WATER MANAGEMENT AND THE LITHOSPHERE

Contribution for Chapter 8 "Case Histories"
Water Resources Management and Rising Groundwater Levels
in the London Basin. (Revised Version)

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1. INTRODUCTION

Up to 1970 over-abstraction coupled with falling Chalk groundwater levels was regarded as the principal problem by those dealing with the water resources management of the London Basin (Water Resources Board, 1972). But by the mid–1970s it had become apparent that groundwater levels had in fact bottomed out in the late 1960s and a general rise in confined Chalk groundwater levels was under way (Marsh and Davies, 1983). The rise brought about a new concern – that of the geotechnic effects of rising groundwater levels on deep structures such as piles, tunnels and basements. (Wilkinson, 1984; Chisholm, 1984). Moreover, the potential risk appeared to be present in other cities in the U.K. as well as Europe and the United States (Hurst & Wilkinson, 1985).

This case history presents an up to date account of the exploitation of the London Basin's groundwater resources putting it in context with the current state of the total surface and groundwater resources serving the London area and the requirement for developing new resources in an integrated and responsible manner.

2. BACKGROUND

2.1 HYDROGEOLOGY

The London Basin is an asymmetric synclinorium in Cretaceous and Tertiary (mostly Eocence) strata. The major axis trends WSW to ENE and plunges towards the North Sea. Being formed during the Alpine orogeny, the southern limb of the syncline is steeper than the northern one.

The outcrop geology of the London Basin is shown in Fig 1. The principal Tertiary (Eocene) formations are the London Clay, Woolwich & Reading Beds and the Thanet Sands. The principal Cretaceous formation is the Chalk which is a soft fine grained fissured limestone.

The principal aquifer of the London Basin, and indeed the U.K., is the Chalk which forms the undulating hills to the north and south of the general London area. The outcropping unconfined Chalk provides the natural recharge for the clay-covered confined region which occupies the central area of the basin over which the London Clay is the predominant formation at outcrop.

Where the Chalk is overlain by Tertiary strata a two-layer leaky system is formed made up of the uppermost 50 metres of Chalk and the so called "Basal Sands". The latter is composed of the lower sandier beds of the Woolwich & Reading series together with the Thanet Sands and has a thickness ranging from 12 to 25 metres (see geological column in Fig 1).

Transmissivity ranges from about $30m^2/d$ in the deeper parts of the confined aquifer where the London Clay plus Woolwich & Reading Clay overburden is greater than 50 metres to over 2000m^2/d in the major Chalk valleys on the unconfined region. Specific yield in the unconfined Chalk region is about 0.02 and confined storativity is about 0.0001.

Superficial gravels (Pleistocene and Recent) of up to 9 metres thickness occupy the present and past watercourses of the basin. Where London Clay and/or Woolwich & Reading Clays are present, the gravels form a separate water table to that of the Chalk/Basal Sands system.

Associated with the superficial gravels is a somewhat enigmatic feature probably of periglacial origin referred to as a 'scour hollow' (Berry, 1979). These are steep-sided holes infilled with alluvial material which penetrate the London Clay and sometimes continue down into the sandy Tertiary deposits below the London and Woolwich & Reading clays; they are generally associated with the superficial gravel tracts. At least 40 scour hollows are known to exist and are believed to be important both hydrogeologically, because they offer a relatively high permeability route between the Chalk/Basal beds aquifer and the superficial gravels, and geotechnically, because their geotechnical properties are less desirable to those of the surrounding London Clay.

2.2 NATURAL CONDITIONS

The groundwater catchment of the London Basin as defined in this case study is delineated in Fig 2. The distribution of groundwater head believed to exist prior to any abstraction is also shown. As can be seen, regional flow is from the unconfined Chalk and Basal Sands into the central confined region where the Chalk/Basal Sands aquifer is confined by the London Clay and Woolwich & Reading Clays.

The groundwater catchment area as defined in Fig. 2 is about 4500 km^2. The Chalk and Basal Sands outcrop area (unconfined region) forms the higher ground to the north and south of urban London and is about 2000 km^2 in area. The 25-year average for natural recharge over the unconfined region is 1200 x 10^3 m^3/d ± 5% and the estimate for combined baseflow and spring flow is 1000 x 10^{3}m^3/d ± 15% (under natural conditions) leaving a residual of 200 x 10^{3}m^3/d ± 20% to flow into the confined region. Even the lower estimate (160 x 10^3 m^3/d) of input to the confined region constitutes a substantial groundwater flow which tends to be born out by historical evidence. For example, large Chalk springs were known to exist in the bed of the River Thames estuary and that marshy areas existed where the Basal Sands outcrop such as in the Hackney Marshes region at the Lower end of the Lee Valley. In addition, it now seems likely that scour hollows may have played a significant role in conducting Chalk/Basal Sands groundwater to the surface.

The picture of the London Basin prior to exploitation is therefore one of copious Chalk streams and springs flowing on the unconfined region with the excess natural recharge flowing down to the centre of the basin and discharging as seepages and springs in the Thames estuary and other low lying areas where the clay cover is absent.

3. EXPLOITATION

3.1 GROUNDWATER ABSTRACTION

The first known Chalk abstractions in the London Basin started up in the early 1820s and tended to be concentrated in the central London area (See Fig 2). The earliest abstractions were for industrial and commercial usage and prior to 1840 probably did not exceed 20 x 10^3 m^3/d in aggregate with individual sources probably not exceeding 500 m^3/d.

