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A HYDROGEOLOGICAL MODEL FOR LONDON DOCKLANDS

A F Howland MSc DIC PhD CEng FIMM CGeol FGS (1), K R Rushton BSc PhD DSc CEng MICE MIWES (2), S E Sutton BA MA DPhil MIWEM FGS (3) & L M Tomlinson BSc (4)

(1) Principal and (3) Consultant, A F Howland Associates, 88 Newmarket Road, Norwich, Norfolk NR2 2LB; (2) Professor of Civil Engineering and (4) Research Fellow, University of Birmingham, Edgbaston, Birmingham B15 2TT

SYNOPSIS

As part of a rationalised approach to provide a regional understanding of the natural setting of the Docklands area of east London a mathematical model of the hydrogeology has been developed. This accommodates the complex geological control present in the area and models the interaction between two separate aquifers, which are each influenced by a local system of docks and rivers. The model successfully describes the hydrogeology and provides a predictive tool able to evaluate the consequential interaction between groundwater and the continuing development of the area.

INTRODUCTION

London's Docklands cover an area of about 22 square kilometres along the River Thames to the east of the City of London (Fig. 1). The area was formerly industrial land dominated by a number of separate dock systems and other heavy industries. During the early part of the second half of the twentieth century the area underwent a period of economic and social decline which followed the progressive closure of the docks and the loss of other industry in the area.

In 1981 the London Docklands Development Corporation (LDDC) was created by Government to provide the necessary impetus for the regeneration of the area. The principal aim of the LDDC was to stimulate private sector interest in the area. It immediately embarked on an extensive programme of infrastructure improvements. In addition, in order to overcome any uncertainty over ground conditions it instigated a programme of data collection and an on-going appraisal to develop a regional understanding of the engineering geology. This coincided with a growing awareness of the changes which were occurring to the groundwater beneath London. The study for LDDC showed that although Docklands was partly affected by the cone of groundwater abstraction in central London the situation was further complicated by its particular geological setting and such factors as the presence of the former docks and the river system. In 1986 the engineering geological appraisal was extended to provide a more systematic evaluation of the hydrogeology of the area.

GEOLOGICAL SETTING

Structure

Docklands lies on part of the modern flood plain of the River Thames within the geological province of the London Basin. The London Basin is a shallow fold in Cretaceous and younger rocks which plunges gently towards the east and extends from the mainland out into the southern North Sea (Fig 2). It has a geomorphological expression defined by the Chalk downlands of the Chilterns and the North Downs to the north and south respectively, and in the west by the Marlborough Downs where the two limbs of the syncline converge. The River Thames runs through the Basin but is discordant with the axis and crosses the southern limb in the Docklands area.

The main structural axis of the London Basin is principally east west but this does undulate on a large scale. The classic work on the London Basin has suggested that the main axis is crossed by a number of smaller structural features. One of the more substantial of these, the Greenwich Fault, is traditionally shown to cross the Docklands area (Ref. 1). However, the geological modelling of the area carried out for the LDDC has shown that the Greenwich Fault may not be present, rather that the dominant structural feature is a north plunging syncline, which has been termed the Greenwich Syncline (Refs 2).

The Greenwich Syncline is a shallow open fold with a northeast southwest strike. Its eastern limb dips at about 2 degrees and the western limb at about 0.5 degrees. There are no complementary features of a similar scale in the immediate area, but low amplitude anticlinal features are evident to both the east and the west.

Stratigraphy

The London Basin has formed a depositional centre for a variety of estuarine and marine sediments following a number of marine incursions into and across the area throughout the Palaeogene. Of these, the Thanet Sand, the Woolwich and Reading Beds and the London Clay formations, together with the Chalk crop out below the superficial cover in the Docklands area (Fig. 3).

The Chalk is approximately 200m thick, with the Upper Chalk present in the highest levels. This is overlain by the Thanet Sands, the youngest of the Palaeogene sediments, which is about 16m thick in Docklands and comprises a quartz sand over most of its thickness although minor fractions of clay and occasional thin clay laminae are present. The basal layer of the Thanet Sands is called the Bullhead Bed and is characterized by dark green rounded flint pebbles in a silty clay matrix.

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The Woolwich and Reading Beds rest unconformably on the Thanet Sands and overstep them to the west of London to lie directly on the Chalk. They have a similar thickness to the Thanet Sands but form a much more varied sequence. In Docklands, seven distinct facies have been identified (Refs 2). These reflect the variability of a marginal near shore depositional environment present in Woolwich and Reading Bed times.

