

1 **Groundwater resource modelling for public water supply management in**  
2 **London**

3  
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13  
14 **Abstract**

15  
16 In London, groundwater abstractions for public supply are predominantly from the  
17 Chalk aquifer. However, water resource pressures put existing abstractions at risk and  
18 often require complex analysis to support new source development. Thames Water  
19 develops and uses regional groundwater models for such analysis to support  
20 communication with stakeholders such as the Environment Agency, the  
21 environmental regulator of England and Wales. Using two case studies, the  
22 importance of regional models as Thames Water assets is demonstrated.

23  
24 While Thames Water has developed regional models as a context for sub-catchment  
25 scale analysis of groundwater source development, they are subsequently used to  
26 address other issues. As a result, the models are updated regularly, enhancing both  
27 conceptual understanding and calibration. These models cost less than 1% of the  
28 capital cost of new water source schemes. However, as they are enhanced and applied  
29 more widely, the models accrue further value as active decision support tools.

30  
31 Regional model usage to investigate a range of local systems and interactions is of  
32 particular value to Thames Water. It is important, however, to appreciate and  
33 promote the clarity and consistency generated when stakeholder-specific issues can be  
34 analysed within an agreed regional model framework.

35  
36 Abstract ends

37  
38  
39 Thames Water provides a public water supply to around 8.5 million customers in  
40 London and the Thames Valley, an area largely covering the River Thames catchment  
41 (Fig. 1). On average, around 2,600 million litres per day (Ml/d; 2.6 million m<sup>3</sup>/d) of  
42 potable water are put into supply to meet demand across the supply area, with this  
43 being drawn from a water resource base comprising about 35% groundwater and 65%  
44 from river water. However, owing to catchment water resource pressures, some  
45 groundwater abstractions are at risk of licence reductions, while the development of  
46 new abstractions and management of operational abstractions can require complex  
47 hydrogeological analysis. As a result, to justify development of new sources and to  
48 define operational abstraction management to mitigate environmental impact, Thames  
49 Water develops and uses regional groundwater models to assess catchment and sub-  
50 catchment scale issues.

51

52 The importance of Thames Water’s regional groundwater models as business assets is  
53 presented here. This is demonstrated through their use, for example, in supporting the  
54 development of new abstractions with capital values of around £35 million up to  
55 about £50 million. In addition, the potential is considered for deriving further value  
56 from these models in future.

57

## 58 **Water supply and hydrogeology in the Thames Water area**

59

60 Fig. 1 shows simplistically that the underlying solid geology of the River Thames  
61 catchment is dominated by low permeability clays. For example, the Tertiary London  
62 Clay underlies much of the south-eastern part of the catchment, including London,  
63 with the Cretaceous and Jurassic Gault and Oxford Clays underlying much of the  
64 north-western catchment. Clearly, however, there are major aquifers interbedded with  
65 these clays, specifically the Cretaceous Chalk and Lower Greensand in the central and  
66 south-eastern parts of the catchment, and the Jurassic Oolitic Limestone in the west.  
67 In addition to these solid geological aquifers, the overlying superficial Gravels in the  
68 lower River Thames catchment have some local importance for water supply. The  
69 relative, licensed contribution to public water supply made by Thames Water’s 180  
70 groundwater sources from each of these aquifers is as follows:

71

72 (a) Gravels	1%
73 (b) Chalk	90%
74 (c) Lower Greensand	4%
75 (d) Oolitic Limestone	5%

76

77 The importance of the Chalk as a source of public water supply is clear. Groundwater  
78 abstractions from the Chalk are dominated by withdrawal from unconfined aquifer  
79 areas, and only about 10% of Thames Water groundwater abstractions, by licensed  
80 volume, are from deep, confined aquifer units. However, in London the confined  
81 Chalk (Fig. 1) has again become an increasingly important source for public and  
82 private water supply. This has been driven partly by delivery of the GARDIT  
83 (General Aquifer Research, Development and Investigation Team) Strategy, in the  
84 late 20<sup>th</sup> century and early 21<sup>st</sup> century, to mitigate the risk from rising groundwater  
85 levels (Jones 2007). In addition, groundwater in the confined Chalk of London is  
86 increasingly being used as a source of geothermal energy and a sink for heat rejected  
87 for new developments (Fry 2009).

88

## 89 **Groundwater resource challenges and opportunities**

90

91 Within the Thames Water supply area several challenges influence the availability  
92 and development of groundwater resources. These challenges include low river flows  
93 and their consequential link with abstraction, as well as a general lack of available  
94 water resources, making source development difficult. This is true for the whole  
95 River Thames catchment, the Thames Water supply area as well as London  
96 specifically. The water resource challenges in London are set within the framework  
97 provided by the Environment Agency’s Catchment Abstraction Management  
98 Strategies (CAMS) for London (Environment Agency 2006) and the Darent/Cray  
99 catchment (Environment Agency 2007). For both of these Chalk dominated  
100 catchments, the CAMS establish that the water resource status ranges from 'no water  
101 available' to 'over-abstracted' where actual abstraction results in river flow targets not

102 being achieved. A fuller explanation of the CAMS regulatory process is provided by  
103 Whiteman *et al.* (this volume).

104

105 Although CAMS is a relatively recent development, it broadly reflects the general  
106 water resource status as previously understood. In London, the water resource  
107 challenge of low river flows, where groundwater abstractions may be affecting river  
108 baseflows and associated aquatic habitats, is a real issue with a long history. Such  
109 potential abstraction impacts now often require investigation under the Environment  
110 Agency's Restoring Sustainable Abstraction programme (RSAp), with reductions in  
111 licensed abstraction quantities being a potential outcome; see Whiteman *et al.* (this  
112 volume) for a fuller explanation. In London, investigations of abstraction impacts on  
113 the River Darent have ultimately resulted in a phased reduction of Thames Water's  
114 licences as part of the Darent Action Plan. The final phases of this plan have resulted  
115 in the development of the new Bean Wellfield to compensate the licence reductions.  
116 This development is discussed as Case Study 1.

117

118 In the confined Chalk beneath London, groundwater levels declined during the 19th  
119 and early 20th century, then recovered in the second half of the 20th century. This  
120 was the result of groundwater abstraction that continued to grow until the 1940s  
121 resulting in over-exploitation of the aquifer and declining groundwater levels. The  
122 consequence was a reduction in abstraction yields, which was accompanied by a  
123 decline in abstraction for industry and manufacturing within London after the 1939-45  
124 war. Despite this reduction in abstraction, Chalk groundwater levels continued to  
125 decline until the mid-1960s, reaching a depth of almost 90 m below sea level in the  
126 centre of the London Basin, then recovered dramatically at maximum rates of 3  
127 metres per year. During this period of groundwater level decline and initial recovery,  
128 the confined Chalk aquifer, and the overlying Basal Sands aquifer, became partially  
129 dewatered for a number of decades. The pattern of groundwater level evolution in the  
130 20<sup>th</sup> century is illustrated by the groundwater hydrograph from the Trafalgar Square  
131 borehole in the centre of the London Basin (Fig. 2, after Jones *et al.* 2005).