The earliest public supply sources were put down in the late 1840s and were located away from central London in areas of higher transmissivity throughout both the confined and unconfined regions. In the latter case abstractions tended to be concentrated in valleys containing perennial Chalk streams, the principal valleys being those of the Lee and Colne on the northern outcrop and the Darent on the southern outcrop.

Confined abstractions peaked in 1940 at 220 x 10^3m^3/d. A steady decrease took place thereafter and by 1985 confined abstractions had fallen to 90 x 10^3 m^3/d. Unconfined abstractions also increased steadily up to 1940, but in contrast to the confined, continued to increase up to the early 1970s when the total abstraction for the London Basin was 1280 x 10^3 m^3/d – some 80 x 10^3m^3/d in excess of natural recharge (1200x10^3m^3/d+5%). The contrasting confined/unconfined abstraction trends after 1940 are readily explained by the increased demand created by the drift in population and industry away from the centre of London and towards the suburban conurbations located on the fringes of the basin.

Since the early 1970s, however, there has been an overall decline in unconfined abstractions caused by a reduction in industrial usage, the latter exceeding a slight rise in public supply over the same period. By 1985 unconfined abstractions accounted for some 90% of the total output of 1150 x 10^3 m^3/d.

Artificial recharge was first carried out on an experimental basis between 1953 and 1973 in the confined region of the lower Lee Valley (Boniface, 1959; Edworthy et al, 1978) and also more recently between 1977 and 1984 (Hawnt et al, 1981). The experiments were highly successful having the desired effect of mounding Chalk/Basal Sands groundwater levels locally without any serious loss from the recharge mound. The total quantity recharged between 1953 and 1970 was relatively small (equivalent to a flow of 5 x 10^3m^3/d over 18 years) and was unlikely to have added significantly to the general rise in confined groundwater levels which took place after 1970, described in the next section.

The abstraction trends described above are shown in Fig. 3. and are presented in the form of three graphs representing "total", "public supply", "non-public supply"; confined and unconfined abstractions are also indicated. To emphasise the degree to which the groundwater resources of the London Basin have been exploited, the 25-year average annual recharge value of 1200 x 10^3 m^3/d has also been included.

3.2 EFFECTS OF ABSTRACTION

As one might expect the increasing abstractions in the London Basin since the 1820s have produced different effects in the unconfined region compared to the confined region. In the unconfined region the main effect has been the marked reductions in baseflow and spring flow whereas in the confined region the main effect has been the creation of a large regional cone of depression of up to 80 metres drawdown at the centre of the basin.

Generally drawdowns in the unconfined region have not been excessive except in areas where there has been a high concentration of public and industrial abstractions as in the case of parts of the Colne and Darent valleys. In these areas the water table for all but the wettest periods is near to or below stream bed level thereby reducing baseflow to zero and often producing reverse leakage back into the Chalk. However, for most of the unconfined streams abstraction has intercepted between 10% and 60% of the natural baseflow. Ironically, because of the large component of treated sewage effluent now being discharged into these streams, today's observed streamflows are probably not much lower than they would have been under pre-exploitation conditions.

In contrast, the confined region has suffered massive drawdowns which have dewatered large areas of Basal Sands and Chalk. Under natural conditions Chalk/Basal Sand groundwater levels at the centre of the basin were generally between 20 and 50 metres above the top of the Basal Sands aquifer, the variation being caused by the tight folding running parallel to the main synclinal axis. The lowest conditions were reached in the mid 1960s when the Chalk groundwater level ranged between 5 and 25 metres below the top of the Chalk formation, equivalent to a regional drawdown of between 70 and 80 metres. The regional groundwater contour pattern for these extreme conditions (1965) is shown in Fig. 4. Note that superimposed on the regional decline are two deeper cones of depression centred on west central London and the region to the north of the Thames estuary. These areas were centres of relatively high industrial and commercial usage and low transmissivity (probably less than 150m^2/d).

By 1970 Chalk groundwater levels throughout the confined region had begun to rise and have been doing so at rates between 0.3 and 2 metres per year for the last seventeen years. If this rate of rise were to continue it would take between 10 and 80 years before the Basal Sands became resaturated, depending on location.

The reason for the rise is clearly the reduction in abstractions which have been taking place in the confined region since the 1940s and in the unconfined region since 1971/2. However, the reason for the timing of the rise, i.e. between 1965 and 1970, is not immediately obvious. The most probable explanation is that between 1965 and 1970 confined abstractions had fallen to a level (about 160 x 10^3 m^3/d) which was now less than flow into the basin from the unconfined region. If this is the case, then it would appear that the flow from the unconfined into the confined was not significantly reduced by the increase in abstractions on the unconfined region between 1965 and 1970. It should also be added here that an additional factor which could be relevant to the "modern" water balance calculations of the London Basin is that of mains leakage (Burrows and Broomfield, 1984) which by the late 1960s could have been contributing significantly to flows on the unconfined region.

3.3 IMPLICATIONS OF RISE

Fig. 5 is based on several hydrographs and shows an idealised trend of the fall and rise in Chalk groundwater levels under the central London area. The trend is superimposed on a typical geological sequence for the area. Also shown are three chronological markers highlighting the development of London's underground structures. The first is the commencement of the Northern Line underground railway at the turn of the century which marked the construction of the first deep structure. Note that at this time groundwater levels were already approaching or below the base of the London and Woolwich & Reading Clays. The second time marker is 1950 which really heralded the start of the present day expansion in deep structures: foundations, underground railway and water tunnels and service ducts. By this time groundwater levels had generally fallen below the Chalk/Basal Sands boundary and were still falling.