Following deposition of the Woolwich and Reading Beds a deep water marine environment developed across south east England which resulted in the deposition of the London Clay. Over its greater thickness the London Clay is a dark grey or purplish grey fissured clay with varying proportions of silt and some sand although this becomes increasingly sandy and silty over the basal few metres.

The formations of the solid geology are overlain by superficial materials of Quaternary age which can be separated conveniently into the Thames Gravels, Alluvium and Made Ground.

The Thames Gravels form a distinctive suite of siliceous sand and gravel which extend throughout the middle and lower Thames valley. They were deposited during the colder phases of the Pleistocene under braided conditions following episodic periods of high stream discharge and can be separated into a series of local terraces. However, despite this there remains an overall consistency within the mechanical character of the various gravels such that further distinction is unnecessary. Thames Gravels is therefore a convenient general term which can be used to describe the sequence.

After the last glacial period an overall rise in sea level together with the reduced stream discharge allowed the deposition of alluvial muds and silts with subordinate and locally extensive peats across the present flood plain of the Thames which has continued to the recent historical past. In Docklands, the present distribution and condition of the alluvium has been markedly influenced by the effect of man. Across much of the urbanized parts of the flood plain the alluvium has been surcharged by made ground placed above it, or has been partly or completely removed.

The made ground covers much of the area and has accumulated in order to raise the general level or as a consequence of other activities. It is thickest at the edge of the River Thames where it forms a wedge covering the natural strand to provide increasingly deeper water frontages. Elsewhere it is thickest in a number of backfilled docks, locks and basements where it may be typically up to ten metres thick. More usually it forms a cover of about two to three metres. The character and condition of made ground is inherently variable and this is no exception in Docklands. Material found in the made ground has been derived from a number of sources. Around the docks area this includes the natural materials, usually the Alluvium and Thames Gravels produced during construction of the docks. It

also includes demolition rubble as subsequent phases of development occurred. In certain areas substantial amounts of industrial waste products are also found.

Hydrogeological Setting

Docklands is underlain by two principal aquifers termed the upper and lower aquifers. The 'lower aquifer' comprises the Chalk together with the overlying Thanet Sands and more sandy basal units of the Woolwich and Reading Beds. The 'upper aquifer' consists of the Thames Gravels. Over part of the area these are in contact, but to the west they are separated by an aquiclude consisting of the relatively impermeable London Clay or the cohesive strata of the upper units of the Woolwich and Reading Beds so that the lower aquifer becomes confined.

In the natural state the groundwater contained in the lower aquifer is artesian. However, following exploitation of the lower aquifer in central London the piezometric levels began to fall and a cone of depression developed and by the second half of the twentieth century this had deepened to over 85m (Refs 3-4). The cone spread east towards Docklands where it has resulted in significant changes to the water system which previously operated.

Before exploitation of the lower aquifer the Thames would have acted as a lower discharge boundary for the natural water system and the river discharge would have been supplemented by the consequential groundwater flow. With the depression of the groundwater table flow in the lower aquifer would be directed towards central London so that the flow in the aquifer became divorced from the Thames. By 1965 the piezometric surface in the lower aquifer across Docklands fell from Ordnance Datum south of the Thames at Woolwich, to -8m OD on a line which crossed the Royal Docks and the southern Isle of Dogs. From there, the cone deepened rapidly westwards to -40m OD through Wapping (Fig. 4). A further cone of depression was also present in the Bow/Stratford area of the lower Lea Valley following local abstraction. This deflected the direction of flow in the lower aquifer below the Docklands towards the north and west.

The hydrogeology of the upper aquifer has also been affected by the general urbanisation of the area. The Thames Gravels are naturally confined by the overlying alluvium. This has been aggravated by extensive tracts of more recent made ground which have developed over them. Lateral constraints have also been caused by the construction of river walls, docks and other deep structures.

The natural surface recharge by infiltration has been intercepted by the impermeable surface of urban development and further modified by the construction of drains and sewers which can act either as recharge sources or discharge points depending on the local situation. The reduction of head in the lower aquifer has resulted in an underdrainage to the Thames Gravels.

The groundwater system results from a balance of the inflow and outflow to the area. The head distribution is governed by the characteristics of the materials through which the water travels, the direction of flow governed generally by the geographic distribution of the recharge and discharge points and the local hydraulic gradients developed from the resulting head distribution.