132

133 The rise of Chalk groundwater levels after 1965 posed a risk of structural damage to  
134 tall buildings with deep basements, service tunnels and underground railways, via  
135 changed geotechnical properties of founding clays and settlement (CIRIA 1989). As  
136 the dewatered Chalk refilled, the hydraulic gradient driving inflow from the Chalk  
137 outcrop declined and the rate of groundwater level rise slowed, but the risk was  
138 ultimately mitigated by a strategy of increased abstraction promoted by GARDIT.  
139 This strategy, led by Thames Water, London Underground and the Environment  
140 Agency, delivered an increase of over 50 Ml/d in licensed abstraction, predominantly  
141 for public water supply (Jones 2007). Although the recovery of groundwater levels  
142 was initially perceived as a risk, it provided a wider opportunity for potential  
143 development of additional groundwater abstractions as groundwater storage  
144 increased. This opportunity in part underlies the development of the ELRED  
145 Wellfield discussed here as Case Study 2.

146

147 Abstraction increases delivered under the GARDIT Strategy have begun to cause  
148 groundwater level declines; notably, in south-west London groundwater levels have  
149 fallen at rates of around 3-4 m/year when such abstractions have been operational  
150 (Environment Agency 2010). As a result, the opportunity for managing groundwater  
151 storage is developing to ensure that maximum groundwater levels do not impact  
152 subsurface infrastructure, with minimum levels defining a water resource limit and/or

153 a level at which other abstractors are derogated (Jones 2007). Such management  
154 would need to be driven by artificial recharge, and could deliver a south London  
155 equivalent to Thames Water's operational North London Artificial Recharge Scheme  
156 (NLARS) (Harris *et al.* 2005; O'Shea and Sage 1999). The potential for developing a  
157 South London Artificial Recharge Scheme (SLARS), by modifying existing into dual  
158 abstraction-injection boreholes is described in Jones *et al.* (2005).

159

## 160 **Groundwater resource modelling framework**

161

162 Thames Water's investigation of each of the groundwater resource challenges and  
163 opportunities outlined above has been supported by the development of conceptual  
164 and numerical models. The approach taken for developing groundwater models is  
165 driven by supply-demand balance, i.e. can sufficient quantity of water be abstracted  
166 sustainably at the required time to meet demand. This requires a "bottom up"  
167 approach based on developing a groundwater model to answer a specific question.  
168 However, once a model has been developed, then it is often re-used to answer other  
169 questions, often in different locations. Examples of the questions that can be  
170 considered include the sustainability of a proposed wellfield next to a quarry (Case  
171 Study 1) or the impact of abstraction in inducing brackish water into the aquifer (Case  
172 Study 2). This leads to an approach that is focussed on a particular issue in a  
173 geographical area at a particular time. Once the model has been developed and used,  
174 then the focus of model development can be moved elsewhere. The corollary of this  
175 developmental process is that groundwater models are regularly updated, both in  
176 terms of the conceptual understanding built into the models and also the time period  
177 for the historical simulation. The latter means that the recharge model is updated  
178 along with other data, such as groundwater and surface water abstractions, which is  
179 usually accompanied by a calibration update.

180

181 For the assessment of some hydrogeological systems in the River Thames catchment,  
182 groundwater models have been developed by the Environment Agency Thames and  
183 Southern Regions. Thames Water, as a key stakeholder, has had some involvement in  
184 these model developments, and promoted initial collaboration with the Environment  
185 Agency on development of Thames Water's London Basin Groundwater Model.  
186 However, during the last 10 years, Thames Water has developed and used its own  
187 regional Chalk groundwater models to support hydrogeological analysis during  
188 resource investigations, source development and licence applications. This began in  
189 1999-2000 when Thames Water and the Environment Agency initially developed the  
190 London Basin Groundwater (LBG) model jointly to assess regional rising  
191 groundwater level issues. However, Thames Water actively developed and  
192 maintained the LBG model to analyse specific groundwater exploration and source  
193 development issues in various parts of the London Basin, including the NLARS,  
194 SLARS and ELRED operations. Essentially, sufficient business drivers existed to  
195 justify capital expenditure on model development and application. Subsequently, this  
196 has led to Thames Water developing further regional models to include the Darent  
197 and Cray catchments, as well as catchments feeding the middle reaches of the river  
198 Thames to address specific source developments.

199

200 These regional models provide a framework for understanding Chalk groundwater  
201 systems and enable assessment of specific sustainability issues and risks to source  
202 viability. As they are often used to investigate abstraction impacts and secure  
203 abstraction licences, the sensible aspiration is to have models that are agreed with the

204 Environment Agency, the environmental regulator and counterpart stakeholder to  
205 Thames Water as water supplier. Broadly an agreed model is considered to mean a  
206 groundwater model that is:

- 207  
208 (a) a reasonable representation of the underlying conceptual understanding (the  
209 conceptual model) within the context of existing uncertainty;  
210 (b) appropriate to explore the question being considered;  
211 (c) able to provide sufficient confidence in its output to support decision making.

212  
213 Although Thames Water's models have been used to secure abstractions and make  
214 joint environmental impact decisions, indicating agreement to model acceptability for  
215 use, only one of Thames Water's models is currently shared with the Environment  
216 Agency. This is the London Basin Groundwater (LBG) model. Agreed, shared  
217 regional groundwater models would provide a more effective framework for the  
218 analysis of catchment and sub-catchment scale issues.

219  
220 The importance of Thames Water's regional groundwater models as business assets is  
221 considered through two case studies. Each is an example of catchment and sub-  
222 catchment scale modelling to support the hydrogeological assessment and licensing of  
223 the Bean Wellfield, north Kent (Case Study 1), and to define operational abstraction  
224 strategies to mitigate the risk of environmental impact from the ELRED Wellfield,  
225 east London (Case Study 2).

### 226 227 **Case Study 1 – Bean wellfield: New source licensing**

228  
229 Investigations of impacts from bank-side Chalk and Lower Greensand abstractions on  
230 the River Darent have resulted in a phased reduction of some of Thames Water's  
231 licences as part of the Darent Action Plan. A large chalk pit (Eastern Quarry) with  
232 potential surplus groundwater from dewatering, located east of the River Darent, was  
233 targeted to compensate for these reductions, including those at Horton Kirby and  
234 Eynsford. Between 2002 and 2005, a series of boreholes were drilled in the interfluvium  
235 east of the River Darent to intercept groundwater flowing to the quarry; these were  
236 successfully developed into the Bean Wellfield, feeding the Lane End water treatment  
237 works (Fig. 3). However, the interfluvium hydrogeology is complex with karstic flow  
238 tubes influencing groundwater flow in the Chalk, and the overlying Clay-with-Flints  
239 routing runoff to focussed recharge. Furthermore, historic quarry dewatering has  
240 influenced groundwater heads and flows, while redevelopment of the quarry will  
241 result in management of the groundwater to a higher base level. Within this complex  
242 framework, it was essential to ensure that the wellfield abstraction would have no  
243 significant impact on the River Darent, it would be sustainable and, therefore, could  
244 be licensed by the Environment Agency. This analysis was supported using the  
245 Swanscombe groundwater model.