The question of what will happen to existing and future deep structures if groundwater levels were to return to anything like their natural state did not appear to be asked until as recently as 1976 when the design of the British Library in central London got underway (Ove Arup & Partners, 1983). By this time it had become apparent that Chalk groundwater levels in and around the central London area were rising steadily, see Fig. 5.

Because the unconfined region which supplies most of the natural recharge to the confined area is heavily abstracted and there will always be some abstraction from the confined region, it is unlikely that groundwater levels at the centre of the basin will return to their original elevations. Nonetheless, the current ongoing rise is likely to resaturate the Basal Sands and to go some way towards developing the original confining piezometric heads beneath the Woolwich & Reading Clay &/or London Clay. Such groundwater elevations and their associated pore pressures could give rise to various geotechnic problems. These problems and the ways they are being studied are discussed in section 6. However, before this, it is important to put in context the state of London's existing water resources and its growing demand for water.

4. FUTURE DEMAND

4.1 PRESENT WATER SUPPLY SYSTEM

Water is supplied to the London Basin area directly by Thames Water and by various water companies acting as its agents. The total current resource is estimated to be about 2,700 x $10^3m^3/d$ of which 60% is derived from the Rivers Thames and Lee and stored nearby in bunded reservoirs. The rest of the resource is groundwater abstracted from the unconfined (91%) and confined (9%) Chalk aquifer of the London Basin groundwater catchment. Of this total resource Thames Water currently supplies some 2000 x $10^3m^3/d$ directly to the public and industry.

In terms of being able to meet levels of service, the water resource system serving the London area (a population of 5.5 millions) is in deficit, moreover, demand is rising steadily at 1% per annum. In practice this deficit means that our current water resources capability is not sufficient to maintain normal service during drought years of a frequency of about one year in eight. Thus, in the medium term at least, we need to develop new water resources for strategic use during drought years.

4.2 NEW OPTIONS

Fig. 6 shows the **actual** water supplied from 1966 to 1985 and **forecasted** water use from 1986 to 2011 for the area of the London Basin which is supplied directly by Thames Water. The forecast assumes that there will be a 10% reduction in leakage from the distribution system. Superimposed on the forecast are the current resources (1) and possible future options (2 to 9).

The Teddington Flow Proposal (option 2; Thames Water, 1986) is essentially a proposal by the Authority to the Government asking for a variation in the licence governing the flow over Teddington.

Weir (lowest non-tidal reach) so that the River Thames can be managed more effectively during periods of drought. If the Government allows the proposal to be adopted it is estimated that the change in operation will enhance our water resources by 170 x $10^3m^3/d$. Thereafter no easy surface or groundwater options remain. All new options have some degree of technical difficulty or environmental impact, all will take time to implement and all have a high unit cost compared with previous water resource schemes.

5. ARTIFICIAL RECHARGE

5.1 ADVANTAGES

It has been demonstrated above that it would be extremely unwise to undertake any further major abstractions from the London Basin without replenishing the desaturated Chalk/Basal Sands aquifer. To some extent the current rise in levels is doing this naturally, however, the estimated resaturation time is 10 years at the very earliest and likely to be considerably longer. Clearly, the present rates of rise are not sufficient to be of any practical benefit to our water resource needs. Thus, if we are going to make use of groundwater storage in the London Basin as a strategic resource at times of drought, we must undertake artificial recharge.

Artificial recharge of hydrogeologically favourable areas of the London Basin (see options (3) and (4) in Fig. 6.) is the most attractive of the new options from the view points of unit cost and ease of implementation which can be phased over several years thereby keeping pace with demand. There are, however, technical and environmental uncertainties to overcome.

5.2 SCHEME DESIGN

The two new areas being proposed for artificial recharge are the Enfield-Haringey area in North London and an area of the confined Chalk/Basal Sands of South London, see Fig. 7. As mentioned above large scale artificial recharge experiment has already been successfully implemented in the Lee Valley so we know that the technique will work in practice.

The existing Lee Valley scheme consists of six wells and seven boreholes and will yield 80 x $10^3 m^3/d$ over 200 days. Based on our current knowledge of the aquifer system, it is estimated thad the proposed Enfield-Haringey and South London areas are each capable of yielding 100 x $10^3 m^3/d$ and, if developed, would boost current resources by 10%.

The source of the artificial recharge supply is river-derived treated mains water to be injected during off-peak periods. Under operational drought conditions the recharge boreholes will be used to abstract groundwater which is to be treated on site and pumped directly into supply through the existing water distribution network. The recharge/abstraction procedure is illustrated in Fig. 8. and a typical eight year recharge/abstraction operational cycle is shown in Fig. 9.

5.3 UNCERTAINTIES

Uncertainties associated with implementing artificial recharge still remain. In order to clear up these uncertainties, four inter-related research projects were initiated in 1985 and all should be completed by the end of 1987. The four projects are as follows:

Groundwater Quantity: improvement in our present understanding of regional groundwater movement, quantification of losses from recharge mounds, optimization of recharge/abstraction phases, prediction of regional rises in groundwater levels. Regional groundwater modelling (transient finite element) forms the basis of this project.