In Docklands the main discharge point is the cone of abstraction in central London. The recharge to this is provided by some natural recharge on the downlands to the south but more importantly by infiltration from the upper aquifer by surface infiltration and leakage from the rivers and docks system. The balance between recharge and discharge of the system and the controls to that balance define the hydrogeology of the area.

Purpose of the Model

The effect on engineering situations of the changing groundwater conditions in London have been recognised for some time (Refs 4-7). These have been largely concerned with the general effects of a rising or falling groundwater level. In Docklands, the changes which have occurred in both aquifers have produced a marked variation, not only in flow directions of the groundwater but also in the pressure distributions which govern them. These are particularly influenced by local effects resulting as a consequence of the development of the area.

The success of LDDC in regenerating Docklands has meant that the scale of development has increased dramatically from that originally envisaged. The interaction between the redevelopment and the groundwater will therefore also increase. Not only will new structures interfere with the existing hydrogeological system and result in marked changes to the surrounding groundwater regime, but its effect on adequate engineering design will also increase.

In order to give adequate consideration to these factors and the consequences of one on the other it is necessary to appreciate and understand the overall controls, the way that they operate and how they interact with each other. A full appreciation of the mechanics of the groundwater system at the resolution necessary to provide meaningful input to engineering design was only possible by use of a mathematical model.

MATHEMATICAL MODEL

Formulation

The first stage in the development of a mathematical groundwater model is to examine the space and time dimensions which it must incorporate. In Docklands the initial work had shown that the groundwater flows through a multi-strata system. Therefore, the model needed to be three dimensional in space. The initial works also showed that the groundwater system was dynamic and

was responding to both regional and local influences. Nonetheless, it showed that a relatively steady equilibrium existed so that only small changes occurred from year to year although changes over a wider time scale were known to be more significant. Therefore a pseudo steady state approach was adopted in which the model represents average conditions over limited periods. Consequently when the model is used for predictive purposes for long term effects, certain conditions need to be modified.

The next stage is to identify the important features which have a dominant influence on the flow process. These features can be deduced from information about the strata and the groundwater heads and are illustrated in a schematic cross-section (Fig. 5). In the study of Docklands, the important features are as follows.

a. Study Area: The area of interest was the administrative area of the LDDC, but for the purposes of the study a rectangular area was defined, (Fig. 3). Within this area the conditions must be specified for each layer at each boundary.

b. Properties of the Different Strata: The horizontal and vertical hydraulic permeabilities must be specified for each layer. The initial values were deduced from a wide variety of sources collated during the initial study and were modified slightly during the development of the model. The numerical values in the model are given in Table 1.

c. Inflows: For Docklands two main sources of inflow to the groundwater system were assumed to be present:

- Recharge through the Made Ground: The availability of surface infiltration is governed by the nature of the made ground, the presence of any impermeable cover and the extent of artificial drainage. By factoring the input values by an assessment of the immediate local conditions, one of four different recharge intensities were assigned which gave a recharge rate varying from 0.1 to 0.4 mm/d.
- Flow from the Docks: This results from leakage and depends on the effective permeability of the sides and base of each dock and the difference between the dock water level and the groundwater head in the stratum immediately underlying the dock. This was assessed from the impounding records for each dock. For the West India and Royal Victoria Docks the loss is taken as $200 \text{ m}^3/\text{d}$ per unit area for a one metre head difference between dock water level and the groundwater head. For the other docks in the area the loss is taken to be one tenth of this value. The general water levels in the various docks range from 3.0 to 4.2 mOD.

d. Rivers: The main river influencing groundwater conditions in Docklands is the River Thames with a lesser influence coming from the River Lea. Whether or not the Thames loses water to the aquifer depends on the difference between the average river level and the groundwater head in the aquifer. For a 200 m linear section of the River Thames the flow from river to aquifer equals $10 \text{ m}^3/\text{d}$ for a one metre head difference between the river level and the groundwater head at the relevant node. In practice there are certain sections of the river where the river feeds the aquifer and in other locations the reverse conditions hold.

e. Outflows: There are several locations where outflows occur from the aquifer system;

- on the boundaries of the study area from each layer; these flows are discussed further in (f) below,
- from the Thames Gravels in the north-east where the sewers are pumped. The loss from the groundwater system from leakage to the pumped sewers is estimated to be $2800 \text{ m}^3/\text{d}$.

f. Representation of boundary flows: In practice it is not possible to measure the flows which occur into or out of the system at the boundaries. These are therefore determined by indirect methods. At the south and east of the study area the groundwater head is specified in each layer which is in contact with the boundary. To the north and west, significant flows occur through the chalk. This is represented as specified flows from the Thanet Sands and Woolwich and Reading Beds which are adjusted to match known groundwater heads towards the north-west corner of the study area. For the Thames Gravels, a fixed head condition is applied at all the boundaries.

g. Groundwater Heads: Numerous records of groundwater heads are available for each of the layers in the model which were collated through the initial study. However, these are not basic data but are a consequence of the interaction between the inflows and outflows described above. The groundwater heads are therefore used as a check on the validity of the model.

