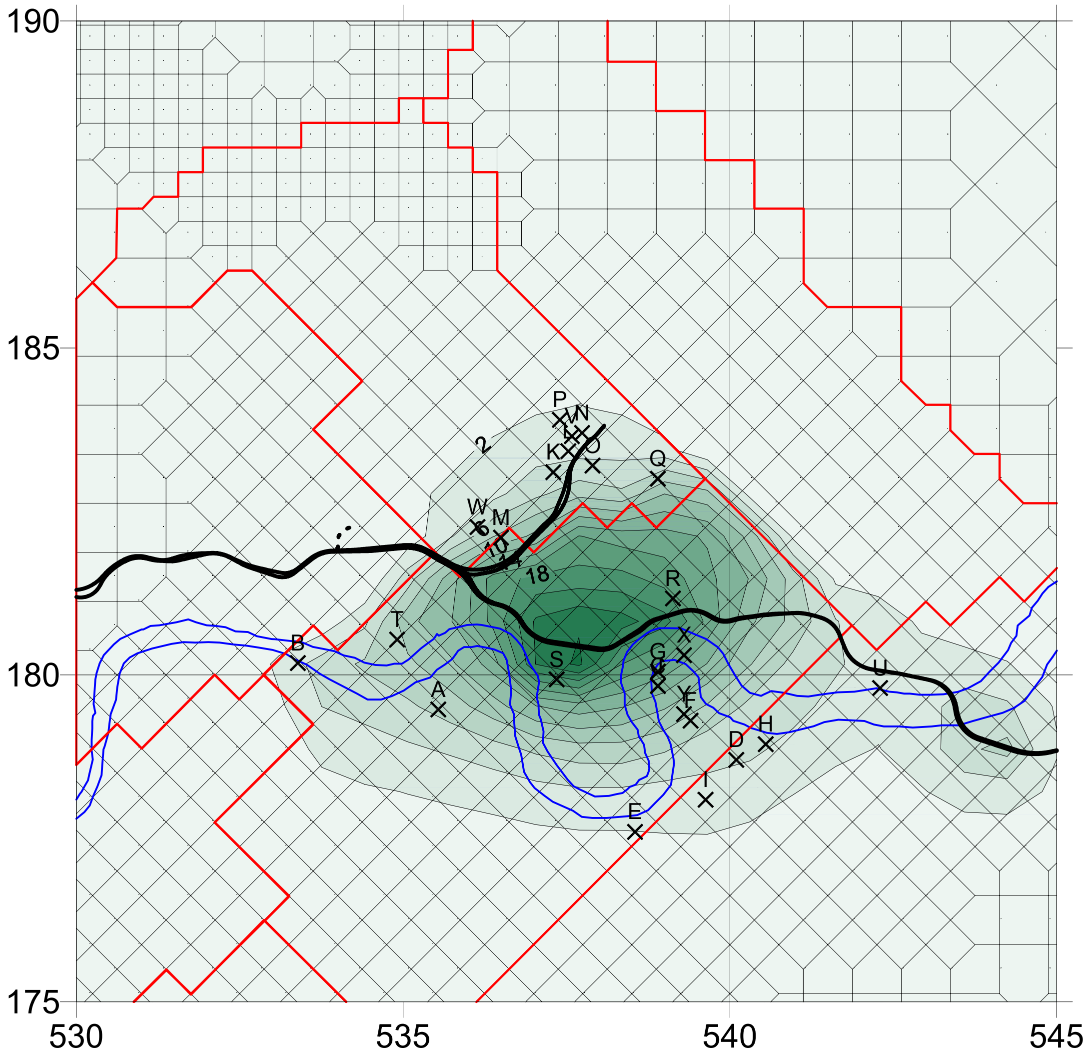
River

Crossrail Route Alignment

+ Dewatering Location

Mott MacDonald

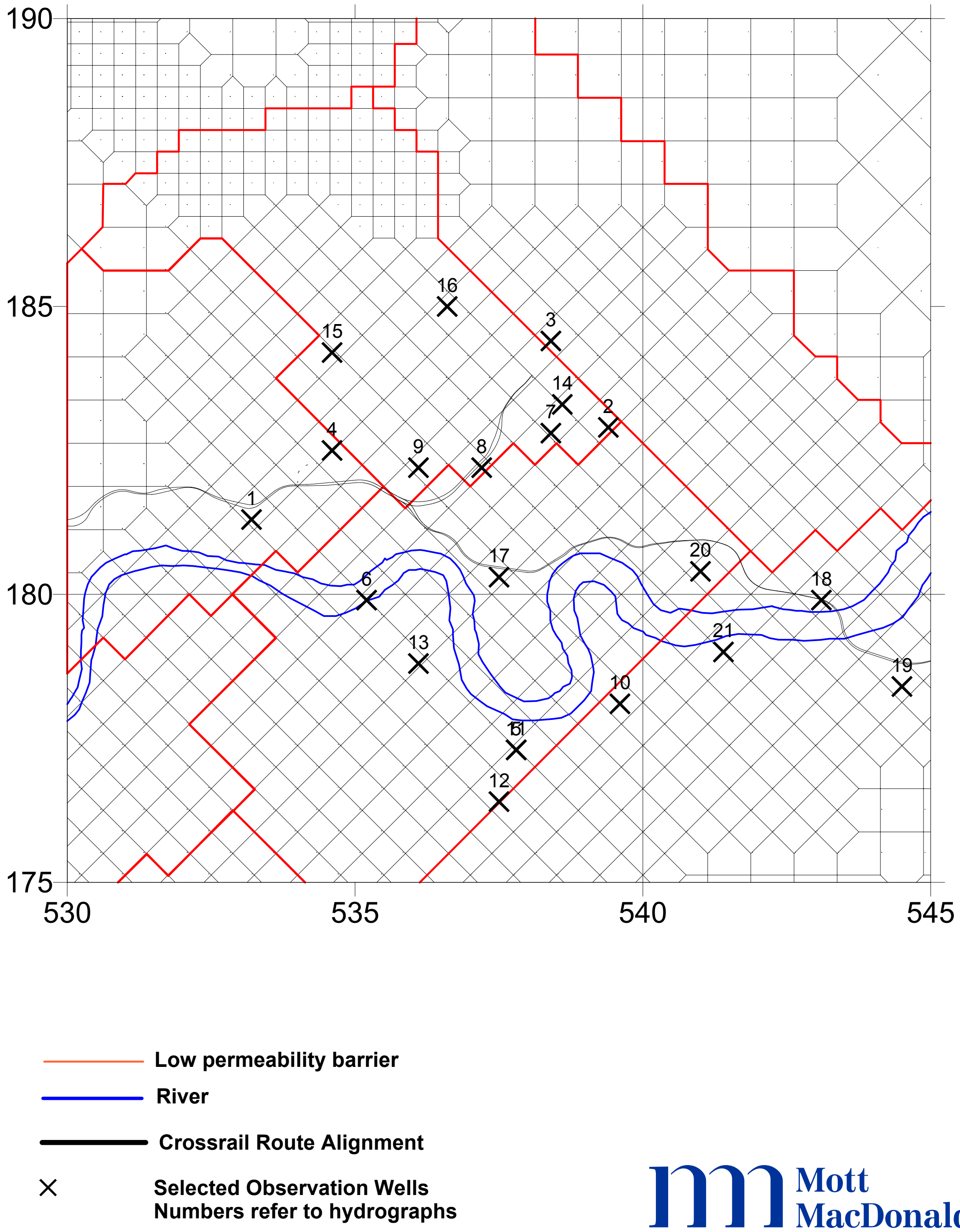
FIGURE E.7
Groundwater Abstractions and Predicted Drawdown: December 2007



Low permeability barrier
River
Crossrail Route Alignment
Groundwater Abstraction
Numbers refer to Table E.8 in Appendix E