Groundwater Quality: improvement in our present understanding of how groundwater quality may be changed by widespread artificial recharge and determine whether there are any significant implications for on-site water treatment. This project includes extensive field and laboratory work.

Water Treatment: research into cheaper and more flexible alternatives to conventional disinfection by chlorination; in particular field trials on the use of ultra-violet radiation are being carried out within a programme of aquifer testing.

Consequences of Rising Groundwater Levels: Thames Water's policy is not to undertake any widespread recharging until the potential environmental problems associated with rising groundwater levels under London have been properly assessed. This project is discussed at length below.

The Water·Research Centre are carrying out the groundwater quantity and quality studies in collaboration with Thames Water, the UV feasibility study is being carried out by Thames Water and the Construction Industry Research and Information Association (CIRIA) are managing the rising groundwater level project.

6. RISING GROUNDWATER LEVELS

6.1 THE **CIRIA** PROJECT

The possible problems associated with rising groundwater levels within the London Basin are wide-ranging and of national importance. It was therefore important from the outset that the project be managed by a broadly supported and non-partisan organisation. CIRIA who command the support of the whole construction industry were therefore ideally suited for managing this project.

The project is funded by the various organisations who have a special interest in the problem. These include the Department of the Environment, London Underground, British Telecom, insurance and property organisations and, of course, Thames Water. The work is being carried out by two leading civil engineering consultants whose specialisation is in foundations and tunnelling. Thames Water and the Water Research Centre are also part of the technical team providing basic hydrogeological data, predictions in future groundwater level rise and water quality information. This project is seen by CIRIA as the forerunner to future studies on other U.K. cities such as Birmingham and Liverpool where a similar history of groundwater exploitation exists.

The project started in December 1985 under the title of "Rising Groundwater Levels in the London Basin and their Engineering Implications" and is divided into two stages: Stage 1 was completed in March 1986 and Stage 2 is currently under way and due to be completed in October 1987.

6.2 POTENCIAL PROBLEMS AND AREAS OF RISK

The overall objective of Stage 1 was to establish the potencial problems and to give an appraisal of the areas of risk. The main findings to come out of the report at the end of Stage 1 (CIRIA, 1986) are outlined below.

The Stage 1 report asserted that an increase in pore pressure brought about by a long-term rise in groundwater levels from the Chalk into the Tertiary strata above could result in the following potentially damaging changes:

a) a reduction in bearing capacity in piled foundations;
b) a change in pre-existing stress conditions between tunnel lining and the surrounding ground;
c) an increase in the load on retaining walls;
d) the development of uplift pressures under foundations and floor slabs; and
e) swelling and heave of clays.

Furthermore rising groundwater levels can also introduce or increase the flow of groundwater giving rise to:

a) leakage into basements, tunnels and service ducts;
b) solution of minerals thereby increasing the possibility of chemical attack on underground structures e.g. mobilisation of sulphates could lead to the degradation of concrete piles and tunnel linings:
c) confinement of hazardous gases;
d) increased drainage and instability of excavations and temporary works.

The Stage 1 report stressed that all of these problems are extremely unlikely to occur everywhere there is a rising groundwater level condition. In general, the degree of risk at a given location will depend upon the following factors:

- whether there has been a significant long-term decline in groundwater levels;
- the geological profile;
- the type of structure(s) in question;

- the eventual limit of groundwater level rise (water table or pressure surface).

The first three of these factors are relatively easy to evaluate. However, the fourth factor (limits of rise) is more difficult and is one of the objectives of the groundwater modelling study being carried out by WRc.

Using these factors and assuming for the fourth factor that groundwater levels would return to their natural condition (a possible but unlikely worst case) it was possible to identify over the London Basin three critical areas in which certain types of exceptional structures could be at risk.

In the case of tunnels it was concluded that deep bored tunnels were the most vulnerable over sections which either passed through the sandy Tertiary strata below the Woolwich & Reading Clays or where they were within the clay strata but within 3 to 5 metres of the sandy Tertiary strata. In the latter situation it would be possible for tunnel enlargements, shafts or site investigation boreholes to penetrate downwards into the more permeable sandy formation thus providing a high permeability connectin to the tunnel fabric. Tunnels and foundations contained wholly within the London Clay were considered not to be generally at risk. However, the geotechnic implications of the local presence of scour hollows are to receive further attention in Stage 2 of the study.

6.3 STAGE 2

The aim of Stage 1 was to take a broad and comprehensive look at all the potential problems associated with rising groundwater levels in the London Basin. Stage 2 on the other hand, is aimed at tackling those problems which could actually occur. This aim is embraced in a twofold objective firstly to determine the specific nature and locality of these problems when groundwater levels reach their ultimate elevations and secondly to recommend the most cost-effective preventative measures.

Preventative measures could consist of either the control of groundwater levels by pumping or the carrying out of remedial engineering works such as tanking deep basements or underpinning foundations. Control by pumping could range from very localised pumping aimed at lowering the groundwater level around a specific building through to regional control in which several strategically placed boreholes would be employed to lower groundwater levels over several square kilometres. Whether the control is local or regional, the disposal of the resulting groundwater discharge is likely to pose a major practical problem in such a heavily urbanised area as London.

It is anticipated that the choice between remedial works or groundwater control, or some combination of the two, will depend largely on costs. In the case of control, the groundwater model will be used to evaluate the abstraction rates necessary to maintain groundwater at specified acceptable levels, the latter having been assessed by the engineering and geotechnical analysis carried out in the first part of Stage 2.