246  
247 The Swanscombe model is a three layer, regional model of the Chalk, developed for  
248 Thames Water by the British Geological Survey using the ZOOM suite of object-  
249 oriented codes (Spink *et al.* 2003). The models consist of a recharge model,  
250 ZOODRM (Hughes *et al.* 2008), a groundwater flow model ZOOMQ3D (Jackson *et al.*  
251 *et al.* 2005) and a particle tracking code ZOOPT (Stuart *et al.* 2006). A summary of the  
252 recharge model is provided by Hughes *et al.* (2003) and the groundwater flow model  
253 by Jackson *et al.* (2003). The model covers an area of about 810 km<sup>2</sup>, an area  
254 extending from the River Medway in the east to the Ravensbourne-Cray interfluvium in

255 the west, and from the Chalk outcrop in the south to beyond the Thames Tideway in  
256 the north (Fig. 4). Calibrated for the period 1970 to 2005, the key feature of the  
257 model is the use, within the regional model limits, of refined nested grids around areas  
258 of particular interest. This included much of the Darent-Cray catchment and the  
259 wellfield-quarry area (Fig. 4), with the latter developed to enable a group pumping  
260 test to be simulated within the existing regional model (Jackson *et al.* 2003).

261

262 Using the Swanscombe model, it has been inferred that raising the quarry base  
263 groundwater level would reduce discharge to the quarry and therefore also reduce the  
264 loss of groundwater resource from the interfluvial area. Approximately 15+ Ml/d of  
265 additional groundwater resource would be made available as a result. In addition,  
266 although groundwater levels decline in the interfluvial area as a result of the wellfield  
267 abstraction, groundwater levels would recover along the river Darent. As a result, the  
268 modelling has shown that the Darent baseflow is restored by abstraction relocation  
269 coupled with appropriate quarry redevelopment. The Bean Wellfield now comprises  
270 10 boreholes abstracting from the unconfined Chalk, with yields varying from 1 to 8.5  
271 Ml/d and a total average licensed abstraction rate of 18.4 Ml/d. Without the  
272 Swanscombe model, it is unlikely that the abstraction licence would have been  
273 secured without onerous conditions, but its cost equates to less than 1% of the capital  
274 cost of the total scheme development.

275

#### 276 **Case Study 2 – ELRED: Risk minimisation analysis**

277

278 To support the assessment of many recent groundwater resource developments in the  
279 confined Chalk of London, Thames Water has used the London Basin Groundwater  
280 (LBG) model. It is a regional model covering an area of about 2300 km<sup>2</sup>, extending  
281 from the North Downs scarp slope in the south to the limit of the confined Chalk in  
282 the Chilterns (Fig. 5). It is a five layer model representing the Chalk as two layers,  
283 the Basal Sands aquifer, the Lambeth Group aquitard and the confining London Clay.  
284 The model was developed for Thames Water by Mott MacDonald using their  
285 proprietary Integrated Catchment Management Model (ICMM) code. ICMM is an  
286 integrated finite difference model that allows for variable gridding and simulation of  
287 groundwater flow in multi-layered aquifer systems. The model integrates surface  
288 water features (rivers) with the groundwater system. The key features of the model,  
289 shown in Fig. 5, are:

290

- 291 (a) representation of the hydrogeological compartmentalisation of the confined Chalk  
292 as aquifer blocks;
- 293 (b) aquifer blocks bounded by variable, sometimes low permeability zones,  
294 represented by hydraulic properties assigned to model cell faces;
- 295 (c) grid refinement in areas of particular interest, e.g. ELRED, as well as NLARS and  
296 SLARS (North and South London Artificial Recharge Scheme, respectively).

297

298 The model is currently calibrated for the period 1965 to 2008, covering the period of  
299 major recovery of groundwater levels and their control via groundwater development  
300 as part of the GARDIT Strategy. However, since its initial calibration in 2000, the  
301 model has been updated and enhanced in several phases undertaken to enable  
302 assessment of artificial recharge potential in SLARS, its expansion in NLARS as well  
303 as the development new abstraction sources such as ELRED.

304

305 ELRED is a linear wellfield (Fig. 6), developed from part of the Channel Tunnel Rail  
306 Link (CTRL) construction dewatering scheme, with a complex water treatment works  
307 (WTW) at East Ham commissioned into supply in 2005 (Hamilton *et al.* 2008). It  
308 comprises 9 abstraction sites with outputs ranging from 0.6 to 6.5 Ml/d, and was  
309 licensed to abstract an annual total equivalent to 22.8 Ml/d. Owing to the over-  
310 abstraction in the London Basin prior to the 1940s, brackish water intrusion had  
311 occurred from the tidal River Thames estuary, then subsequently receded as  
312 abstraction reduced and groundwater levels recovered. As a result, abstraction from  
313 ELRED, 3-5 km north of the tidal Thames, required analysis to determine the  
314 intrusion risk and definition of operational abstraction strategies to mitigate the risk  
315 and optimise abstraction.

316  
317 Using the LBG model, it was inferred that ELRED abstraction at a constant 22.8 Ml/d  
318 would, after only 5-6 years, increase flow from the River Thames into the Chalk,  
319 reaching flows comparable to those modelled in 1965. The significance of this is that  
320 in 1965 groundwater levels in the centre of the basin were at their lowest and  
321 hydraulic gradients steepest away from the river, giving rise to increased brackish  
322 water intrusion. As a result, a return to 1965 flow conditions could give rise to an  
323 increased risk of groundwater quality deterioration, which would make the licence  
324 unsustainable and inconsistent with European Water Framework Directive objectives.  
325 However, in verifying the LBG model accuracy, comparison of its output with  
326 observed groundwater level impacts suggested this to be an overly pessimistic  
327 assessment of the risk. Specifically, during simulation of the CTRL construction  
328 dewatering and ELRED test pumping, the model over-estimated the extent of  
329 groundwater level drawdown southwards to the River Thames estuary, and thus over-  
330 estimated brackish water intrusion into the Chalk aquifer. Furthermore, no evidence  
331 of groundwater quality deterioration was detected during the 2-3 years of CTRL  
332 dewatering. Even though the risk of groundwater quality deterioration may have been  
333 over-estimated, a strategy of seasonally variable abstraction from ELRED was  
334 defined to address the uncertainty and aimed to:

- 335
- 336 (a) assist meeting seasonal peak demands, e.g. winter mains burst and summer peaks;
  - 337 (b) assist in managing water production outage, e.g. algal blooms in raw water storage  
338 reservoirs;
  - 339 (c) maintain WTW viability with a minimum abstraction to pump through the works;
  - 340 (d) minimise abstraction to preserve and promote recovery of aquifer storage;
  - 341 (e) maintain groundwater resources to meet sustained drought demands.
- 342