Mott MacDonald

FIGURE E.8
Locations of Selected Observation Wells



Mott MacDonald

Figure E.9: Change in Water Balance Components due to Crossrail Dewatering

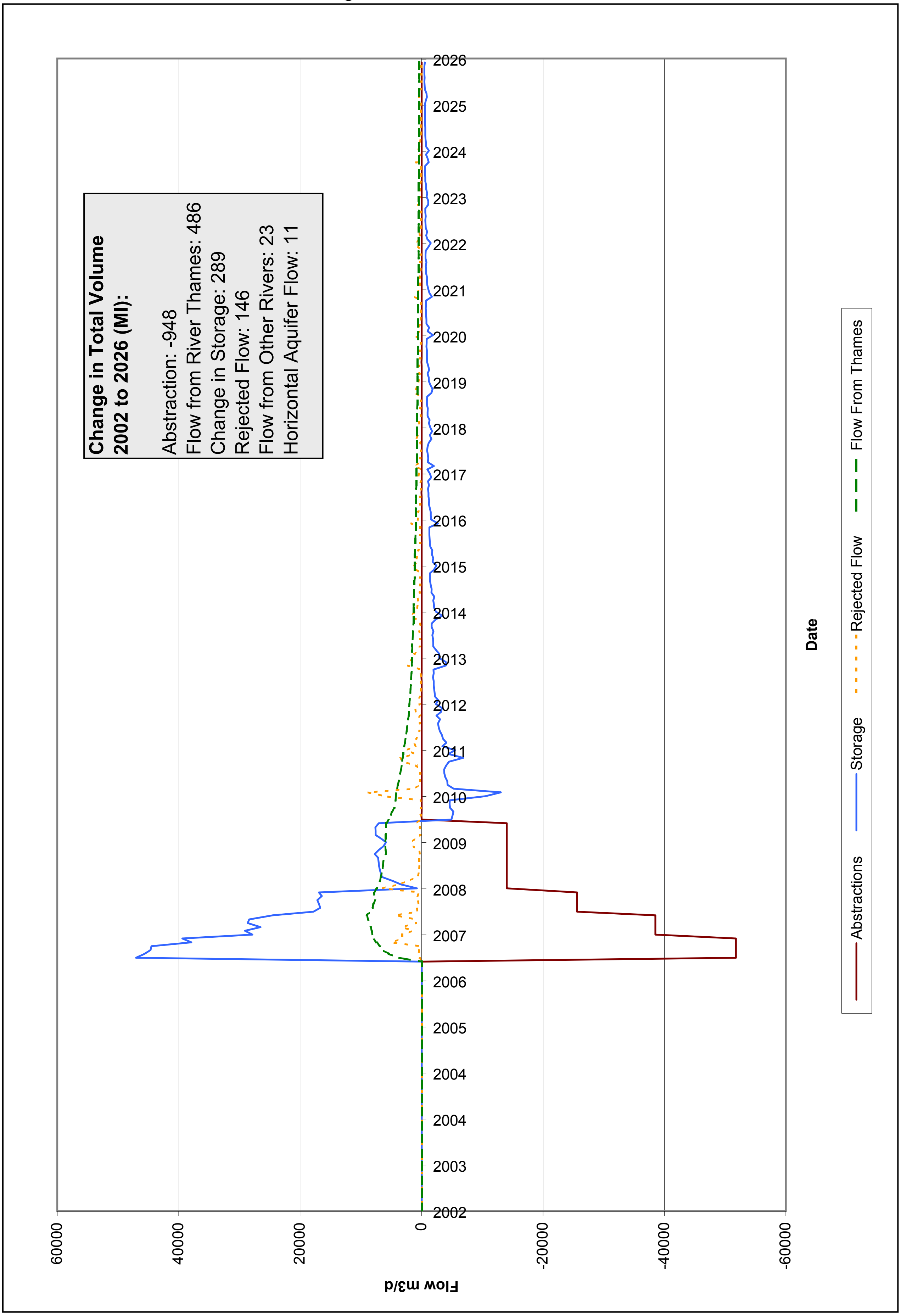
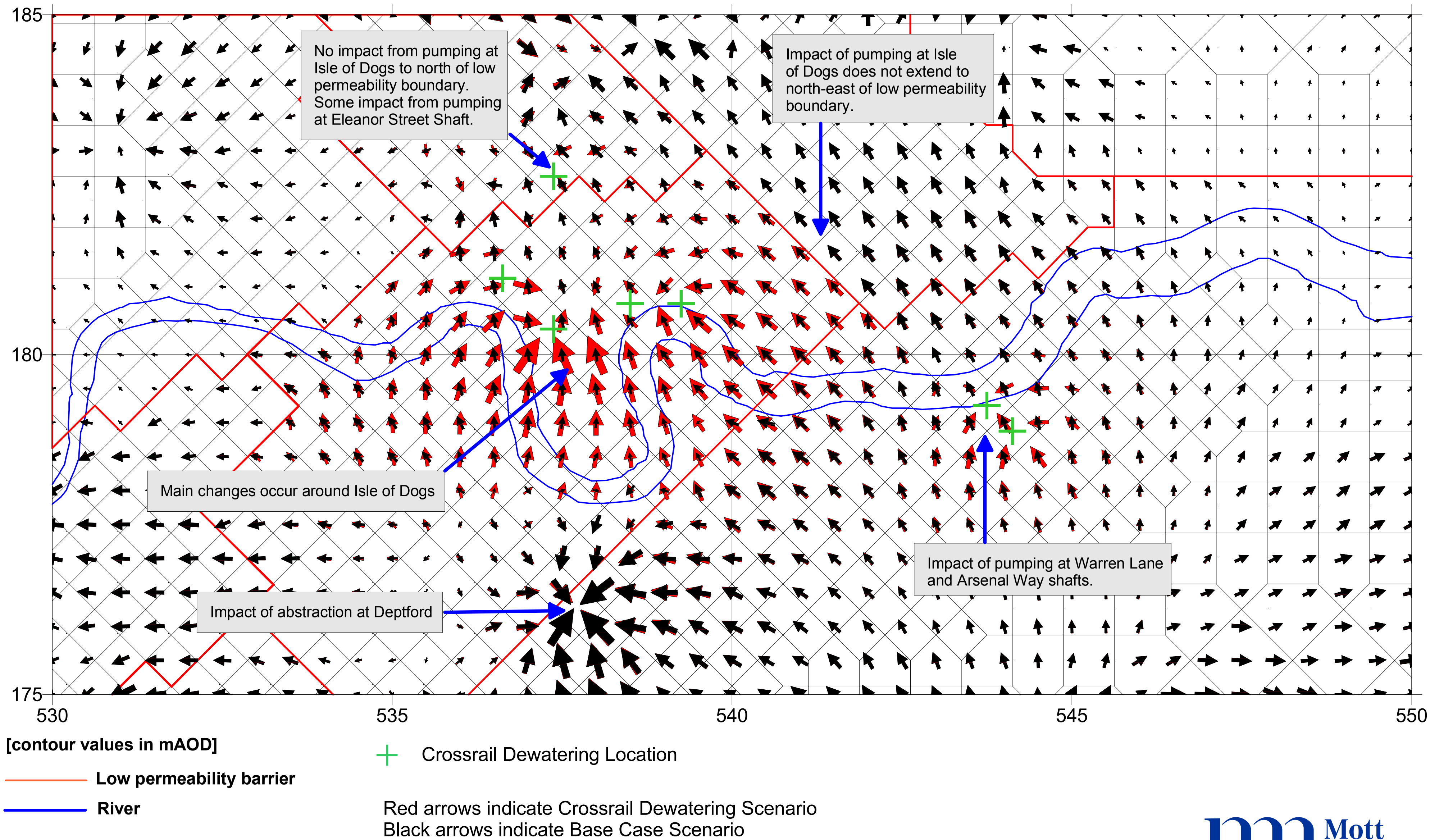
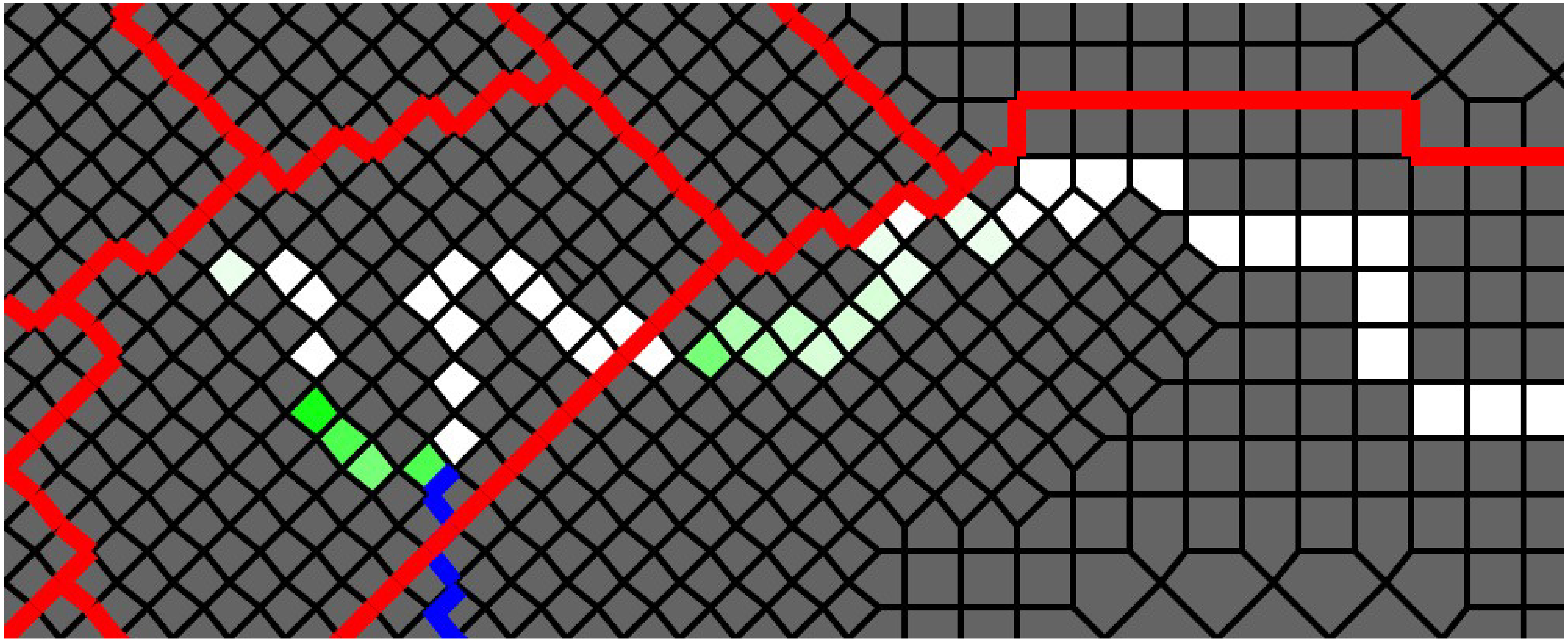


