PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Urban Influences upon Groundwater Conditions in Thames Flood Plain Deposits of Central London

D. A. Gray and S. S. D. Foster

Phil. Trans. R. Soc. Lond. A 1972 **272**, 245-257
doi: 10.1098/rsta.1972.0049

Phil. Trans. R. Soc. Lond. A. **272**, 245–257 (1972) [245]
Printed in Great Britain

Urban influences upon groundwater conditions in Thames Flood Plain deposits of Central London

By D. A. Gray and S. S. D. Foster
Hydrogeological Department, Institute of Geological Sciences,
Exhibition Road, South Kensington, London, S.W. 7

[Plates 1 to 3]

Study of the groundwater in the riverine deposits of the Flood Plain Terrace of the River Thames in Central London indicates that the current conditions are dominated by man-made influences, particularly the underground railway systems and the river walls. Operation of the proposed Thames barrier in a half-tide mode would modify these influences and could lead to additional drainage problems and affect basement structures.

Introduction

The principles governing the occurrence of groundwater in the flood plain deposits of rivers are well established, but the modifications induced by man's long-continued occupancy of a flood plain on the scale of that in London are not well known. Except where such deposits have been developed intensively for water-supply purposes, their groundwater has been considered only in relation to excavation and construction problems at individual sites rather than on an overall basis.

The Thames Barrier Project Groundwater Working Party, established by the Greater London Council, initiated studies to determine the probable effect of the construction of a tidal control barrier on groundwater conditions throughout the Flood Plain Terrace upstream of the proposed site in Woolwich Reach. There would be little object in preventing flooding from surface water only to bring about a somewhat similar though more gradual and less catastrophic effect by raising the groundwater levels in the Flood Plain! The area under examination is bounded on the north and south by the outer limits of the Flood Plain, and to the west by Teddington Weir (figure 1).

The study programme was divided into several phases. Initially, the distribution and lithology of the deposits themselves had to be defined and for this purpose existing data in the form of geological maps and drilling records held by the Institute of Geological Sciences were adequate. An analysis of this information has been published (Mather, Gray & Houston 1971). The second stage was to examine existing data on groundwater quantity and quality, but these were insufficient to define the occurrence of groundwater in detail and a drilling programme had to be mounted to meet this need; a total of 39 boreholes had been drilled up to April 1971. Coördinated facts were required on the construction and condition of the river walls to identify those reaches of the river where hydraulic communication between the groundwater body and the river was possible and mass transfer of water could take place. These several lines of approach had to be collated to provide an indication of the overall pattern of groundwater flow in the Flood Plain deposits (Foster 1971).

Information on the shallow foundation design and basement construction of the buildings on the Flood Plain was also required to ascertain the possible significance of changes in groundwater levels in terms of increased seepage to drainage installations, new or additional uplift pressures on basement floor slabs and changes in foundation stresses. Some of the many types of development presently occupying the Flood Plain are shown in figures 2*a*, *b*, *c* (plates 1, 2 and 3). Serious seepage and stability problems occurred in King's County, New York City, when water levels rose following cessation of groundwater abstraction after many decades (Perlmutter & Soren 1963). Similar problems resulting from rising groundwater levels on the flood plains of the Ohio, Mississippi and Missouri have been avoided by installation of new or additional permanent de-watering systems (Leggett 1962).