6.4 RESPONSIBILITY FOR PREVENTATIVE MEASURES

At present no organisation has specific legal responsibility for dealing with the potential problems posed by rising groundwater levels. Thames Water take the view that rising groundwater levels caused by a decrease in abstractions is a natrual occurrence for which the Water Authority cannot be held responsible. If, on the other hand, the Water Authority undertakes artificial recharge to increase aquifer storage then it must be prepared in principle to accept at least some responsibility for rising groundwater levels where the rise is associated with the recharge mound.

The CIRIA project will provide both factual information as well as greater understanding about the potential problems of rising groundwater levels in the London Basin. It is expected that the results will aid the Department of the Environment in producing any new legislation which is necessary for dealing with the responsibility for preventative measures.

7. CONCLUSIONS

7.1 EXPLOITATION

The groundwater catchment of the London Basin (4500Km^2) is an unconfined/confined system in which the unconfined Chalk aquifer occupying the higher ground to the north and south of London provides the confined region with natural recharge estimated to be some 200 x 10^{3}m^3/d under pre-exploitation conditions.

Abstraction of groundwater firstly from the leaky confined Chalk/Basal Sands system at the centre of the basin and later from the unconfined Chalk outcrop grew steadily from about 1820 until 1970 when the total groundwater abstraction from the London Basin for public, industrial, commercial and other uses was 1280 x 10^{3}m^3/d, some 80 x 10^{3}m^3/d in excess of the 25-year average for natural recharge (1200 x 10^{3}m^3/d).

The steadily growing trend in abstractions led to substantial reductions in baseflows and springflows on the unconfined and a large regional drawdown of up to 80 metres in the confined region.

Since 1940 confined abstractions, unlike those of the unconfined, started to decline with the result that the input of natural recharge from the unconfined region probably exceeded the level of confined abstraction some time between 1965 and 1970 thereby producing a regional rise in groundwater levels by 1970.

This rise poses a possible threat to deep structures all of which have been constructed since 1900 when the Chalk/Basal Sands aquifer was being dewatered.

7.2 GROWING DEMAND AND UNCERTAINTIES IN IMPLEMENTING ARTIFICIAL RECHARGE

The total surface water and groundwater resource supplying the London area's 5.5 million population is currently in deficit, and with demand increasing at 1% per annum, there is a need to enhance resources in order to meet levels of service during periods of drought. Artificial recharge (using river-derived off-peak treated mains water) of hydrogeologically favourable areas within the confined region is one of the most attractive new water resource options in terms of unit cost and relative ease of implementation. Although artificial recharge has already been successfully carried out in the lower Lee Valley, uncertainties associated with its wider-scale implementation still remain. In order to clear up these uncertainties a research programme has been initiated in which groundwater quantity, groundwater quality, water treatment and rising groundwater levels form four inter-related research projects.

7.3 RISING GROUNDWATER LEVEL PROBLEM

The rising groundwater level projects is of national importance and is the forerunner of its kind in the U.K. CIRIA is co-ordinating this multi-disciplinary project which is divided into two stages. Stage 1 has been completed and identified three critical areas over the London Basin in which exceptional structures could be at risk when groundwater levels approach their original pre-exploitation elevations.

Stage 2 is currently underway and will report in October 1987 on the specific nature and locality of any potential problems and recommend the most cost-effective preventative measures for dealing with them.

7.4 CONCLUDING REMARKS

Although groundwater levels are rising throughout the London Basin (including those hydrogelogically favourable areas set aside for artificial recharge), the rise is not sufficiently rapid to be of any short term practical benefit to our current water resources needs. Hence the necessity to accelerate this natural increase in storage by carrying out artificial recharge, an action which could significantly increase the rate of rise in those critical areas identified in the CIRIA project.

Preventative measures may have to be undertaken in the critical areas, whether or not artificial recharge is carried out, but at present no organisation has specific legal responsibility for this task. Although Thames Water is well placed to monitor and, if need be, control groundwater levels, it regards the present rise as natural and therefore not its responsibility. If, on the other hand, artificial recharge is carried out on the wide scale proposed, the Authority would have to accept at least some responsibility for undertaking preventative measures where it could be demonstrated that artificial recharge was a significant factor in causing the rise. By providing factual information and a better understanding of the problem, it is hoped that the CIRIA project will point the way forward on this question of responsibility for preventative measures.

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Figure 1 Geology of London Basin