Figure E.10: Difference in Flow Direction and Magnitude with and without Crossrail Dewatering: December 2007

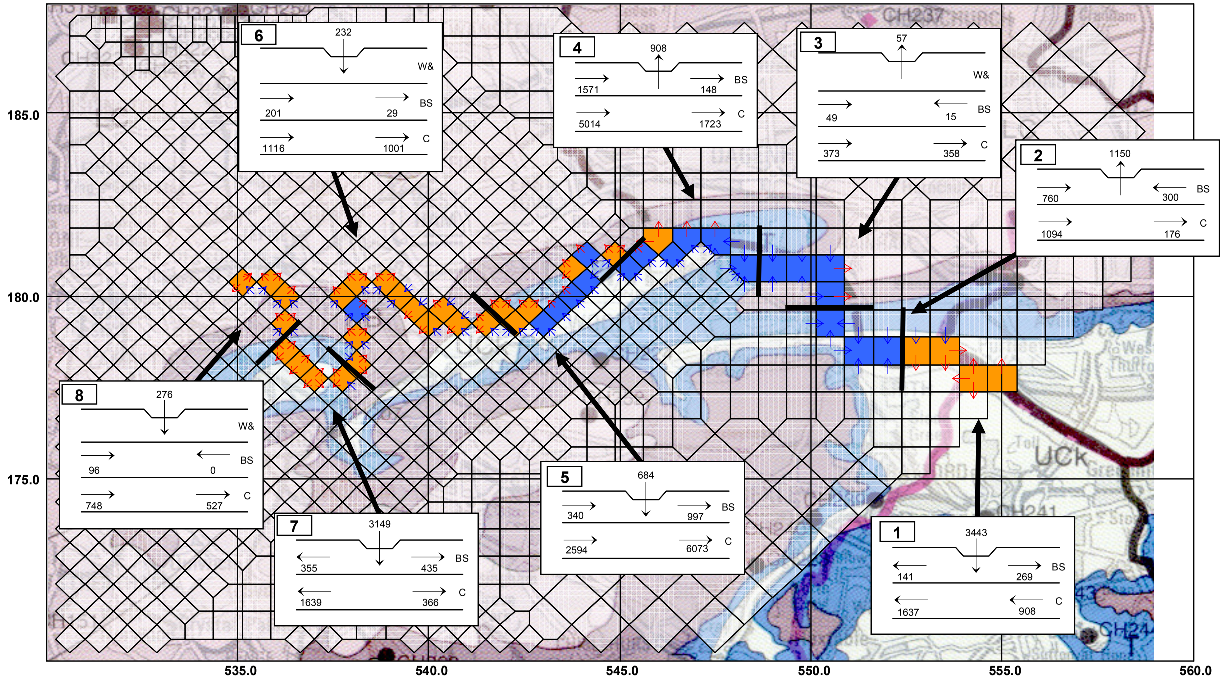


Mott MacDonald

Figure E.11: Increase in Flows from River Thames into Aquifer



Grey cells are not River Thames cells.
The shading from white to green represents the increase in flows from the River Thames. Green areas show the biggest increase.



Legend

Flows into and out of Thames

River is gaining water (removed from model)

River is losing water (recharge to model)

Flows across river node faces (Layer 3)

Flow into river node

Flow out of river node

Notes:
1. All flows shown are in m3/d summed for each reach.
2. C =Chalk (Layers 1+2)
BS = Basal Sands (Layer 3)
W&R = Woolwich and Reading Beds (Layer 4)
3. For all sections left side = south right side = north

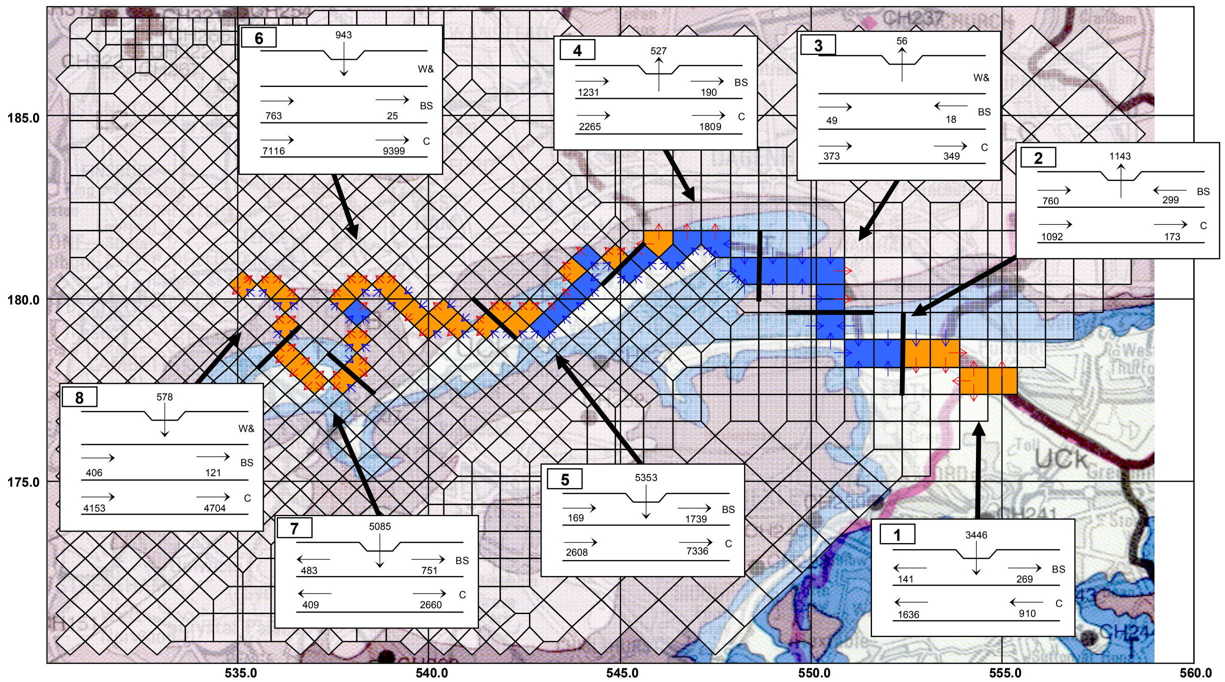
Client

Thames Water

Title

Figure E.12
PiC7 - Base Case Scenario - Interaction Between the Aquifer and the River Thames, December 2007

203357/31/Final/Feb 05
E.12.xls



Legend

Flows into and out of Thames

River is gaining water (removed from model)

River is losing water (recharge to model)

Flows across river node faces (Layer 3)

Flow into river node

Flow out of river node

Notes:
1. All flows shown are in m3/d summed for each reach.
2. C =Chalk (Layers 1+2)
BS = Basal Sands (Layer 3)
W&R = Woolwich and Reading Beds (Layer 4)
3. For all sections left side = south right side = north