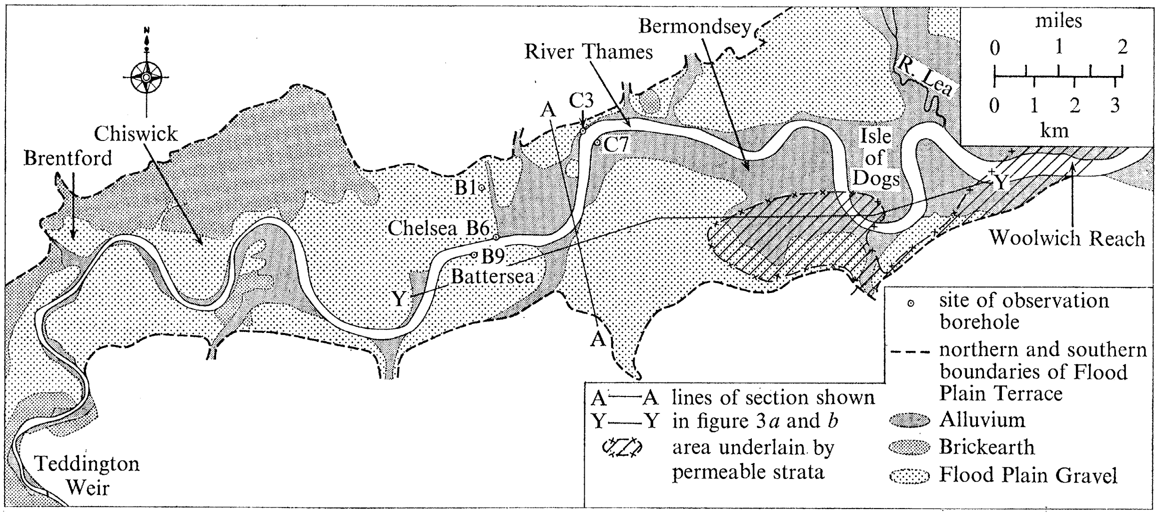

FIGURE 1. Location map and distribution of Flood Plain deposits.

Much of the detail of the groundwater study has been published elsewhere in a format appropriate to the Thames Barrier investigations (Gray 1969; Foster 1971). The present paper is concerned primarily with man's role in the recent past in modifying the natural groundwater conditions and the implications for future major civil engineering works on the Flood Plain Terrace.

DISTRIBUTION OF THE FLOOD PLAIN DEPOSITS

The terraces of the Thames have been the subject of much study and there is an extensive although scattered literature. The Flood Plain is of prime significance in the present paper and the higher terraces are not considered further. The Flood Plain Terrace is at the lowest elevation and comprises typically 6 to 18 m of sediment of three principal lithologies – alluvial silts and clays, brickearth (locally only, particularly in the west) and sands and gravels (figure 3*a* and *b*): it is these latter deposits through which the principal groundwater flow takes place. However, the requirement to consider the saturation conditions throughout the full thickness of the Flood Plain deposits necessitates consideration of the relationship of the groundwater in the low permeability, fine-grained materials to that in the highly permeable gravels. Over much of the Flood Plain, however, the deposits are overlain by made ground, exceptionally up to 6 m in thickness.

The geological history of the Flood Plain deposits was discussed by King & Oakley (1936). For present purposes, however, it is the character of the deposits themselves rather than their geological history which is of immediate relevance and as a first stage in the present study over

FIGURE 2. Oblique aerial photographs illustrating typical building and structures in the lower Thames Flood Plain. (Courtesy Aerofilms Ltd). (*a*) Kings Reach – Westminster – Waterloo (SV 10120). The narrow strip of Flood Plain on the north bank in the Central London area and the ground slope associated with its boundary is shown. The foreground includes the artificial lake in St James's Park and the complex of historic buildings in Westminster, whose original foundations and basements in general are probably shallow and thus potentially affected by changes in groundwater conditions. The modern developments on the south bank have pile foundations and extensive deep basements and subways which must interrupt the continuity of the Flood Plain strata. Much of the river wall in this area is relatively modern and has a deep foundation, nearly, or completely, cutting off the gravel stratum.

FIGURE 2 (*b*). Bermondsey and Isle of Dogs (SV 997). A high proportion of the total area has roof- and paved-cover and artificial surface drainage. Old buildings, probably with shallow foundations and small basements in Flood Plain gravel, predominate with some multi-storey blocks, probably with deep-piled foundations. The variable river-wall construction of the commercial waterfront and the large area occupied by the docks is well illustrated. The railway viaduct is a dominant feature, but probably has a shallow foundation and does not cut off the gravel stratum.

FIGURE 2 (*c*). Kensington area (SV 1009). A significantly higher proportion of open space than in (*b*). Dominantly terraced houses probably with shallow foundations and invariably with small basements in the Flood Plain gravel; increasing size of building is probably accompanied by increasing depth of basement, but shallow foundations were probably still employed.