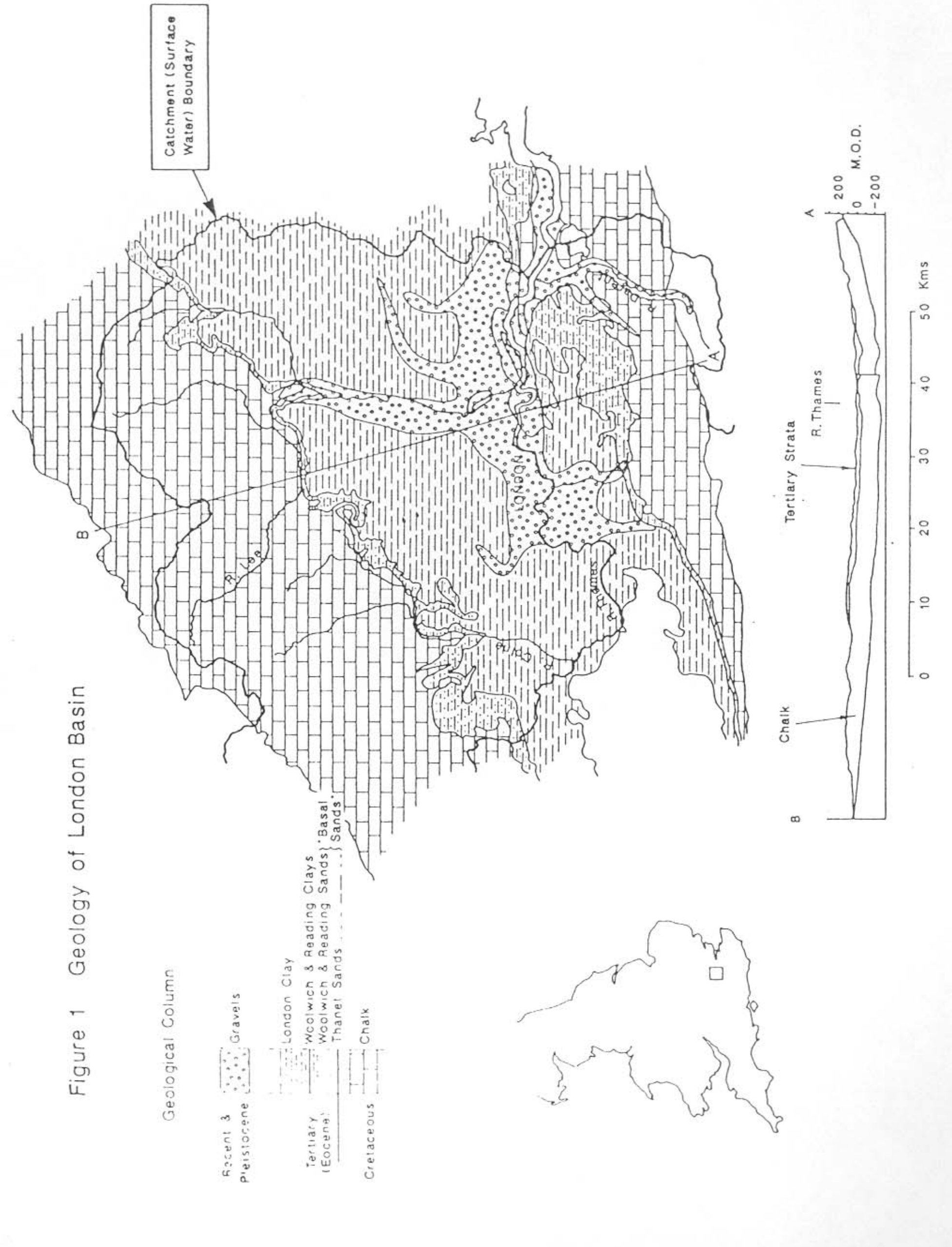


Figure 2 Groundwater Catchment & Natural Groundwater Contours

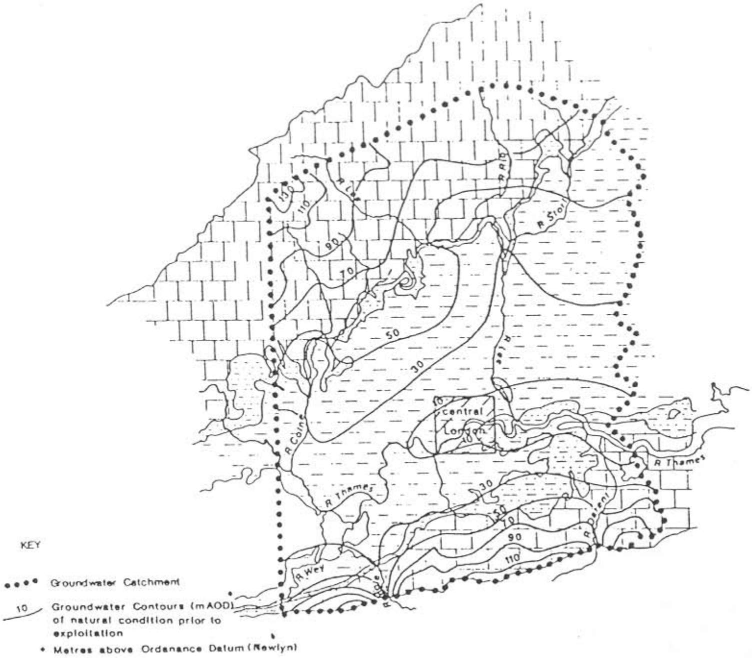


Figure 4

Lowest Chalk Groundwater Level Conditions (1965)