Client

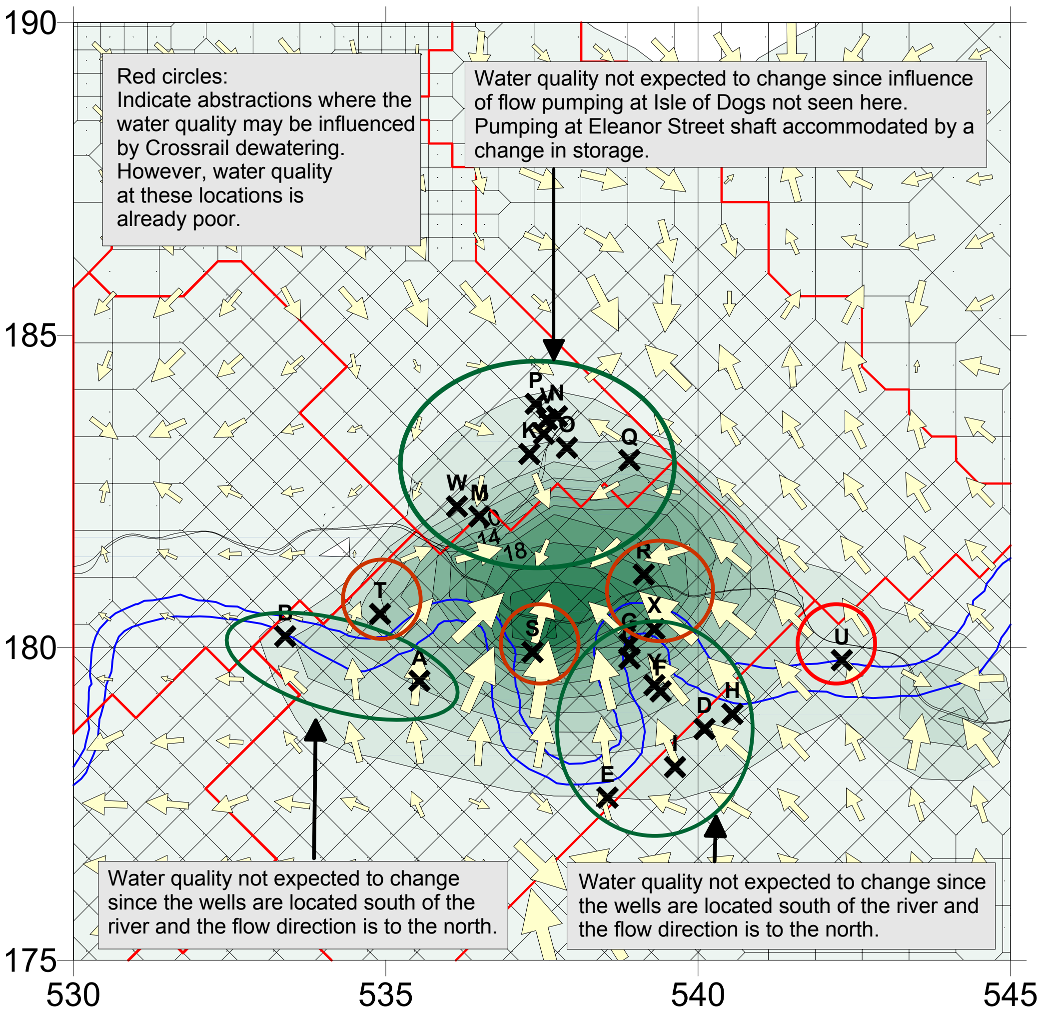
Thames Water

Title

Figure E.13
PiC10 - With Dewatering - Interaction Between the Aquifer and the River Thames, December 2007