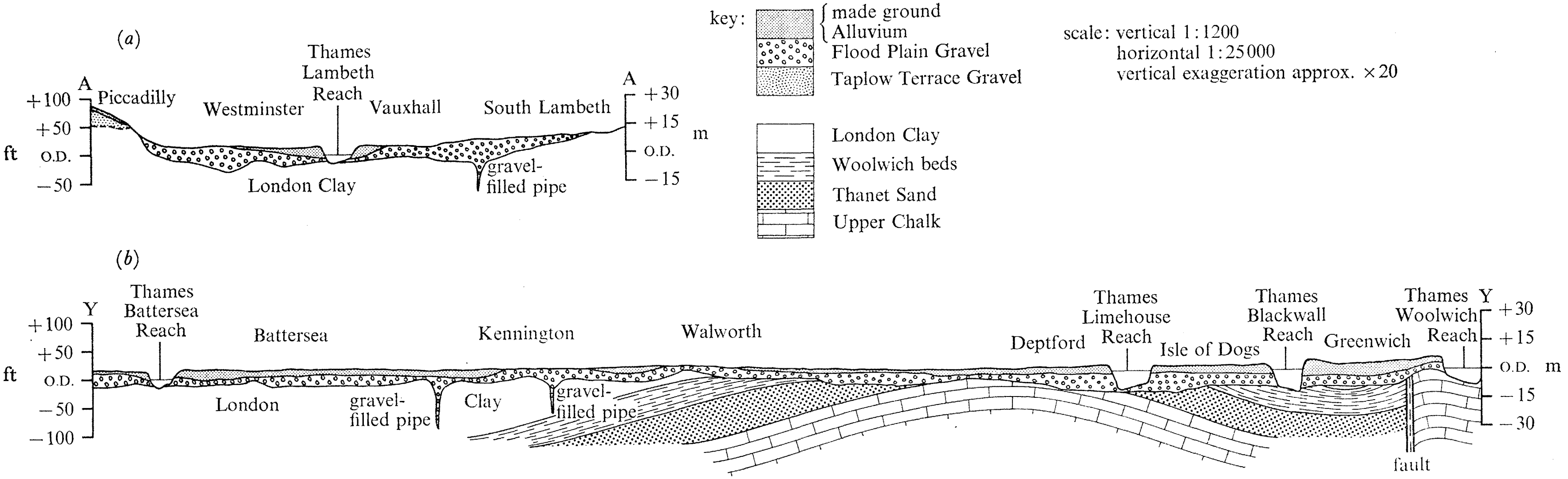

FIGURE 3. (*a*) Cross-section of the Flood Plain deposits. (*b*) Longitudinal section of the Flood Plain deposits.

1000 drilling records were analysed to compile a series of isopachyte and structure contour maps covering the area from Chiswick to Beckton (Mather *et al.* 1971). Five factors are illustrated.

(*a*) Thickness of the sand and gravel deposits.
(*b*) Thickness of the alluvium and brickearth.
(*c*) Contours on the surface of the sand and gravel.
(*d*) Contours on the surface of the solid strata.
(*e*) Percentage of sand and gravel in the Flood Plain deposits.

The deposits occupy a shallow, rather flat-bottomed channel cut in the underlying and impermeable London Clay, except in areas adjacent to the Isle of Dogs where a faulted anticline brings the Lower London Tertiaries (Woolwich Beds and Thanet Sand) and Upper Chalk to a subcrop beneath the Flood Plain deposits (figures 1 and 3*b*). The Thanet Sand and Chalk are permeable and can act as drainage sinks for water derived from the overlying riverine deposits and from the bed of the Thames. There is reference in much of the literature to the 'buried channel' of the Thames and Dewey & Bromehead (1921) indicate that such a channel can be traced downstream from Brentford. However, analysis of the drilling records indicates that a buried channel as a single feature of limited lateral extent does not exist. It is rather a broad, infilled channel with an irregular base in which subsidiary channels are present. At several locations abnormal thicknesses of gravel occur but these are considered by Mather, Gray & Houston (1970) to occupy local pipes such as those described by Edmunds (1931) at Battersea. These gravel-filled pipes are up to 23 m thick but they appear to be isolated from one another and do not form a continuous curvilinear feature. They may have a common periglacial origin (Higginbottom & Fookes 1971).

Hydraulic properties of the Flood Plain gravels

The hydraulic properties of the gravels are important from the present viewpoint and available data have been reviewed and analysed by Foster (1971). The principal relevant properties are summarized in table 1, but sampling and testing procedures are such that the values are

Table 1. Principal hydraulic properties of the Flood Plain gravels

hydraulic property	range of values	reference
permeability derived from *in situ* pumping tests without observation boreholes	0.56–0.81 $\mathrm{m^3\,day^{-1}\,m^{-2}}$ 1150–1650 gal $\mathrm{day^{-1}\,ft^{-2}}$ (0.055–0.080 cm/s)	Glossop & Collingridge (1948)
grain size distribution (g.s.d.) of borehole samples	typically bi-modal distribution with more than 50% of any given sample classified as medium sand (0.2–0.6 mm) and/or medium gravel (6—20 mm)	Foster (1971)
permeability estimated from mean g.s.d. by the Hazen formula†	$1.42\times10^{-3}\ \mathrm{m^3\,day^{-1}\,m^{-2}}$ 2.900 gal $\mathrm{day^{-1}\,ft^{-2}}$ (0.160 cm/s)	Foster (1971)
specific yield	0.14	Foster (1971) after Berry & Dean (1937)

† The Hazen formula relates to sand and its use for gravel material is strictly outside the range of valid application.