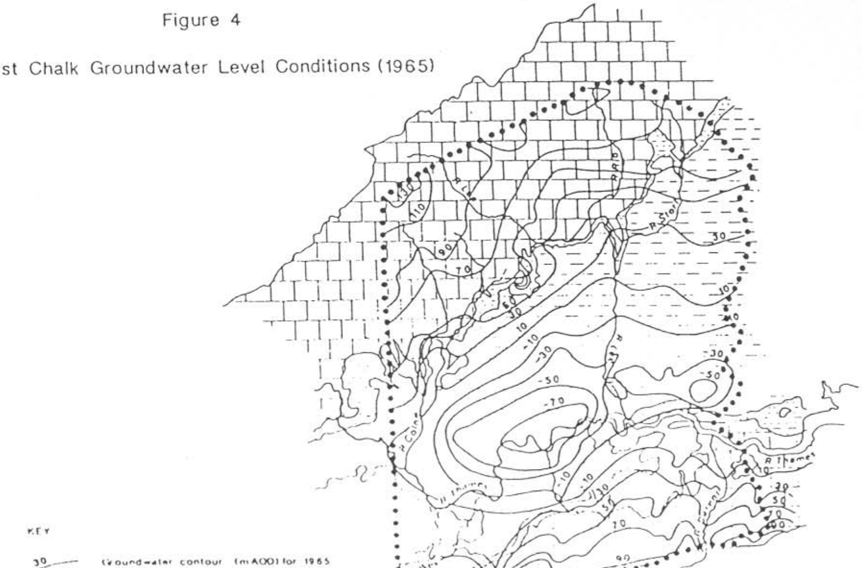


Figure 3 Abstraction from the London Basin 1820 to 1985

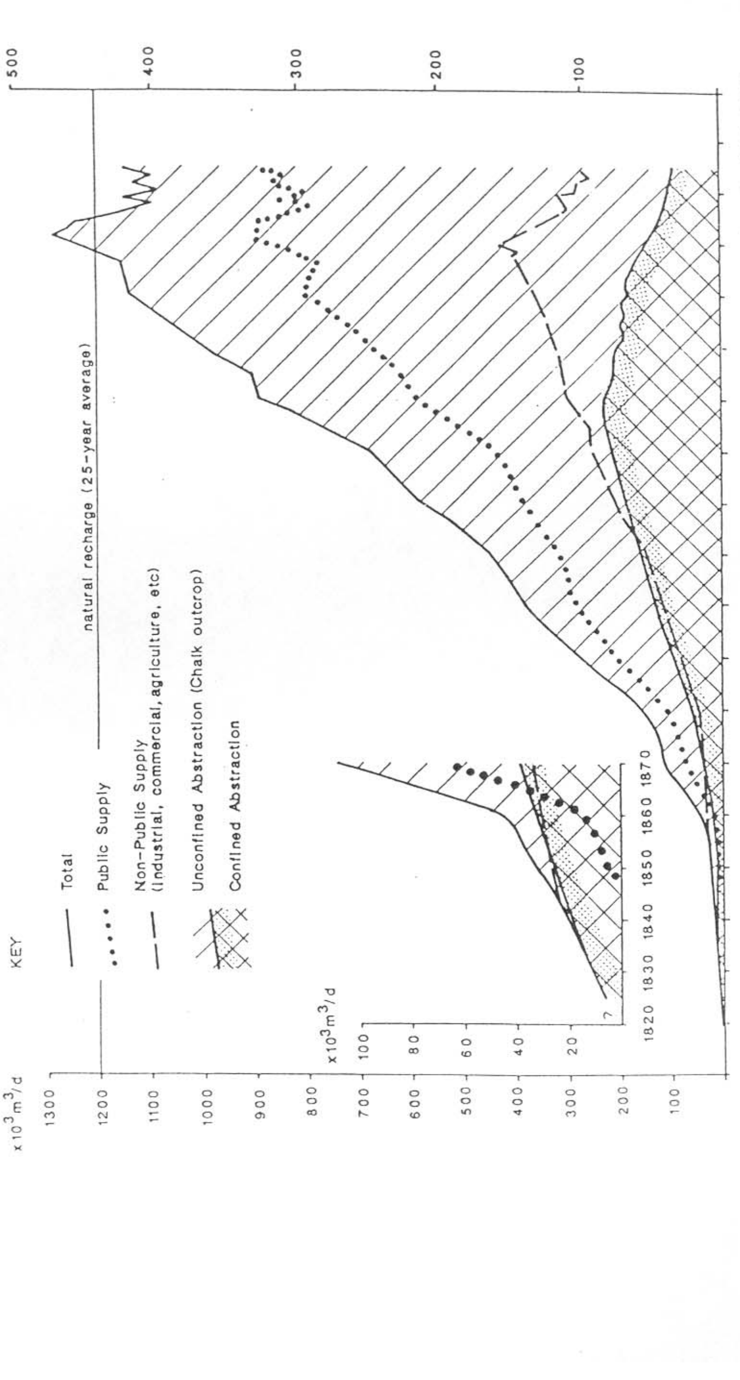


Figure 5 Idealised Section to Show Trend of Fall & Rise in Chalk Groundwater Levels under Central London