343 Simulation of this seasonal abstraction strategy showed a modest increase in the  
344 period of abstraction before flows from the River Thames into the Chalk reached  
345 those modelled for 1965. The critical indicator considered is flow into the Stratford  
346 Chalk block reaching just over 6,000 m<sup>3</sup>/d (6 Ml/d). Fig. 7 shows that, with seasonal  
347 ELRED abstraction from 2004 and constant abstraction from 2008, flows into the  
348 Stratford block are modelled to reach 1965 rates in 2012. This means that the risk of  
349 groundwater quality deterioration increases after 8 years, rather than the 5-6 years  
350 initially identified. Such analysis using the LBG model has assisted in identifying  
351 options for managing operational abstraction risk, but it has also been used to promote  
352 a licence transfer from ELRED to a disused source about 2 km further west (Fig. 7).  
353 This has enabled abstraction to be distributed over a greater aquifer volume and thus  
354 further mitigate future risk of groundwater quality deterioration from brackish water  
355 intrusion. Without the LBG model this detailed analysis could not have been carried

356 out. It has underpinned the development and risk-based operation of a £35 million  
357 new abstraction and treatment works, and enabled a deployable output benefit of  
358 almost 16 Ml/d to be secured. The cost of the LBG model development equates to less  
359 than 1% of the capital cost of the ELRED scheme development. However, the model  
360 has been used to support development of several other groundwater source schemes in  
361 London and, in practice, the LBG model costs equate to significantly less than 0.5%  
362 of the total capital costs of the schemes. This means that as the model is developed to  
363 address a wider range of issues, it accrues additional value as a decision support tool,  
364 with its total development and maintenance cost decreasing as a proportion of scheme  
365 capital costs.

### 366 **The future**

367  
368  
369 Since initial development of the LBG model, Thames Water has enhanced it to meet  
370 its requirements for groundwater resource exploration and development. Although  
371 Thames Water and the Environment Agency Thames Region now have a joint share  
372 in the LBG model, the Environment Agency is working towards the development of a  
373 new model of the London Basin Chalk aquifer with Thames Water as a stakeholder.  
374 In a wider context, the Environment Agency Thames Region now has or is developing  
375 a suite of regional groundwater models that partly or substantially overlap with some  
376 of Thames Water's models. In contrast, where the water supply area extends into the  
377 Environment Agency Southern Region, Thames Water has established an agreement  
378 the Environment Agency for sharing Thames Water's Swanscombe groundwater  
379 model. Clearly there is benefit and a need for stakeholders to agree on:

- 380  
381 (a) whether regional conceptual and numerical models are reasonable representations  
382 of the groundwater system;  
383 (b) what specific hydrogeological issues can reasonably be investigated, i.e. are they  
384 'fit for purpose'.  
385

386 Nevertheless, Thames Water will continue to maintain, develop and use its models for  
387 specific sub-catchment and catchment groundwater investigations, recognising that  
388 the models need to be set in an appropriate regional context. As analysis of  
389 stakeholder-specific issues need a regional context, the use of detailed models to  
390 represent and investigate local systems and interactions would benefit significantly  
391 from being able to draw on regional models agreed by key stakeholders. This would  
392 provide both clarity of the modelling framework as well as consistency between  
393 stakeholders. For example, local investigations may then simply extract internal  
394 conditions from an agreed regional model to form local boundary conditions, and/or  
395 set discrete, detailed model grids for different local investigations within a regional  
396 numerical model (Fig. 8). It is apparent that the Environment Agency has a key role  
397 in this framework. By its development and maintenance of agreed regional  
398 groundwater models, this could provide a framework for both regulatory  
399 investigations by the Environment Agency, as well as investigation/development  
400 work by stakeholders, including water companies.

401  
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406



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466

## 467 **Figure Captions**

468

469 Fig.1. River Thames catchment location map showing key hydrogeological units,  
470 Thames Water water supply area and case study locations

471

472 Fig. 2. Historic Chalk groundwater level evolution at Trafalgar Square (TQ28/119)  
473 and Ashley Gardens (TQ27/88) in the centre of the confined Chalk basin, London.

474

475 Fig. 3. Detailed location map for Case Study 1 showing the Bean wellfield, other key  
476 groundwater abstractions along the River Darent, superficial and bedrock geology.

477

478 Fig. 4. The Swanscombe groundwater model, developed using the ZOOMQ3D code  
479 (Case Study 1), showing the model boundary (red), the detailed grid covering much of  
480 the River Darent and the Bean wellfield (purple) and the wellfield grid (green) used  
481 for simulating a group pumping test.

482

483 Fig. 5. The London Basin groundwater model grid (Case Study 2) superimposed on a  
484 simplified bedrock geology map of London. The conceptualisation of the confined  
485 Chalk hydrogeological compartmentalisation is illustrated by aquifer blocks bounded  
486 by variable, sometimes low permeability zones (red).

487

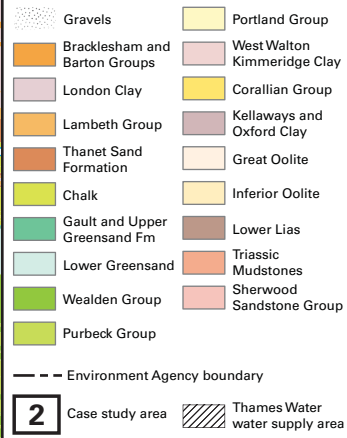
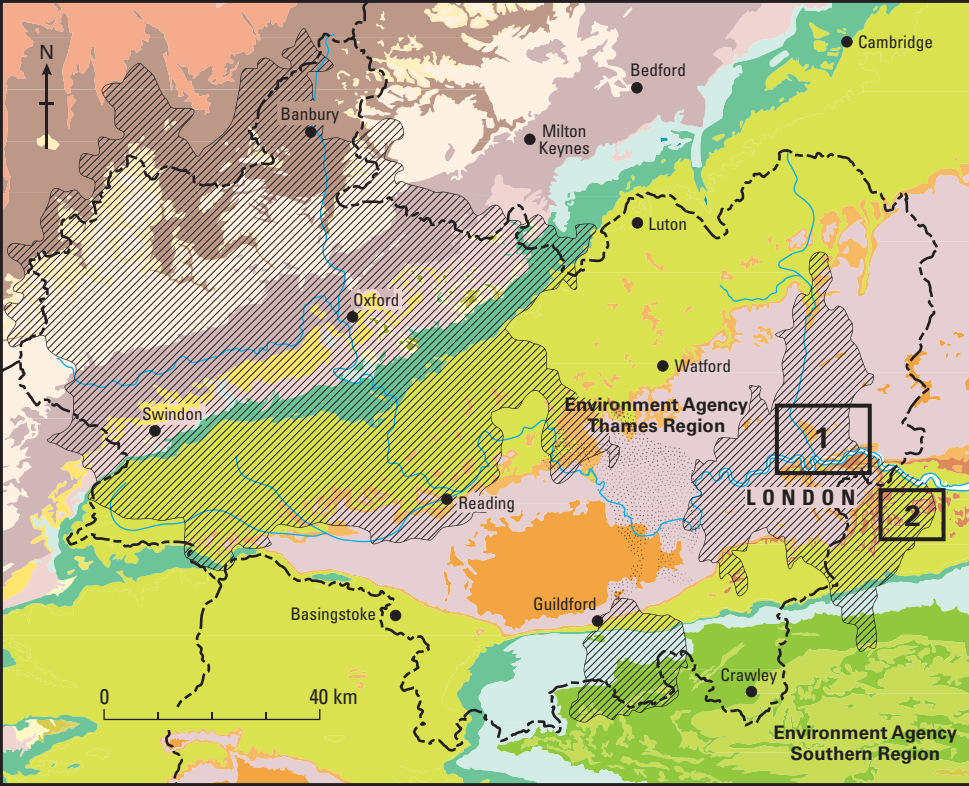
488 Fig. 6. Location of ELRED wellfield (Case Study 2) and the Channel Tunnel Railway  
489 (CTRL) alignment.