Selection of the Model

A number of model codes already existed for three dimensional groundwater flow. These generally divide the area of interest into a rectangular grid of mesh points and are suitable for layered aquifers in which the strata are predominantly horizontal and of constant thickness. The complex hydrogeological setting of the Docklands does not conveniently fit this type of mesh. A special numerical model was therefore developed for the using a finite difference technique.

The Docklands model has a similar square mesh in plan with mesh intervals of 200 m so that each nodal point represents a unit area of 40,000 m². In the vertical direction, five layers are used which correspond to the five operating strata; Thames Gravels, London Clay, Woolwich and Reading Beds, Thanet Sands and Chalk, but because of the geological setting of the area these layers are of variable elevation and variable thickness which are represented by further nodal points in the vertical direction. This approach simplifies the representation of the layers but requires further modifications to allow for areas where strata are missing. In particular, care is required to accommodate the situation where two strata become interconnected when an intermediate strata wedges out. This situation can be identified in the schematic diagram of Figure 5.

Another important feature to be considered is the inclusion of time variant effects within the model. Groundwater heads also change with time in response to tides and to seasonal effects. The initial study showed that the overall conditions in the groundwater system in Docklands change little from year to year and are not sensitive to these effects. Consequently a time-instant approach can be used. In this approach the model is used to represent the aquifer conditions for a specified time period. Since the change in groundwater heads from year to year is small, the time-instant solution represents the aquifer conditions over a period of two to three years. When the model is used for predictive studies, certain conditions are changed to represent a new time-instant situation.

The finite difference formulation leads to a large number of simultaneous equations. The coefficients of these equations vary by several orders of magnitude due to the permeabilities which range over four orders of magnitude from 0.0001 m/d to greater than 10 m/d (Table 1). The method used to solve these simultaneous equations is point successive over-relaxation where the layers are scanned one at a time and the process repeated until the flow balance at each node is accurate to the equivalent of 0.001 mm/d (Ref. 8).

Testing the Validity of the Model

Validation of the model is based on comparisons between the observed and modelled groundwater heads. The general trends are comparable with differences in the Thames Gravels being no more than 1.0 m. Especially useful comparisons can be made in the vicinity of the Docks where both field and modelled groundwater heads can reach 3.0 mOD due to the influence of the leakage from the Docks. To the north-east, groundwater heads in the gravels fall below -2.0 mOD. This is successfully reproduced in the model.

There are also several field measurements of the groundwater heads in the Chalk. To the north-west both field and groundwater heads approach -30 mOD and the in the north-east

they are both about -2.0 mOD. Beneath the West India Docks both field and modelled heads in the Chalk are -4.0 mOD. Beneath the Surrey Docks, the field and modelled groundwater heads in the Chalk are -14.0 and -11.0 m respectively but here such differences are of little significance since the groundwater gradient in the Chalk in that area approaches 10 m per kilometre.

The flows from the Docks determined from the model are also comparable with the estimated losses which have been based on the field records. The model shows that loss from the Royal Victoria Docks approaches $3700 \text{ m}^3/\text{d}$ and for the West India Docks is more than $2000 \text{ m}^3/\text{d}$. In contrast, losses from the Surrey Docks, which are underlain by London Clay, total about $500 \text{ m}^3/\text{d}$.

Main Findings from Model

The model results can be summarised by the flow balance of Table 2 and represented diagrammatically as shown in figure 6 The results show:

- the influence of the rivers is small with losses from the River Thames of $630 \text{ m}^3/\text{d}$,
- the flows to the pumped sewers in the north-east are more significant than outflow from the River Thames,
- the flows from the Docks resulting from leakage totals about $7890 \text{ m}^3/\text{d}$. This is slightly larger than the recharge of $5700 \text{ m}^3/\text{d}$ to the Thames Gravels from surface infiltration, but due to the lack of precise information about these flows, it is more realistic to assume that these two inputs are of the same order,
- there are significant boundary inflows and outflows for the Thames Gravels, Woolwich and Reading Beds and the Thanet Sands,
- the largest and most important element of flow within the system is that from the Chalk to the north and west. This is more than $15000 \text{ m}^3/\text{d}$ and is a direct consequence of the very low groundwater heads in the lower aquifer in Central London.