'order of magnitude' only. No satisfactorily controlled pumping tests with appropriate observation boreholes are known to the authors within the area under consideration.

Theoretical river–groundwater relations

The typical relation between the water in a river and the groundwater of the deposits through which it is flowing is illustrated in figure 4. Fluctuation in the groundwater level is a complex function of several variables of which the principal are the level of the river, the hydraulic gradients prevailing in the riverine deposits and the porosity and permeability of those deposits. In non-tidal reaches and at low-flow stage (figure 4*a*), the river is effluent, i.e. it is gaining flow from the groundwater body. At high river stage the converse occurs and under this influent condition river water is recharged into the alluvial deposits. The high river stage (figure 4*b*) can be caused either by flood flows from upland sources, in which case the water quality will be fresh, or by tidal conditions in the estuarial reaches when saline water will be present. Under tidal régimes, influent and effluent conditions alternate in response to the diurnal tides and secondary groundwater tides are generated having amplitudes and frequencies related *inter alia* to the tidal régime of the river. Analysis of these two factors enables the hydraulic properties of homogeneous deposits to be determined where natural conditions obtain.

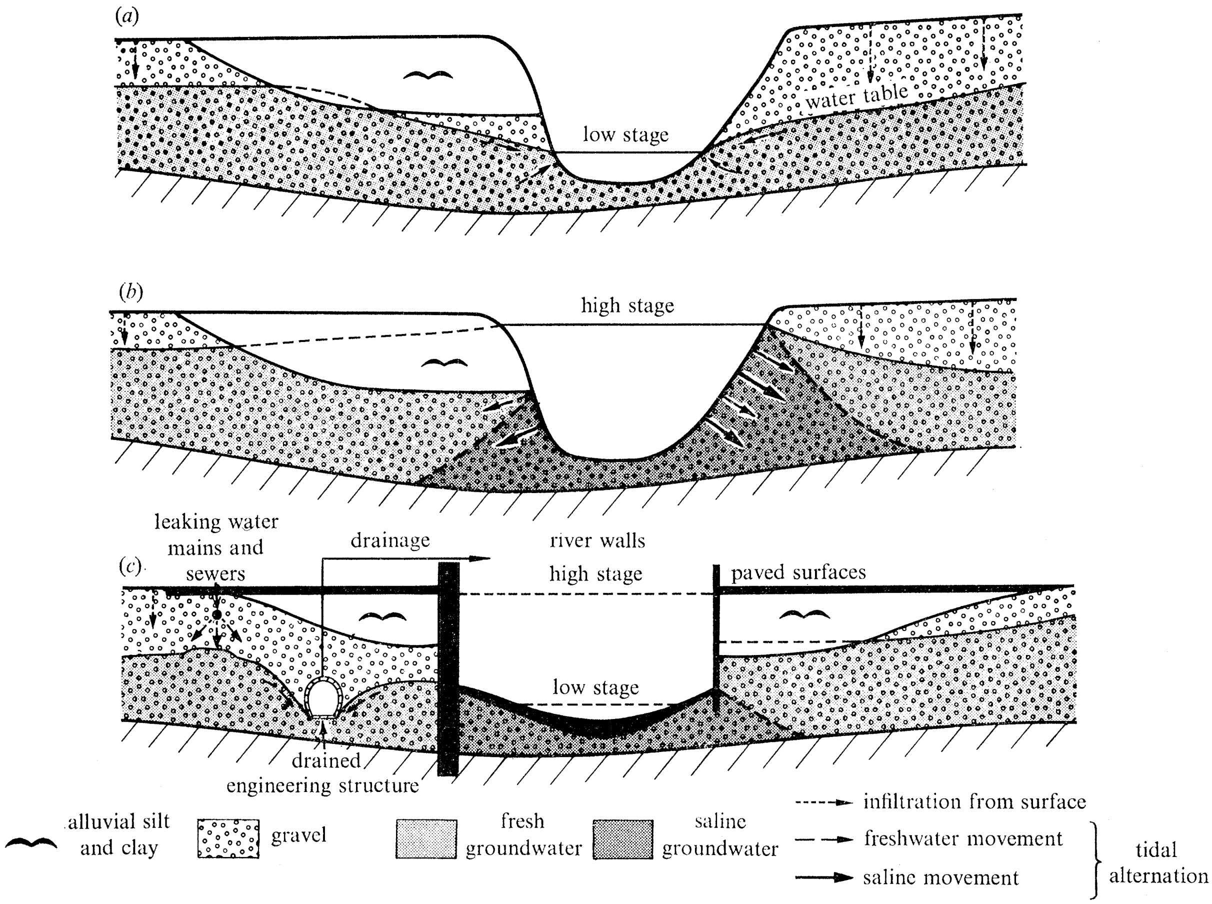

Figure 4. Diagrammatic relationship between the water in a river and groundwater in the alluvial deposits. (*a*) Natural conditions with low flow in the non-tidal reaches. (*b*) Natural conditions with high flow in the tidal reaches. (*c*) Man-modified conditions, including river walls and river-bed deposition.