490

491 Fig. 7. Output from the London Basin groundwater model (Case Study 2) showing  
492 groundwater flows into (blue) and out of (red and green) the Stratford Chalk block, as  
493 influenced by abstraction from the ELRED wellfield.

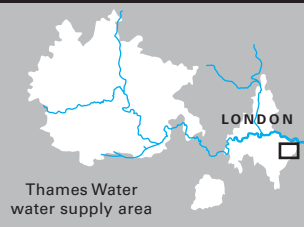
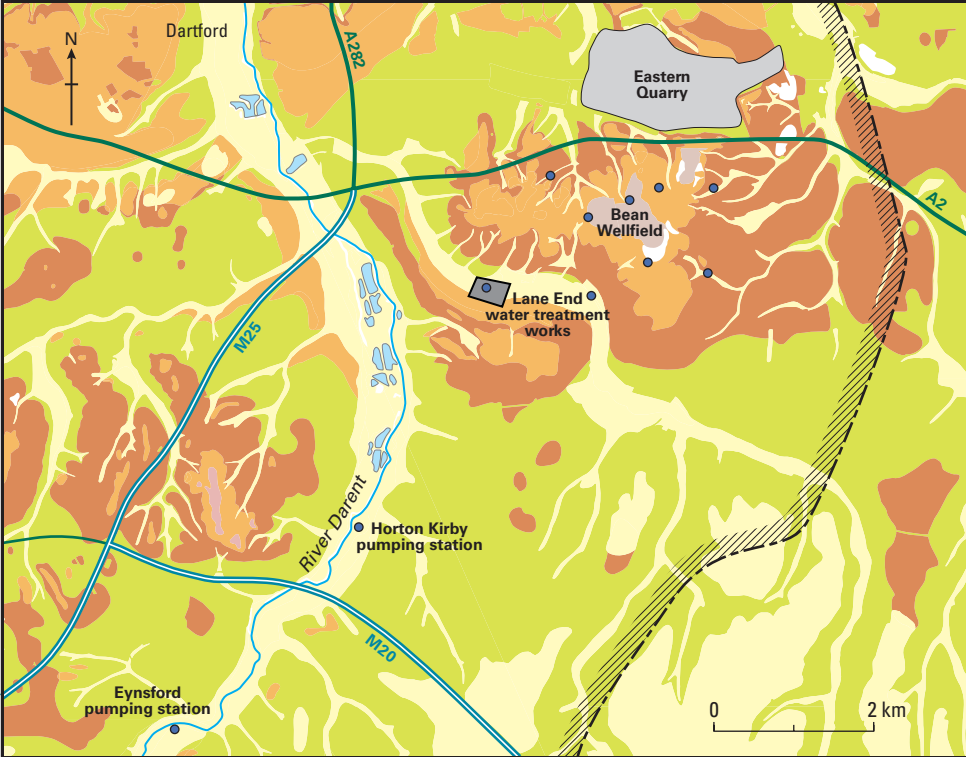
494








495 Fig. 8. Example grids to illustrate a flexible groundwater modelling system to support  
496 local investigations within an agreed regional framework. The example shows the  
497 modification of an extended Swanscombe groundwater model (Case Study 1) to  
498 support (A) analysis of abstraction impact and river flows, and (B) detailed analysis of  
499 wellfield development.

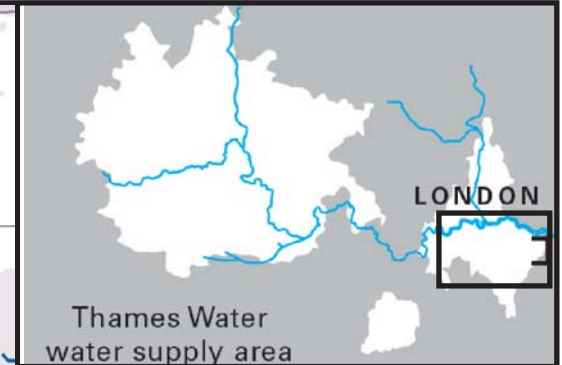
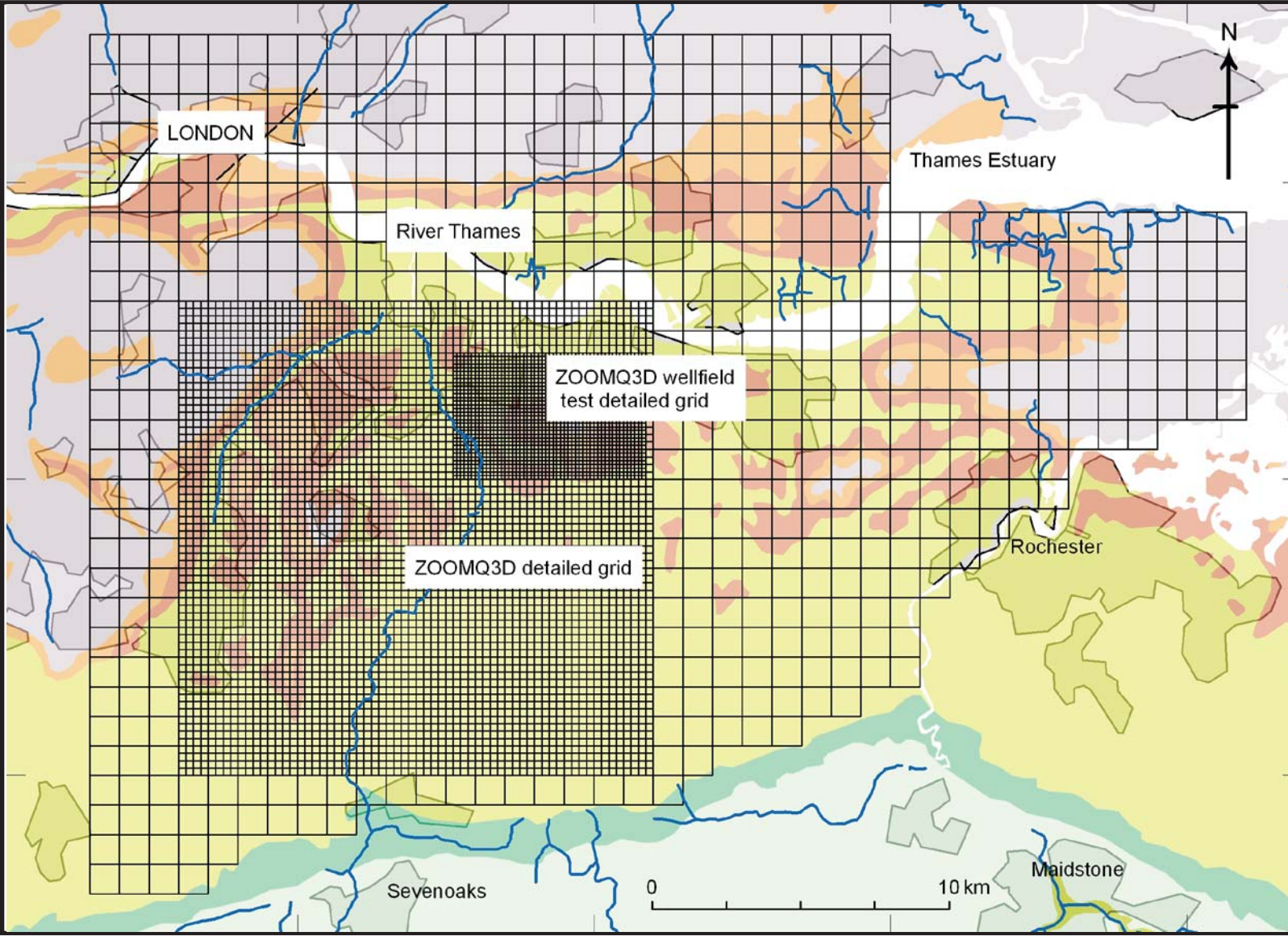