203357/31/Final/Feb 05
E13.xls

FIGURE E.14
Groundwater Abstractions and Predicted Drawdown: March 2008



Low permeability barrier

River

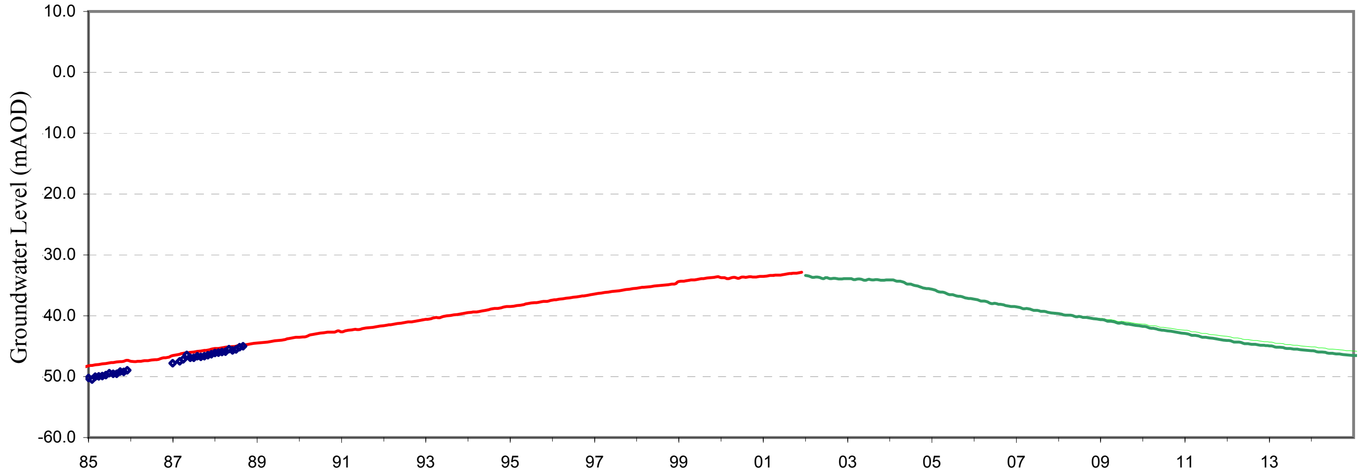
Crossrail Route Alignment

× Groundwater Abstraction
Numbers refer to Table E.8 in Appendix E

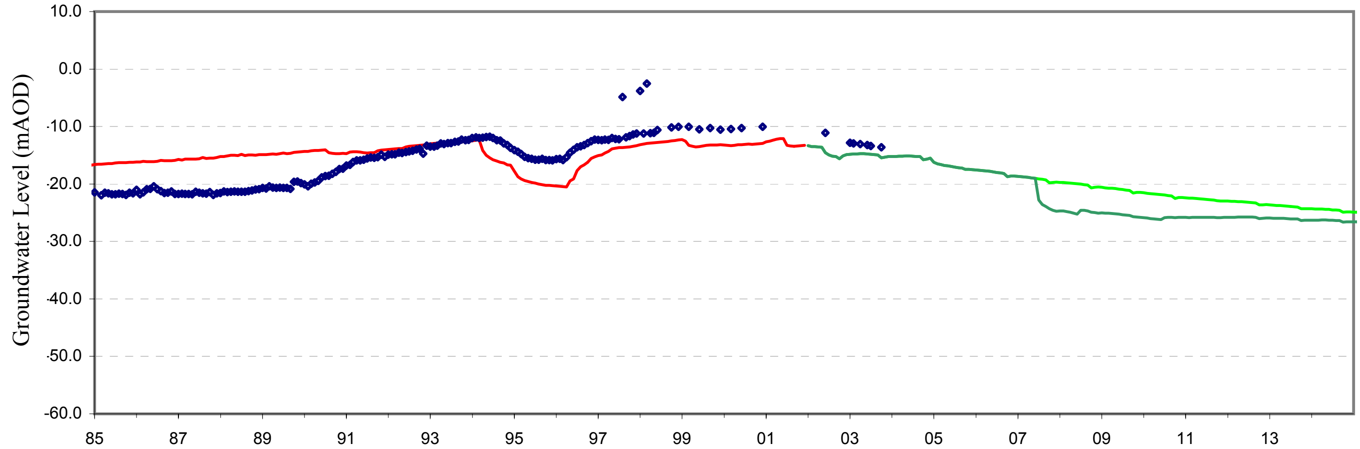
Mott MacDonald

Observed vs Simulated Groundwater Levels: 1985 to 2015

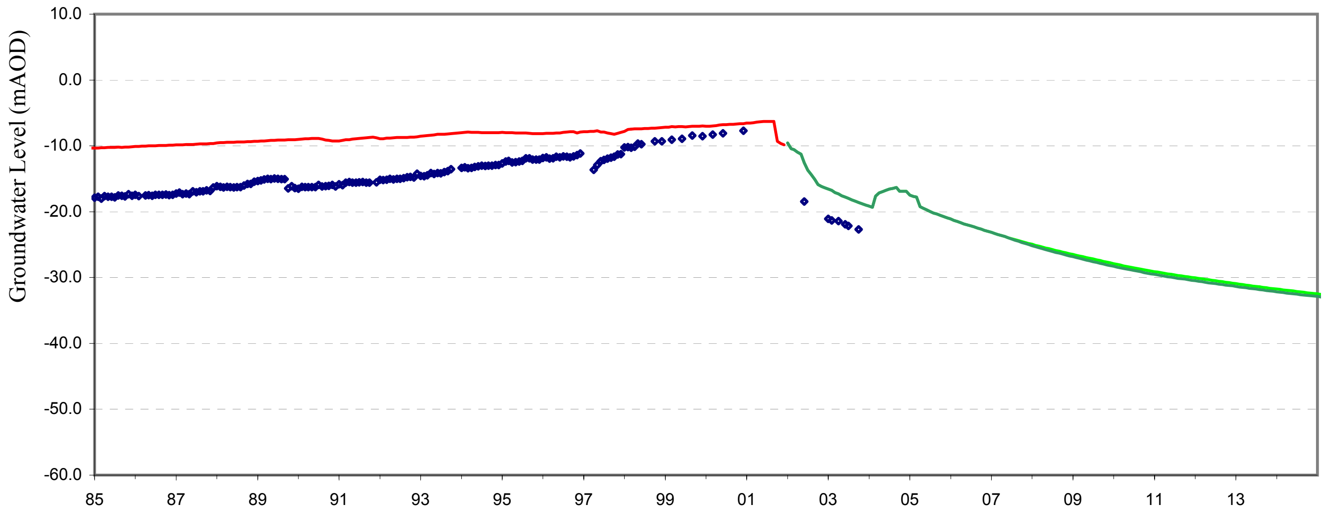
1. LEATHERSELLERS HALL - Node



2. MEMORIAL RECREATION - Node 1418



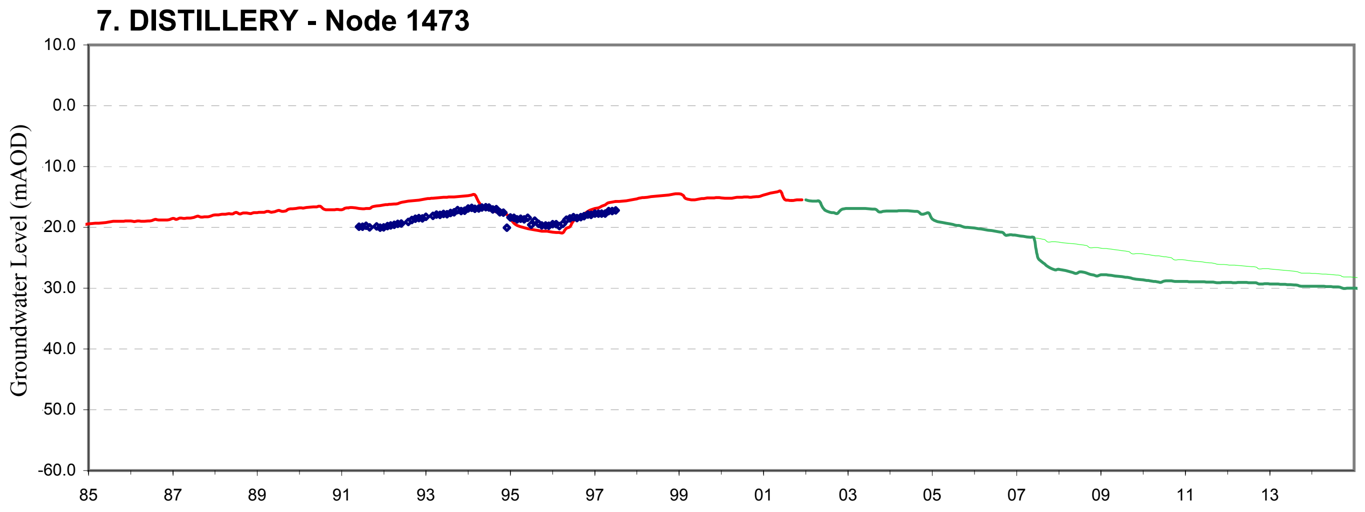
3. STRATFORD GOODYARDS - Node 1609

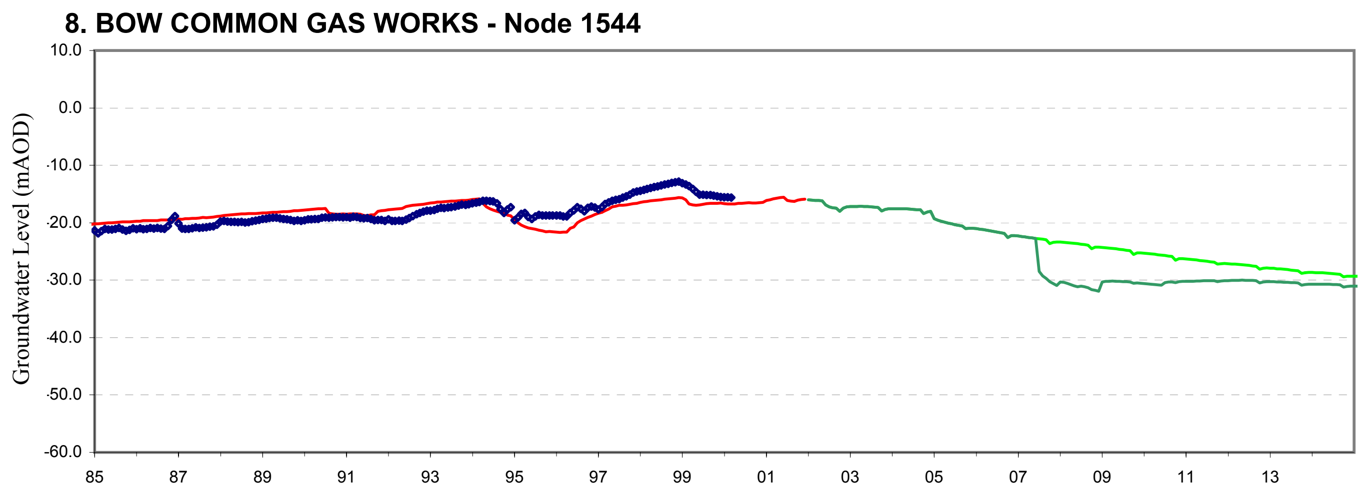


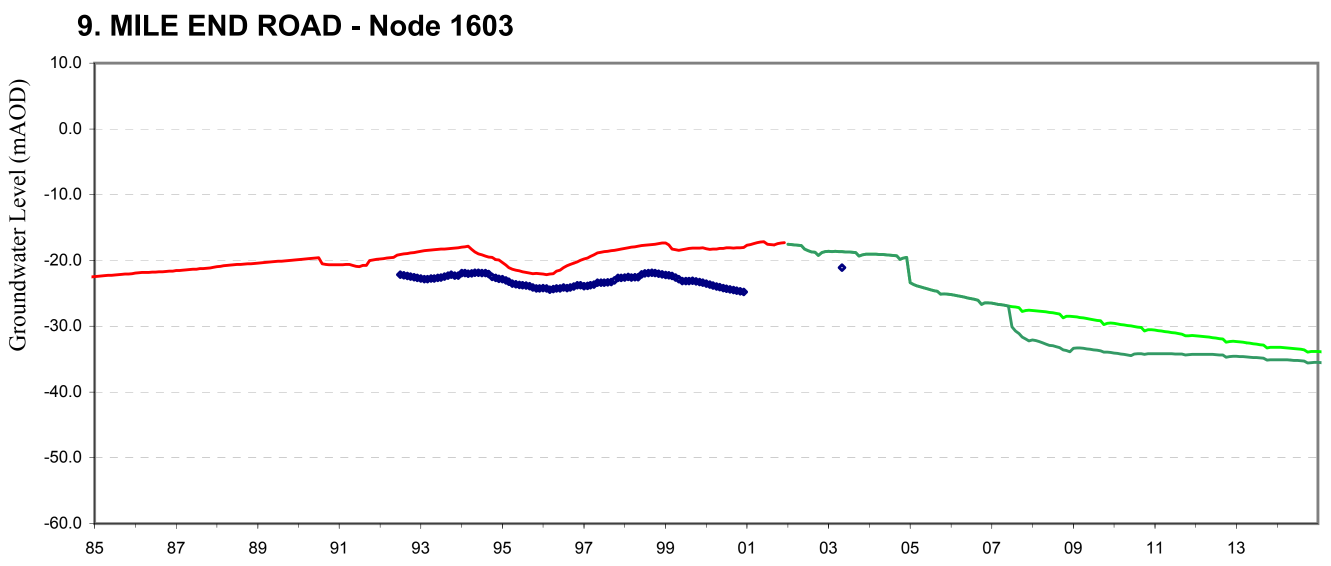
Legend:

Observation | Calibration (Ti50) | Without Crossrail | Crossrail

Mott MacDonald







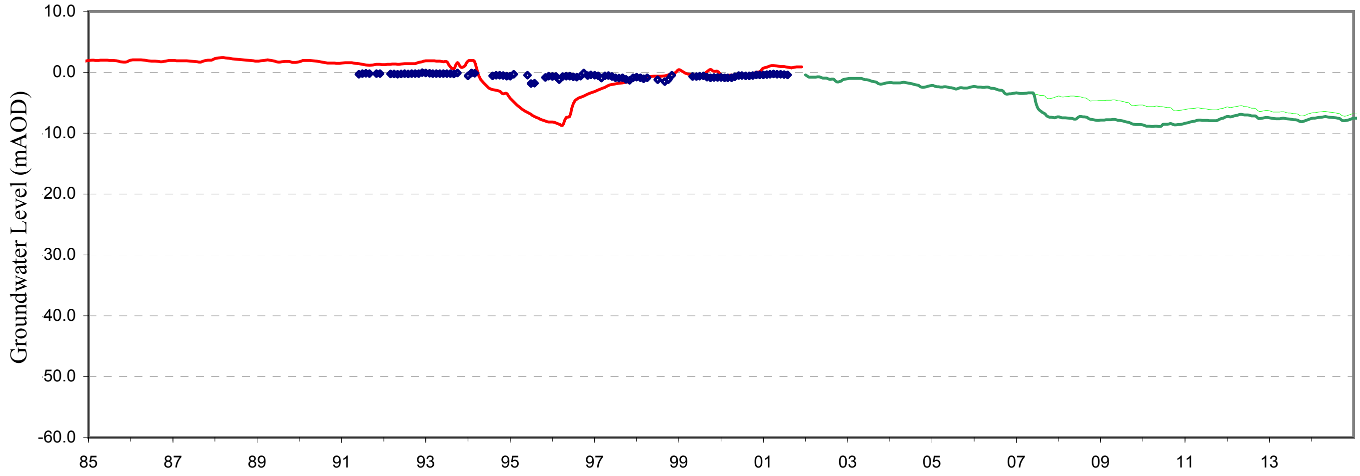
Legend:

Observation — Calibration (Ti50) — Without Crossrail — Crossrail

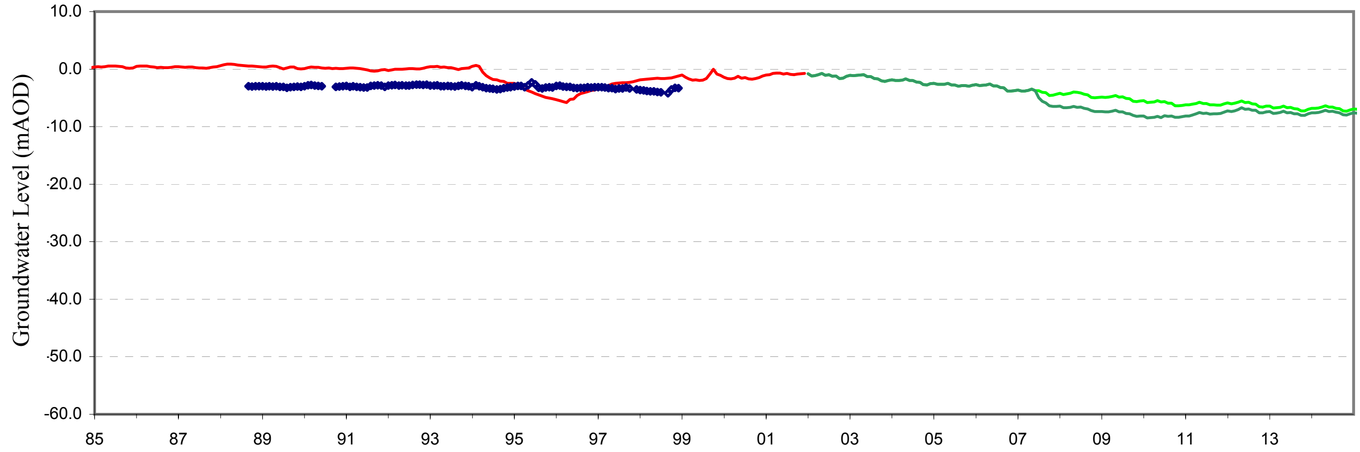
Mott MacDonald

Observed vs Simulated Groundwater Levels: 1985 to 2015

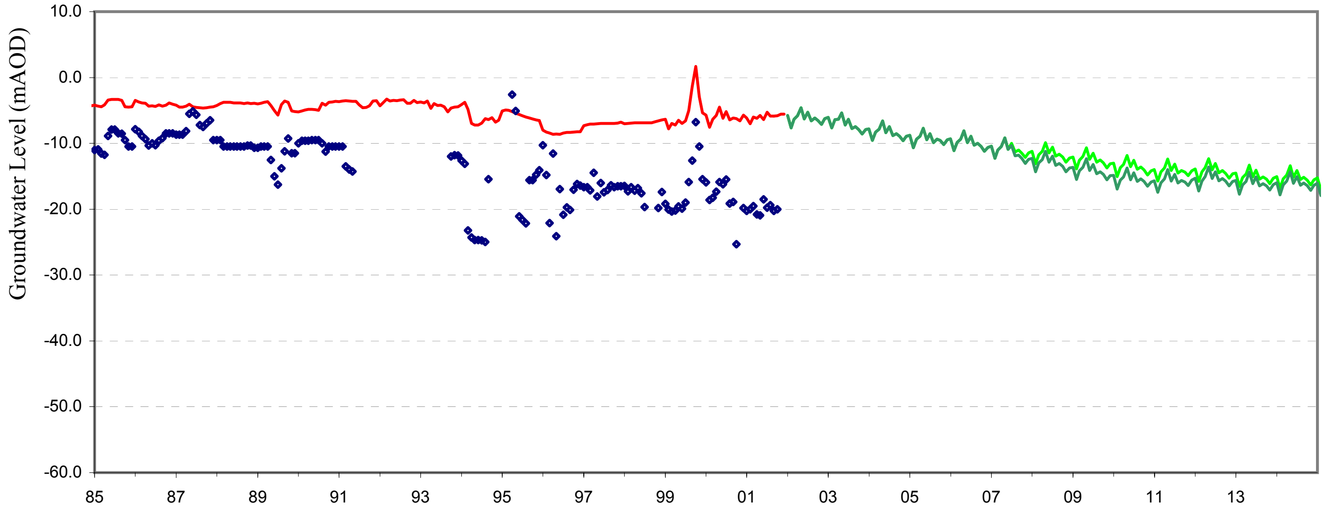
10. GREENWICH HOSPITAL - Node



11. GREENWICH LOWER TUBE - Node 1095



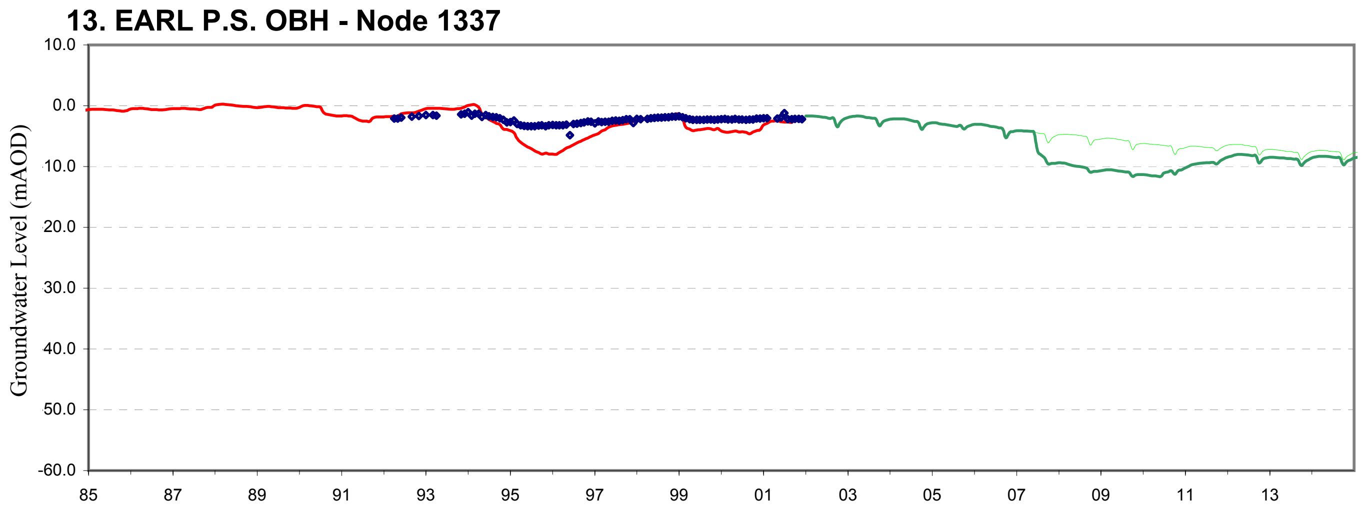