The main conclusion which can be drawn from the model and the study of the current groundwater conditions in the London Docklands is that the system is driven by the balance of the drainage through the Chalk towards Central London and the balance by recharge from surface infiltration and leakage from the existing docks system.

Predictions from the Model

Having developed the model and confirmed that it represents the existing groundwater system in the London Docklands, it can be used to predict the consequences of broad changes to the basic conditions; or the effects of more localised influences; or the extent that either natural or artificial influences could change the groundwater levels present in both aquifers and effect the flow patterns between them. A number of predictive runs have been made to consider the sensitivity of the groundwater system to various changes. For example, the following modifications to conditions in Docklands have been shown to have only a small effect:

- Local abstraction from the lower aquifer: It would be possible to construct certain boreholes to the Chalk to abstract water as a possible source of surface recharge. The model shows that some additional flow would occur from any overlying gravels and that this would increase the leakage from any docks but that the main source of recharge would be from a modification of flow within the lower aquifer itself.
- Changes in base level: An increase in relative sea level to the land is postulated over the next few decades as a result of global environmental changes. This is aggravated in south east England by the continuing response to isostatic readjustment after the last ice age and is further confused in the London area because of the direct response of local soils to the urban development itself. In particular consolidation has developed as a consequence of the considerable loading by the structures of London itself. This is assisted by the further consolidation of the London Clay as underdrainage to the Chalk has caused an increase in effective stress (Ref. 5). Finally, the constraint of the Thames is causing an increasing rise in the tidal levels and projected flood levels for London. The model shows that a postulated rise of the mean level of 0.2m would have only a small effect on the flows from the River Thames to the aquifer system and would cause a rise in groundwater heads of about 0.1 m.
- Changes to the sewer system in the north east: The pumped sewer system in the north east of the study area causes a marked local drawdown in the groundwater levels in the upper aquifer in that area. If pumping stops it would have only a small effect on the conditions in the central Docklands area, although the local conditions would be modified accordingly.

In contrast, a significant effect on the Docklands groundwater system will occur as the postulated rise in groundwater head in the lower aquifer develops in Central London. It is estimated

that by 2010 or 2020, there could be a 50% recovery in groundwater heads in Central London. This is represented in the model by halving the flows to the north and west through the Chalk and associated strata. The model shows that this would result in a significant rise in the groundwater heads in the Chalk in the Docklands area with the heads in the Thames Gravels rising by 0.5 to 1.0 m over much of the study area. The predicted groundwater heads in the Thames Gravels are shown in Figure. 7. This indicates that there are significant areas where the predicted groundwater heads would be above +2.0 mOD.

CONCLUSION

An awareness by the London Docklands Development Corporation of the importance of a regional understanding of the engineering geology of the area in its programme of regeneration led to the collation and development of a geotechnical database of some 4,500 boreholes. This included a review of the hydrogeological setting of the area. The data from otherwise unconnected sites was amalgamated and an assessment made of the general groundwater regime. In order to understand the dynamics of the situation a numerical model has been developed.

The numerical model has shown that the groundwater system in Docklands is governed by a balance of inflows provided by recharge from surface infiltration and leakage from the docks, and outflow through the lower aquifer to the cone of abstraction in central London.

The model allows predictions to be made of the consequences to the groundwater system by changes brought about by either natural effects or the influence of the development of the area. The consequences of one on the other provide a means of assessing possible engineering or legal implication which may develop from changes to the groundwater situation and redevelopment of the area proceeds.

The main prediction is the overriding sensitivity of the local groundwater level in Docklands to the groundwater heads in central London. The cone of depression forms the final sink in the system so that as this fills the hydraulic gradients will flatten. This would result in raised groundwater levels across most of the Docklands area.

A similar approach to the understanding of the regional hydrogeology situation could be used. This has particular advantages where the groundwater system is in a state of flux or engineering development may significantly interact with the groundwater system.