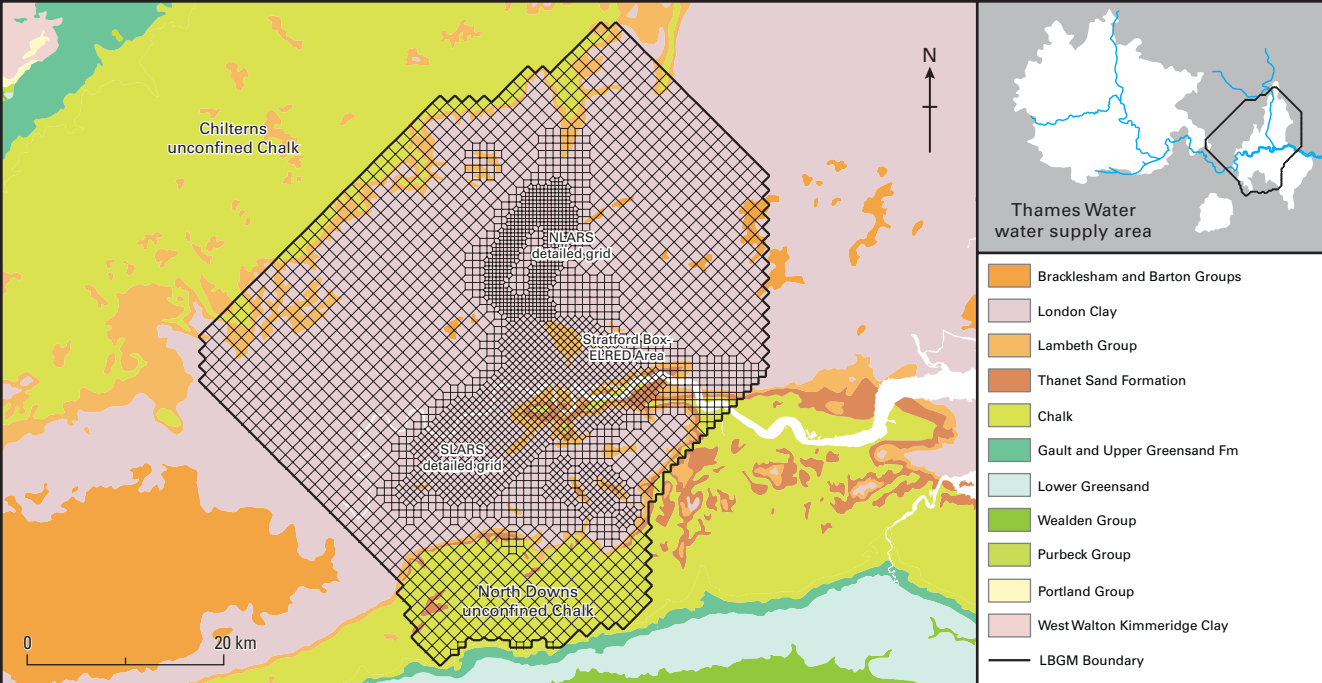
Andrew Hughes June 2010		Max W176mm H236mm
Fig_2 - 1st Proof	Drawn by S D Ward 21/7/2011	
Fig_2 - 2nd Proof	Altered by S D Ward 29/7/2011	
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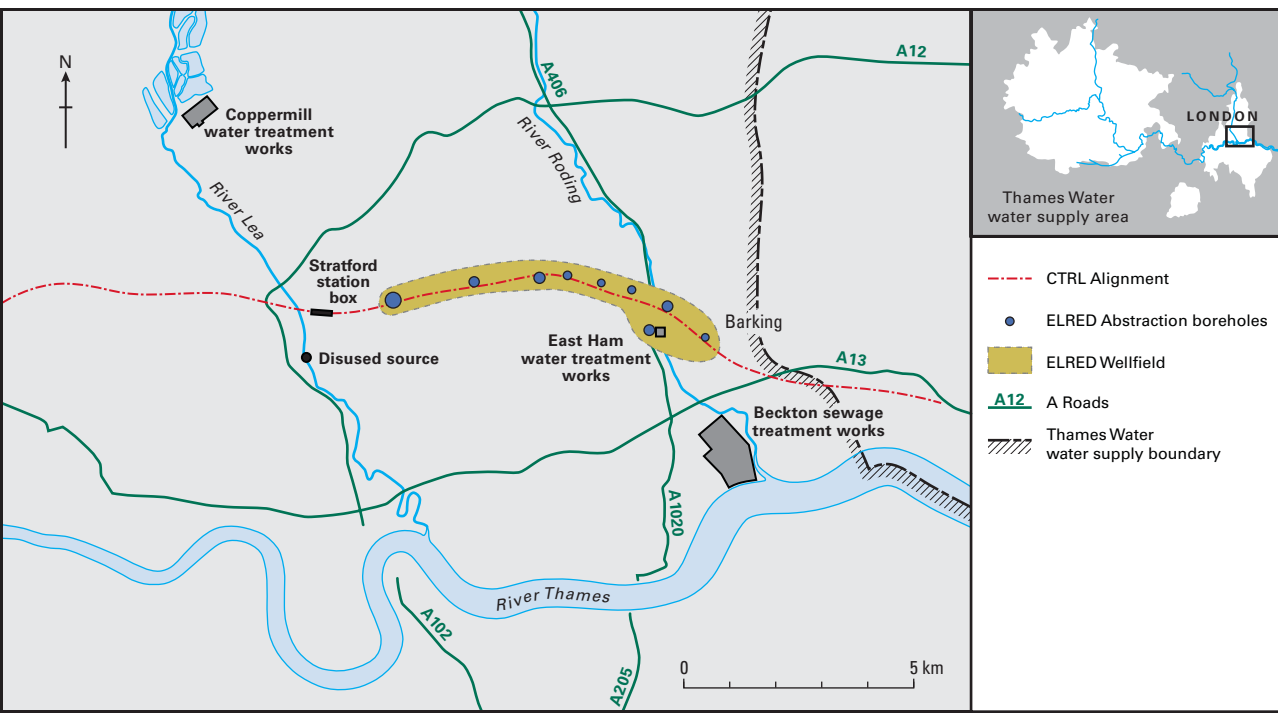
-  Superficial Deposits
-  London Clay
-  Lambeth Group Sand and Clay
-  Thanet Sand Formation
-  Chalk Formation
-  Thames Water water supply boundary
-  Bean Abstraction Boreholes