12. DEPTFORD MAIN WELL - Node 977

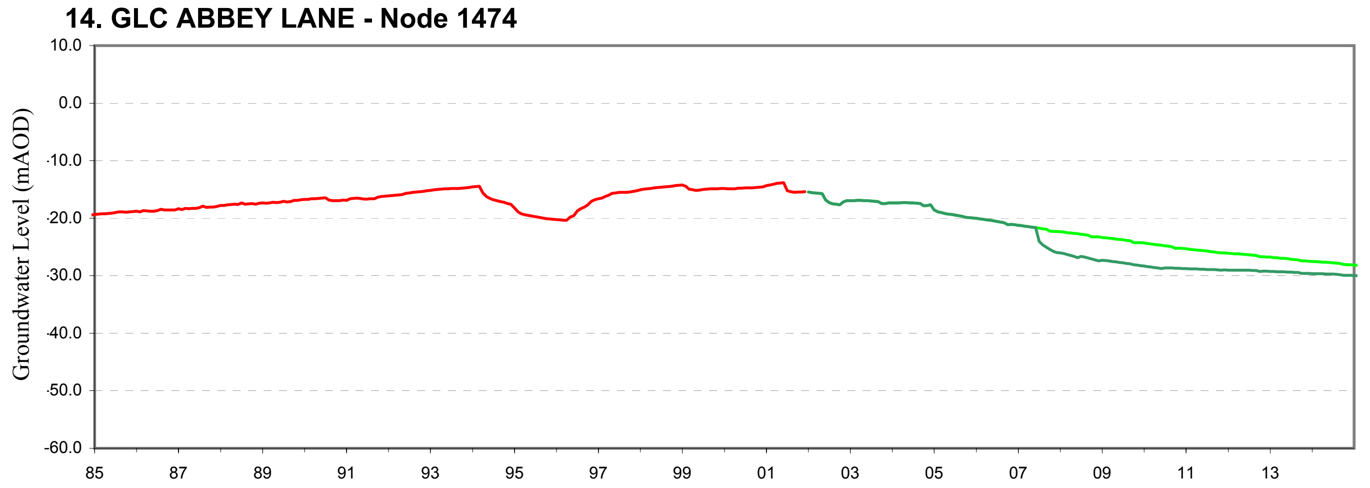


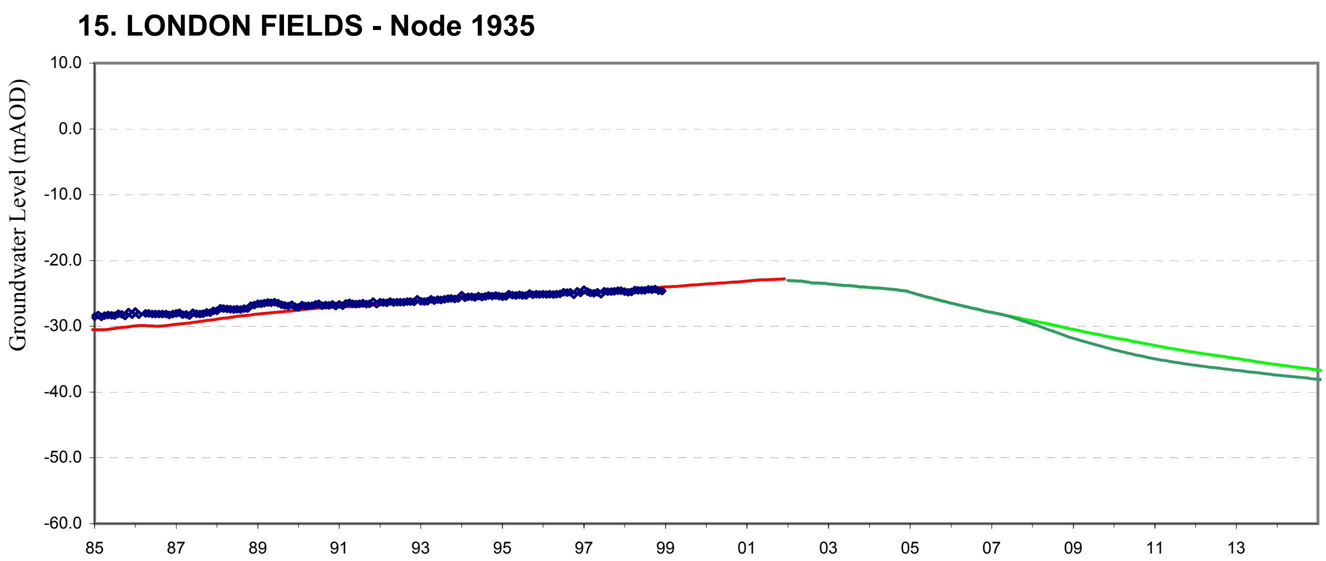
Legend:

Observation | Calibration (Ti50) | Without Crossrail | Crossrail

Mott MacDonald



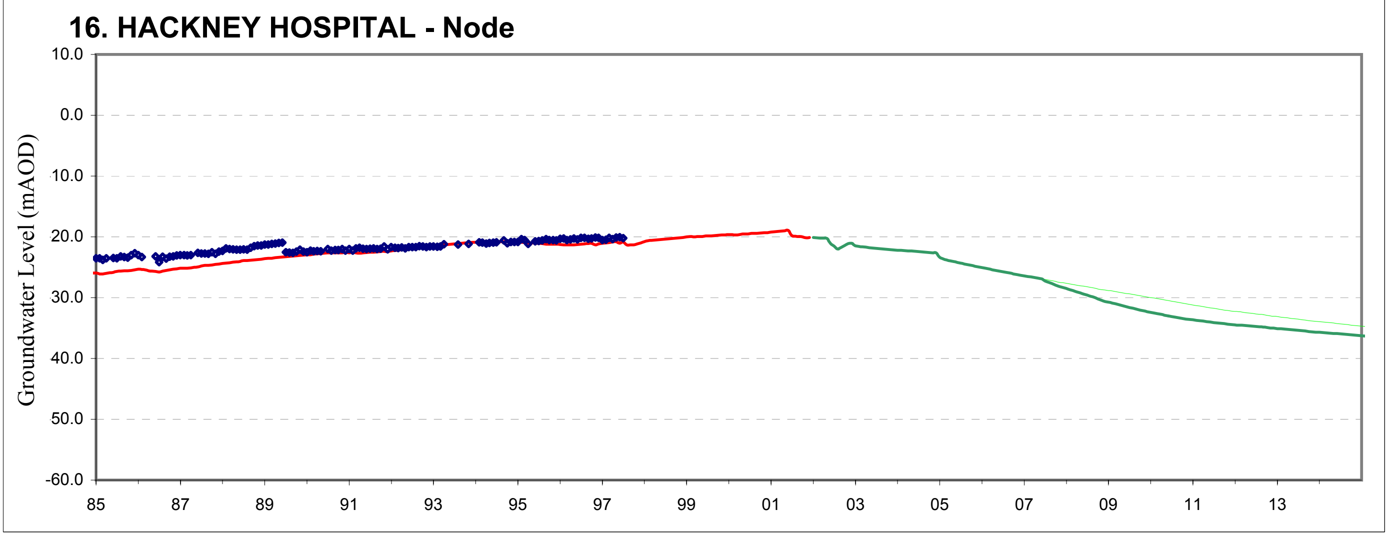


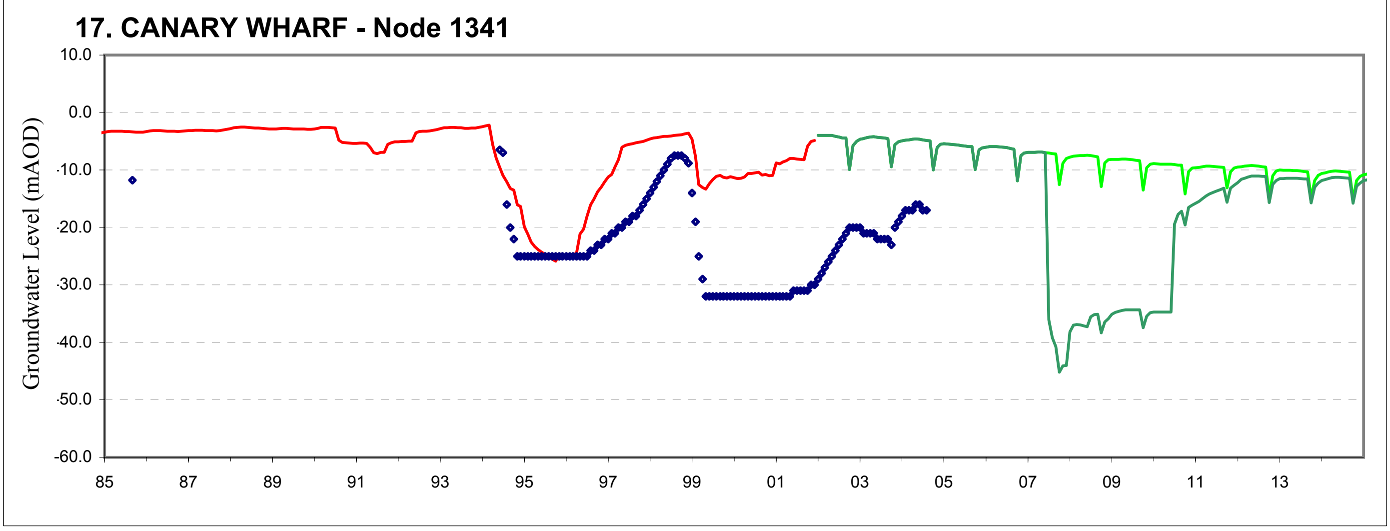


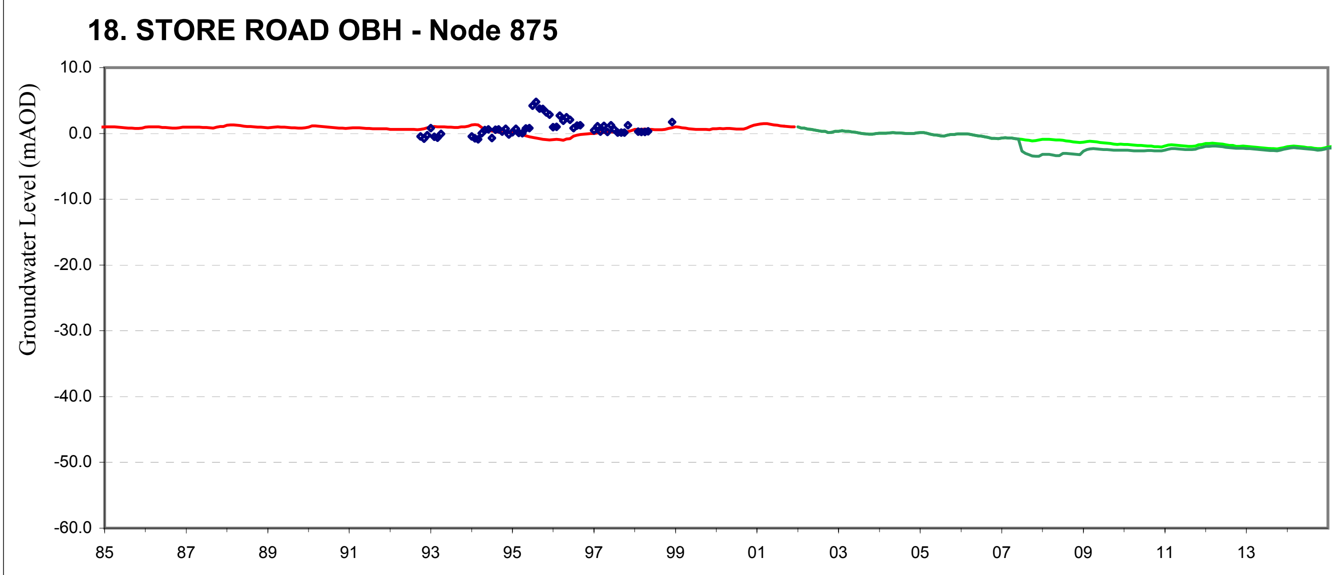
Legend:

Observation | Calibration (Ti50) | Without Crossrail | Crossrail

Mott MacDonald





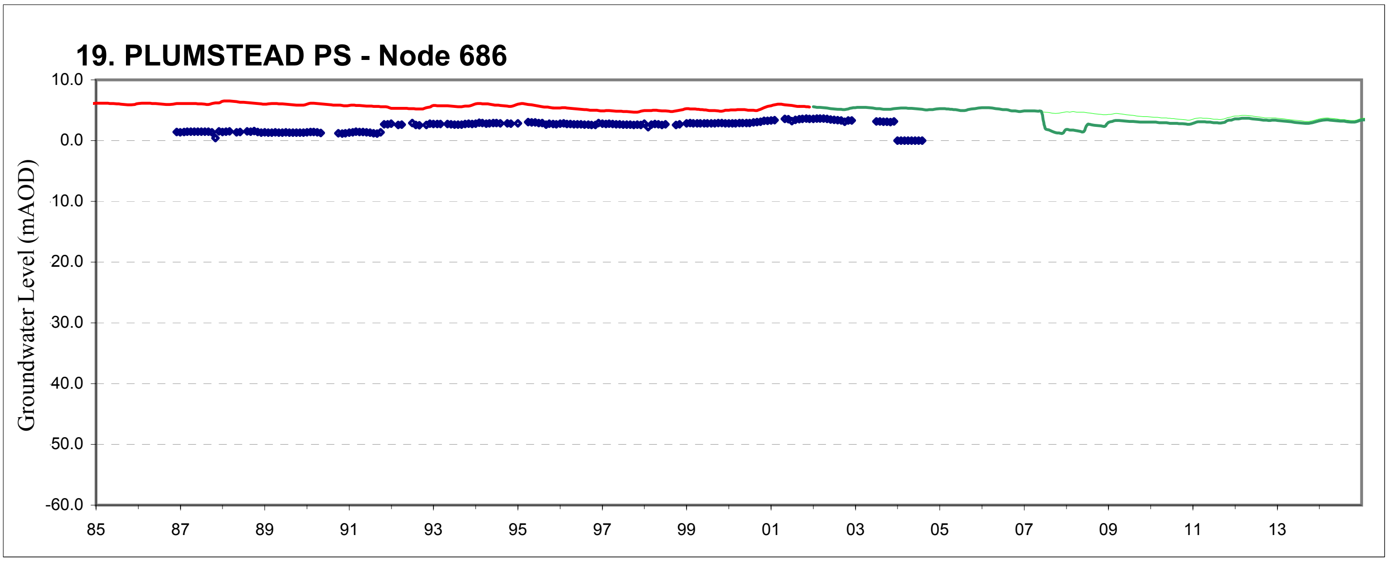


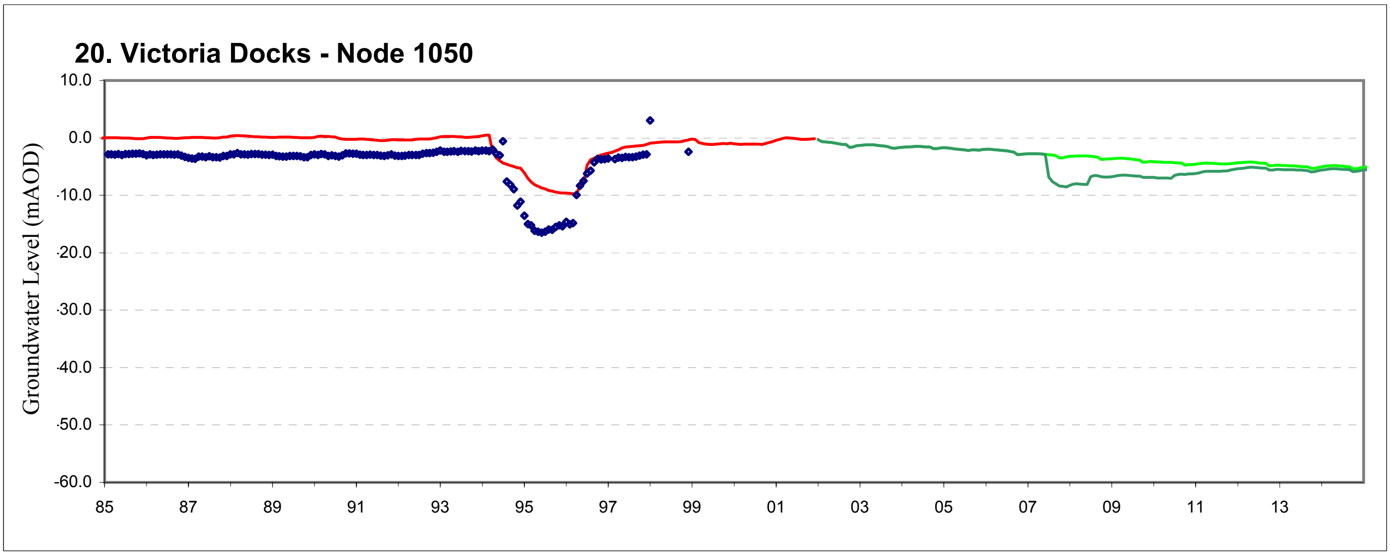
Legend:

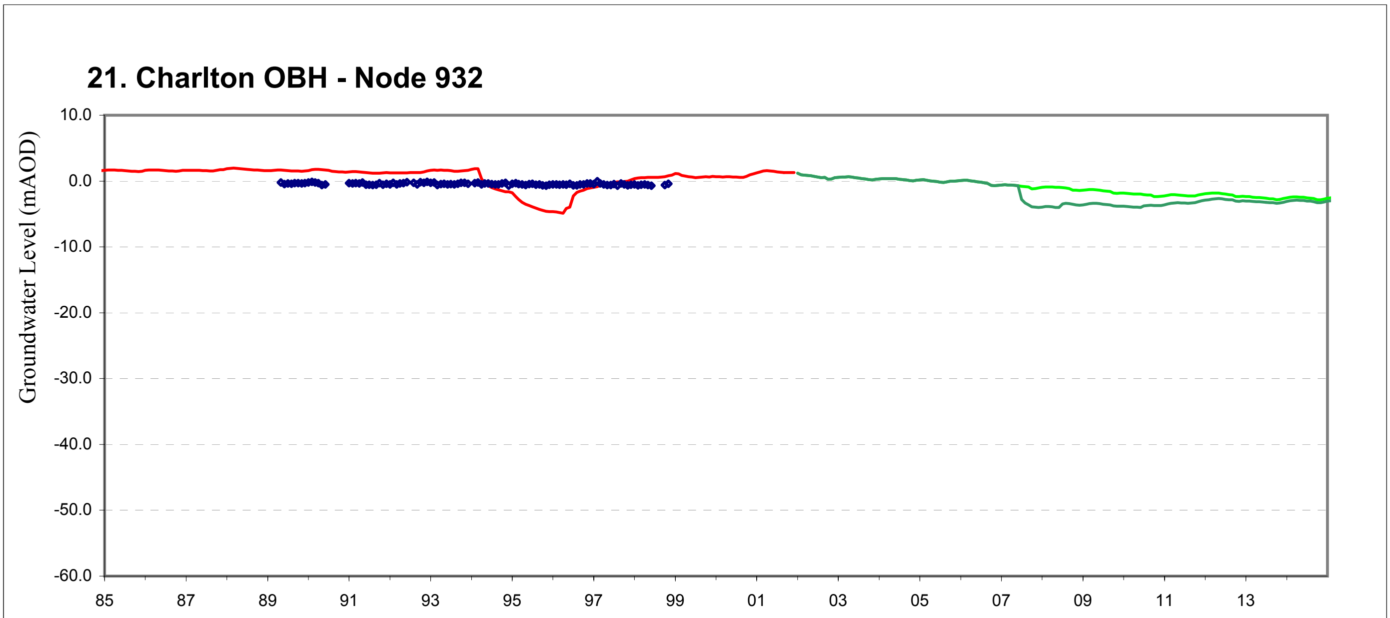
Observation | Calibration (Ti50) | Without Crossrail | Crossrail

Mott MacDonald

Observed vs Simulated Groundwater Levels: 1985 to 2015







Legend:

Observation | Calibration (Ti50) | Without Crossrail | Crossrail

Mott MacDonald