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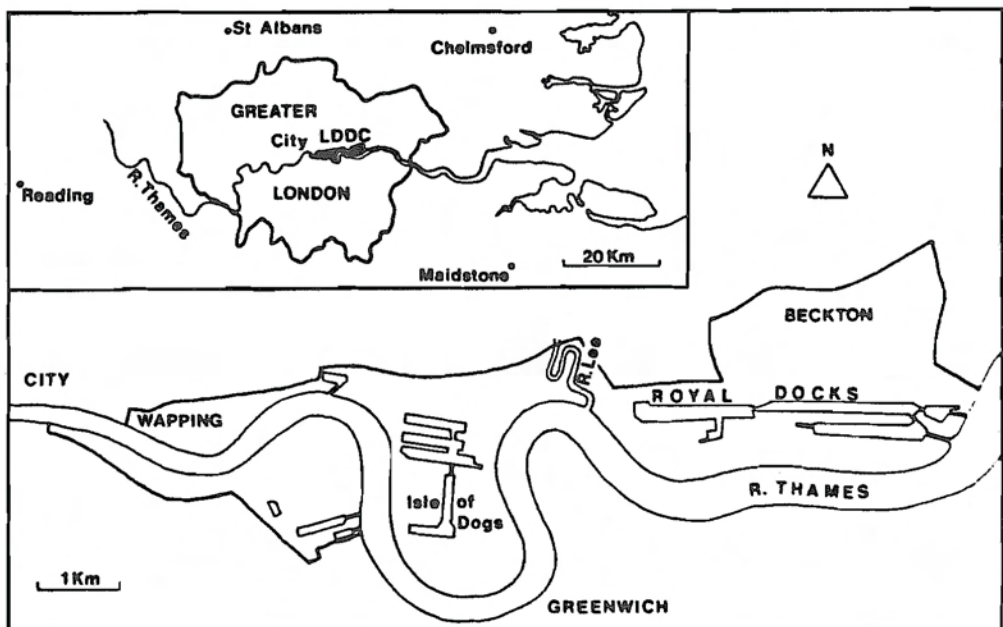


Figure 1 London Docklands (Ref. 2)

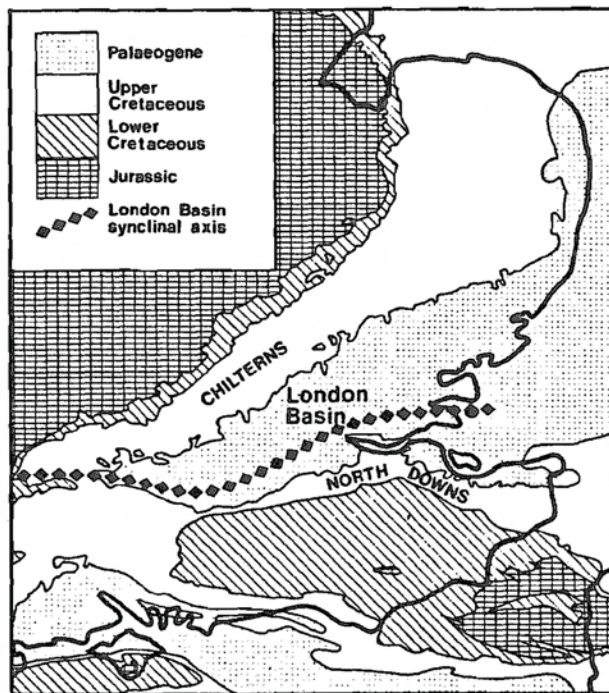


Figure 2 Geological setting of the London Basin (Ref. 2)