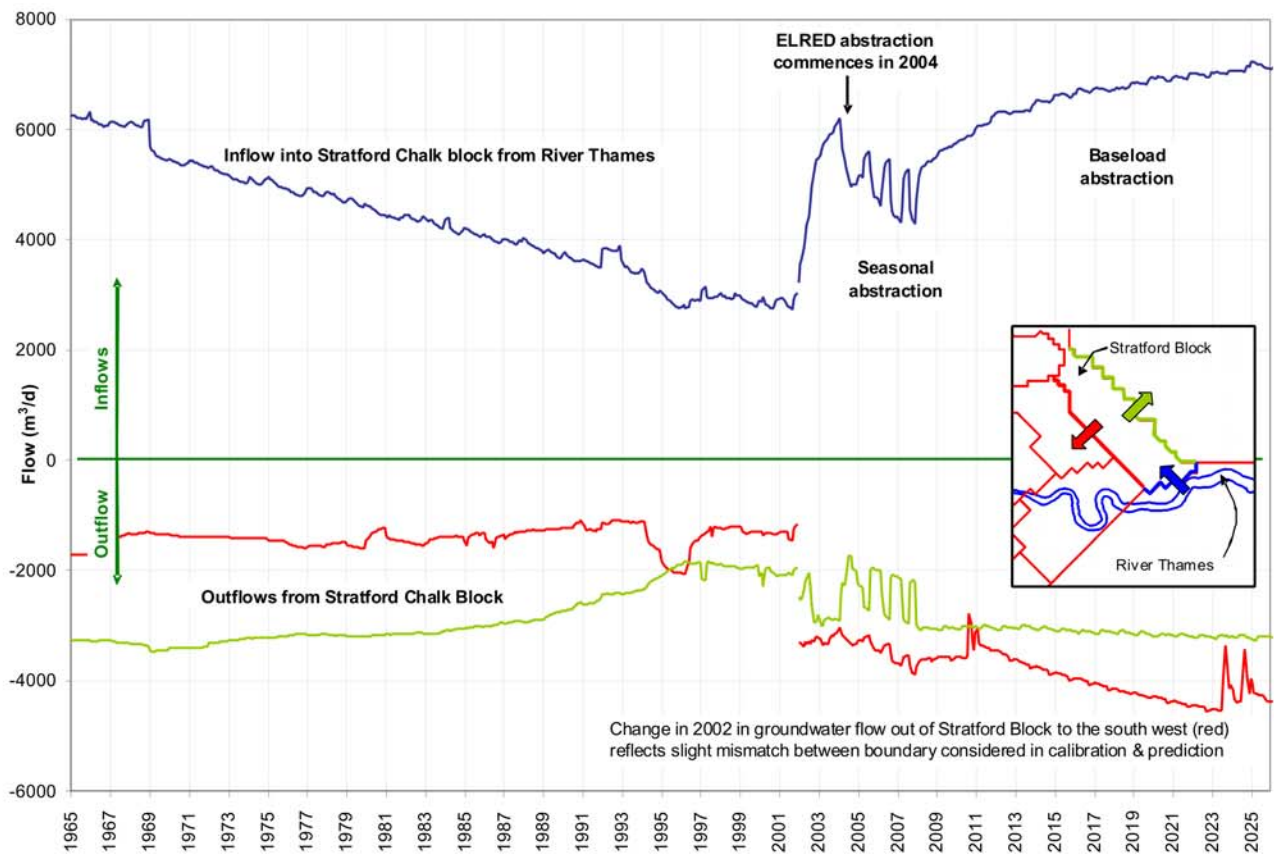
- London Clay
- Lambeth Group
- Thanet Sand Formation
- Chalk
- Gault and Upper Greensand Fm
- Lower Greensand
- Wealden Group
- Urban areas
- Rivers
- Model grid

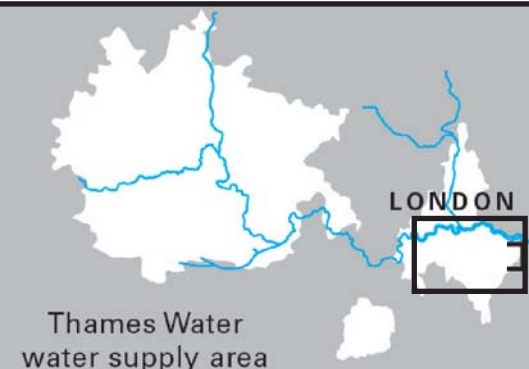
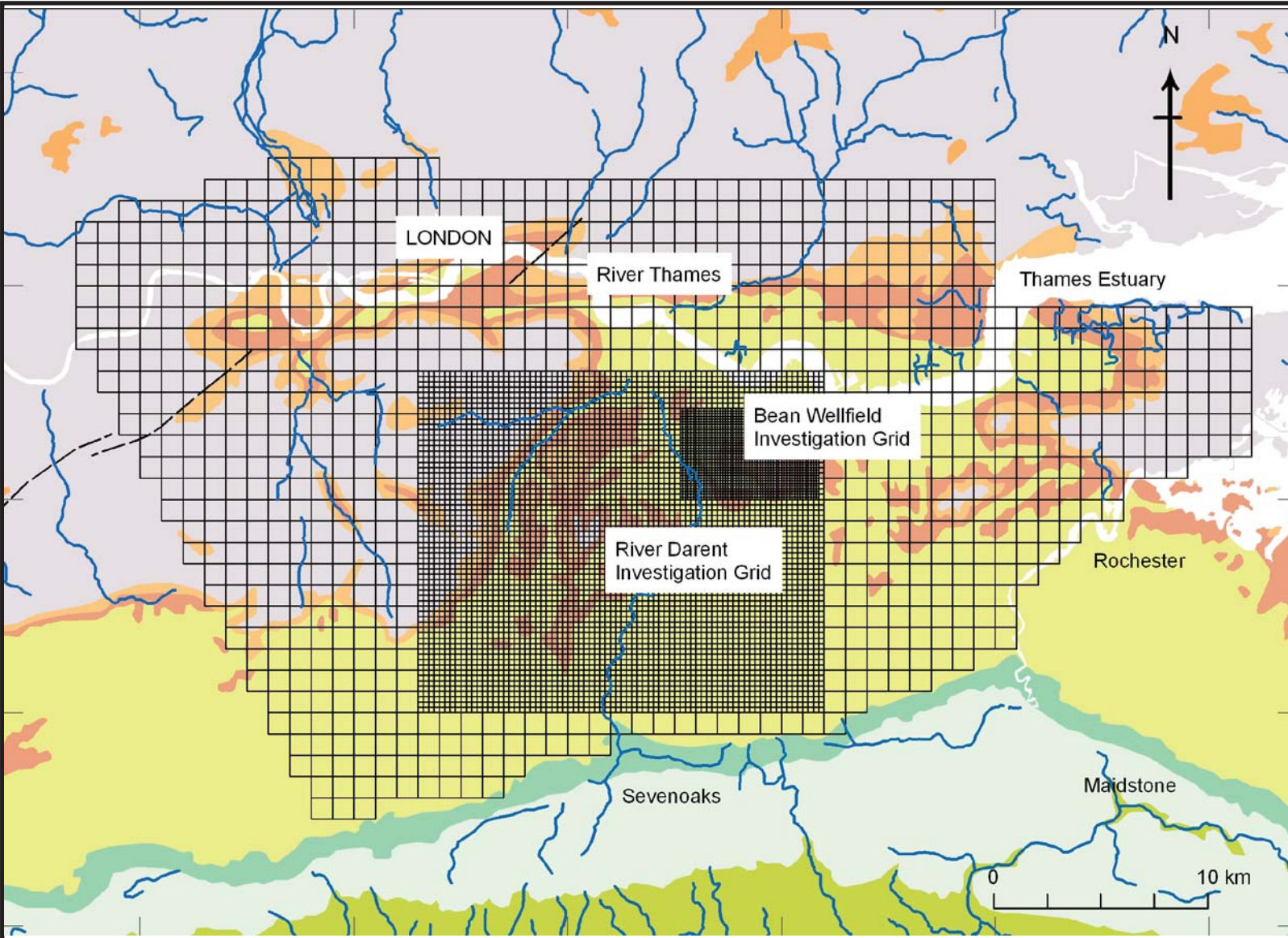