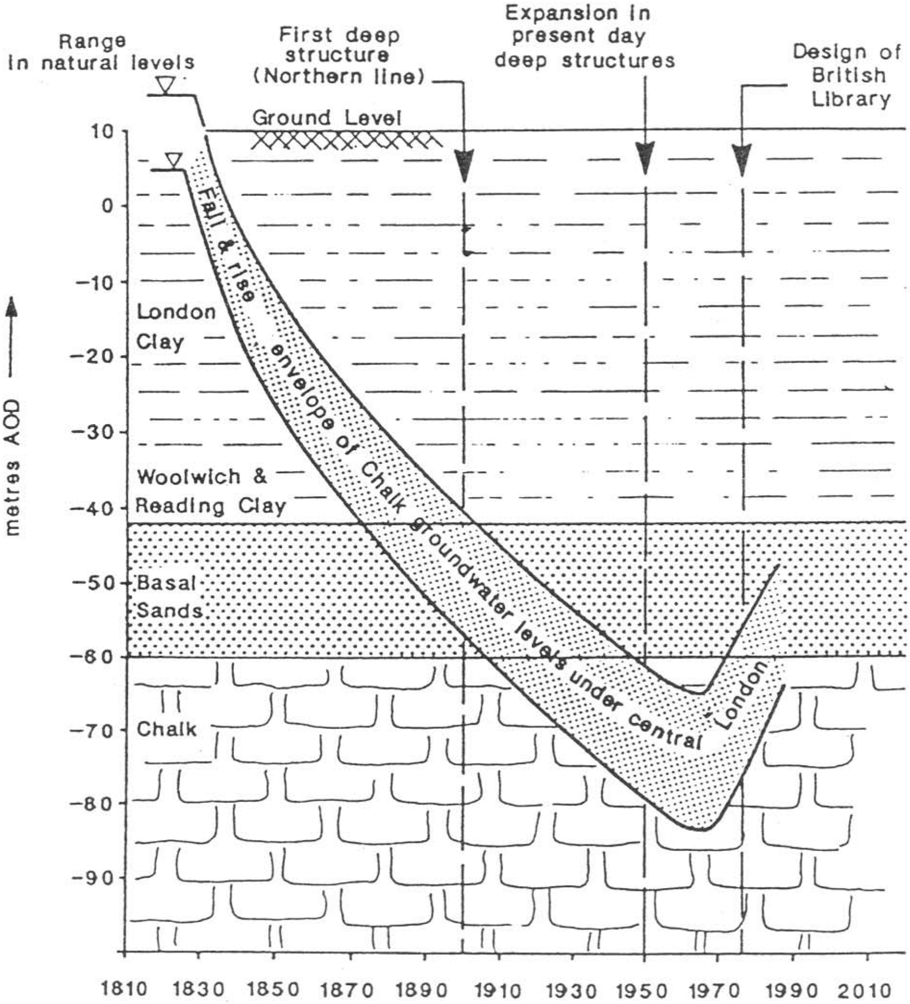


Figure 6 Water Demand and Water Resources Options

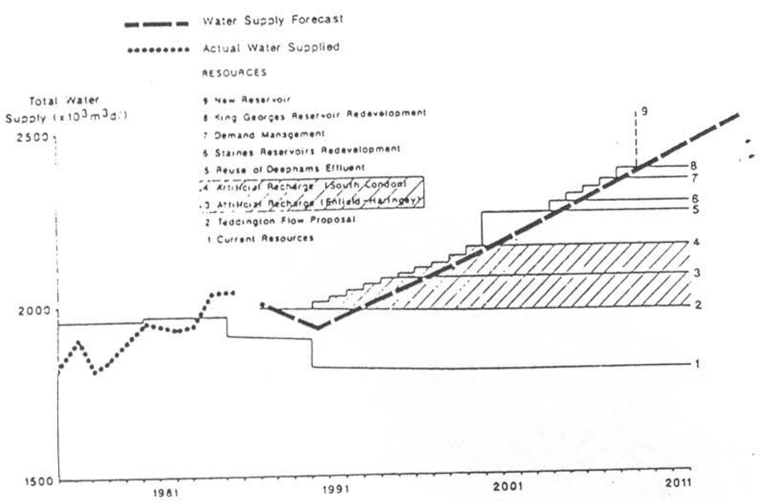
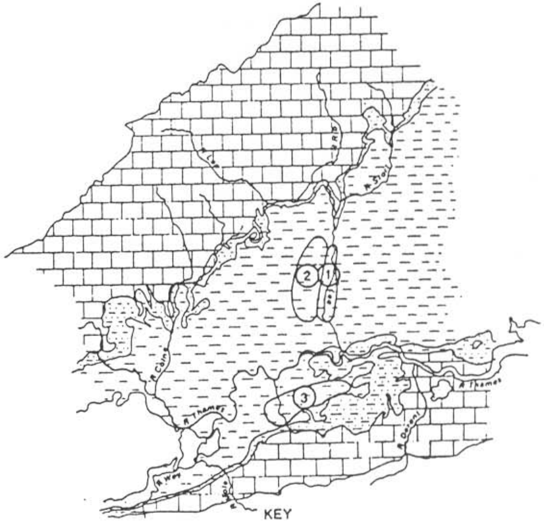


Figure 7 Existing & Proposed Artificial Recharge Areas



KEY

Artificial Recharge Areas

1 Existing Lee Valley Scheme
2 Proposed Enfield-Haringey Area
3 Proposed South London Area

Figure 8 Recharge/Abstraction Procedure

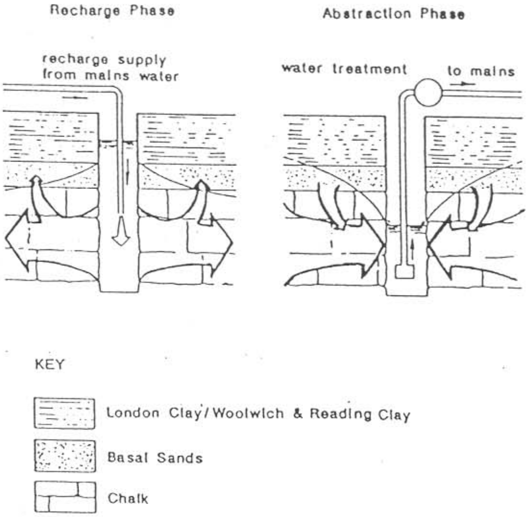


Figure 9 Schematic Representation of Operational Cycle