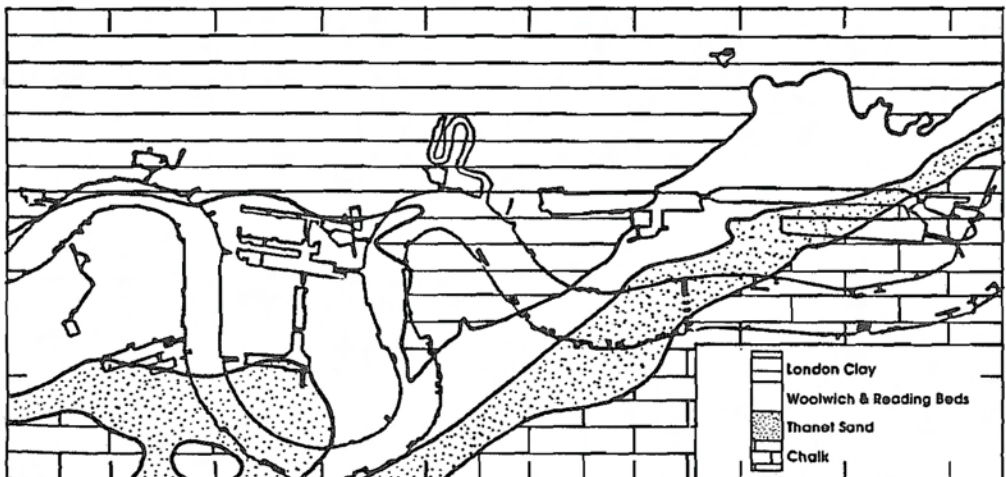


Figure 3 Solid geology of the area of interest

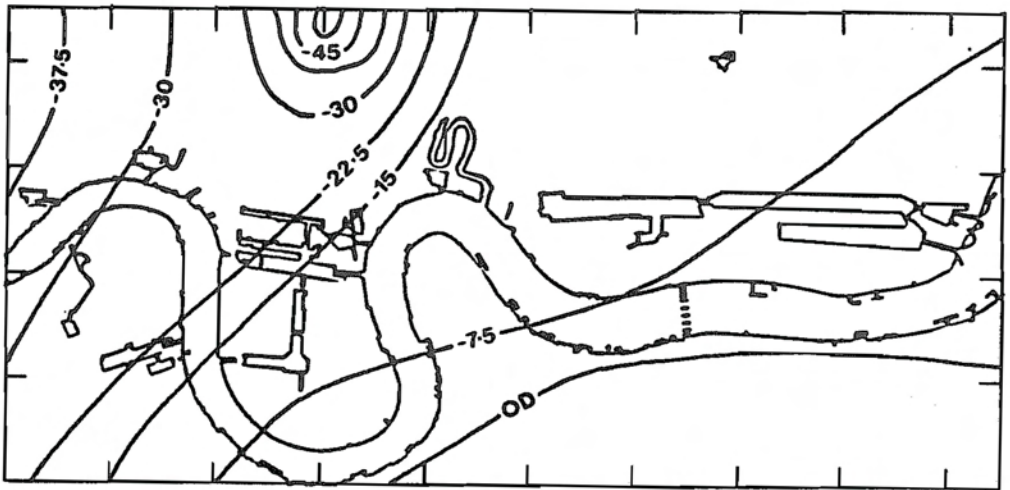


Figure 4 Groundwater level (m) in the lower aquifer in 1965 (Ref. 3)