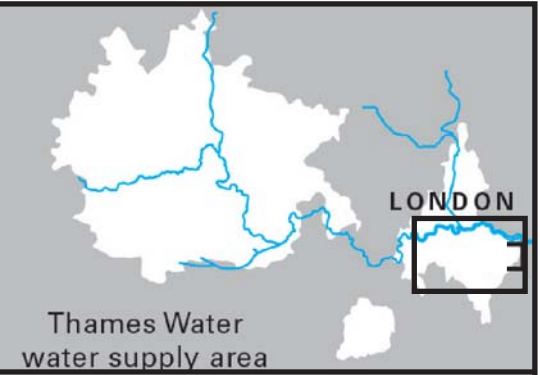
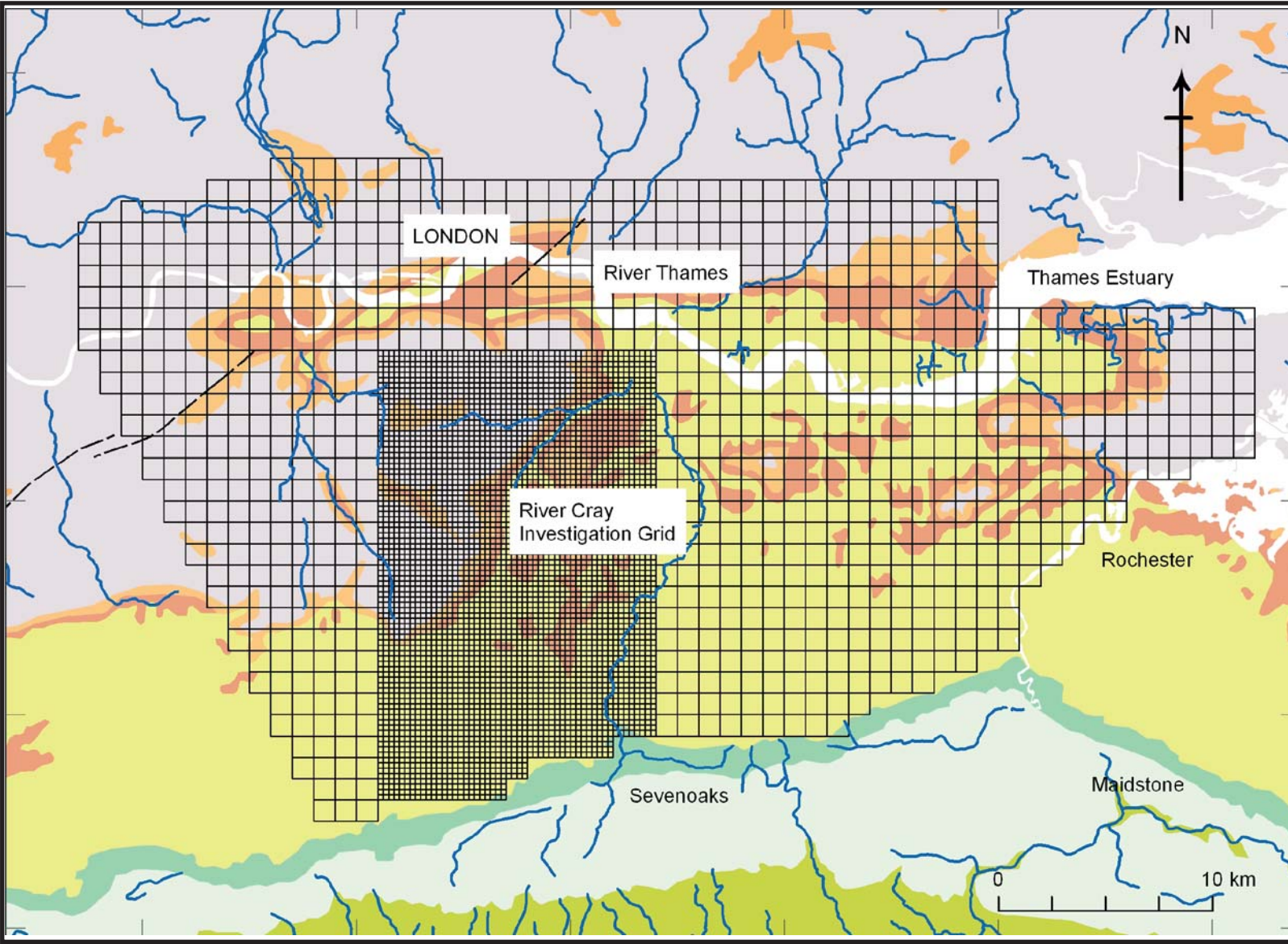
<b>Andrew Hughes</b> June 2010		Max W176mm H236mm
Fig_5 - 1st Proof	Drawn by S D Ward 22/7/2011	
Fig_5 - 2nd Proof	Altered by S D Ward 29/7/2011	
-	-	











- Bracklesham and Barton Groups
- London Clay
- Lambeth Group
- Thanet Sand Formation
- Chalk
- Gault and Upper Greensand Fm
- Lower Greensand
- Wealden Group
- Rivers
- Model grid