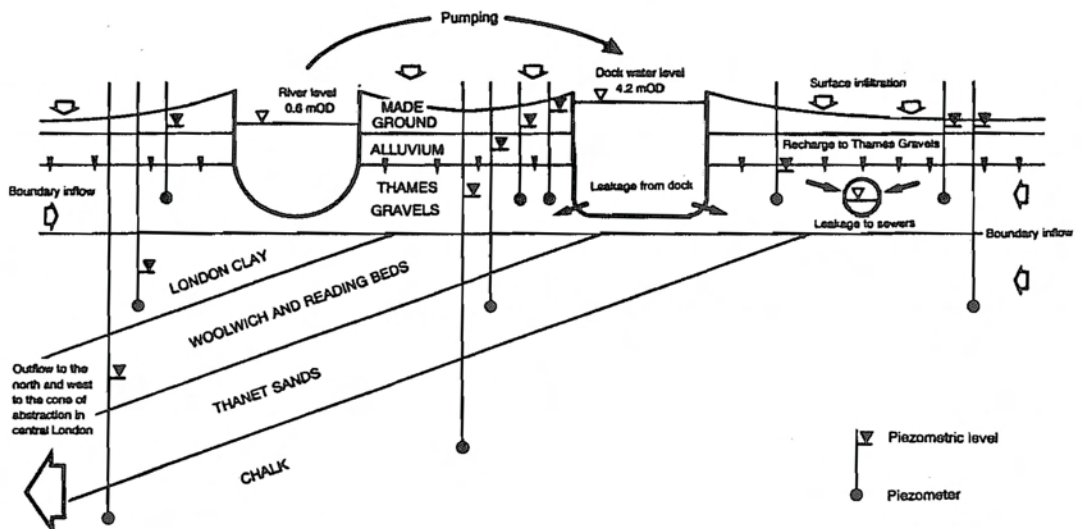


Figure 5 Schematic cross section illustrating strata and groundwater heads

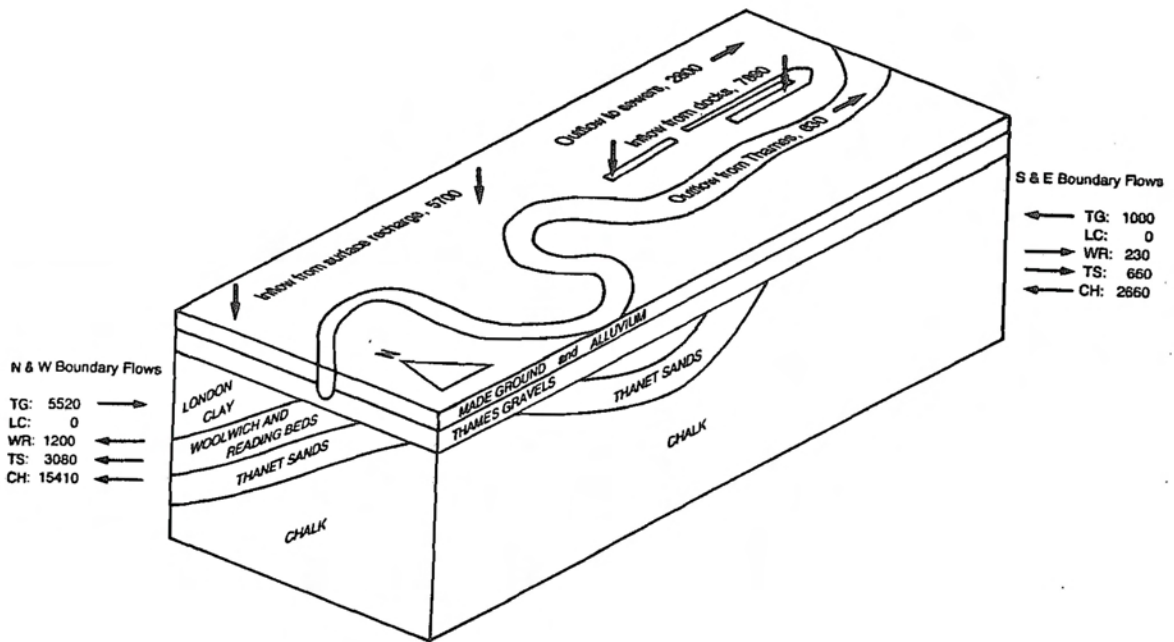


Figure 6 Diagrammatic representation of flow balance

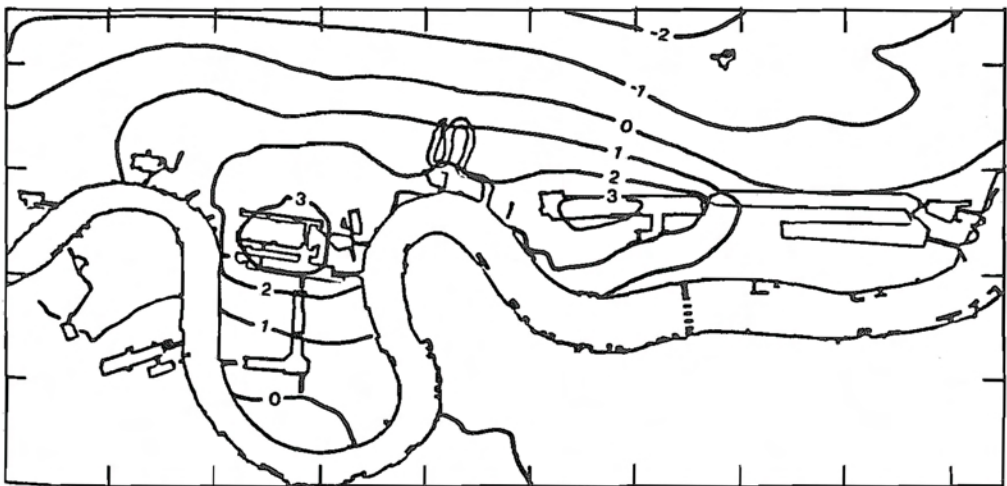


Figure 7 Predicted groundwater levels in the upper aquifer by about 2020 AD

Layer	Thickness m	Permeability, Horizontal	m/d Vertical
Thames Gravels	0 - 14	11.0	2.0
London Clay	0 - 40	0.0001	0.0001
Woolwich and Reading Beds	0 - 16	0.1, 1.0	0.002, 0.2
Thanet Sands	0 - 16	2.0	1.0
Chalk	30	1, 5, 7, 10	1, 5, 7, 10

Table 1 Layer characteristics used in the model

Table 2 Flow conditions for the Docklands area determined from the model