In the tidal reaches, wedges of saline water can extend laterally from the river into the base of the alluvial deposits by virtue of greater density (figure 4*b*). The position of the interface between fresh and saline water will be defined by relative densities of the two fluids and the hydraulic properties of the deposits. This situation is further complicated by variations in the diurnal and monthly tidal heights and salinities and in the rate of tidal movements up and down the river. Superimposed on the effects of the diurnal and lunar tidal cycle there will be a seasonal effect whereby during periods of low upland flow, the saline content of the river at any given location may increase significantly. In the Thames this effect is highly significant (Anon. 1964).

This already complex flow and hydrogeochemical situation has been further modified by several of the man-made factors discussed below.

Principal effects of man's occupancy

Although parts of the Flood Plain of the Thames have been occupied since pre-historic times, London developed from its original settlement on two low hills around St Paul's Cathedral and the City, and on a few lower islands, by a process of embankment and marsh reclamation on the south bank (Stamp 1947). Subsequent large growth in the low-lying marshlands became possible only after the creation of drainage systems on a sufficient scale to modify the natural conditions significantly. The process was gradual; the installation of the major low-level sewers and associated drainage works dating only from the 19th century. Prior to that some minor changes in groundwater level resulted from marsh reclamation and locally from bridge construction, and in the quality of the groundwater from the disposal of organic and inorganic pollutants derived from domestic and industrial sources.

The medieval London Bridge, for example, is likely to have caused a local modification to the hydraulic gradient. Its construction resulted in a fall in river level across the structure during some states of the tide and the higher water level upstream is likely to have led to a small rise in groundwater levels in the Flood Plain deposits under the adjoining banks. The detail of such local effects remains speculative, however, and there are few facts on early groundwater conditions which can be accurately identified as to precise location and elevation. The general outlines of the groundwater flow régime can be deduced from the geography of the tributary streams as these are likely to have acted as the drainage controls.

Since the early and middle 1800s, however, man has modified the original water balance of the Flood Plain deposits as well as the groundwater conditions in them in many ways; some pertain to groundwater levels and flow directions, and others to its chemical and bacterial quality. The principal factors are discussed below but few are mutually exclusive and their interactions have locally produced complex conditions, particularly as some operated at differing scales in different areas at different times and for differing periods.

(i) The creation of extensive impermeable surfaces associated with stormwater sewers for drainage of both roofs and paved areas. This has virtually eliminated natural infiltration over much of the Flood Plain, except in some parks, gardens and other open spaces. Conversely, uncontrolled recharge undoubtedly takes place locally through soakaways, leaking drains, high-level sewers and water mains, but on the present evidence quantification of this factor is not possible.

(ii) The construction of more or less continuous river walls which in some reaches reduce or eliminate hydraulic continuity between the Flood Plain deposits and the river.

(iii) Engineering construction employing various techniques which may alter the local flow net, including the use of blanket drains and the construction of water-tight tanked basements extending into or through the saturated gravel.

(iv) Artificial lowering of the water table by pumping, principally for drainage but occasionally for water-supply purposes. The gravels were a source of water, often grossly polluted, for medieval London, but have been little used in more recent times, either for domestic or industrial supplies.

(v) Raising the ground surface by the emplacement of appreciable thicknesses of made ground (Mather *et al.* 1971) and subsidence due to consolidation of the London Clay following abstraction of groundwater from the Chalk (Wilson & Grace 1942). Settlement of the Flood Plain deposits themselves must also have occurred.

(vi) The local modification of the climate in the Central London area resulting in changes in evaporation and transpiration rates following elimination of natural vegetation.

(vii) Culverting or diverting most of the streams which originally drained the area (Barton 1962). Relatively short lengths of these crossed the Flood Plain Terrace, but they were probably the base levels to which drainage originally took place and as such controlled the groundwater level. It is likely that the gravels beneath their courses may accept flow preferentially, where the more recently induced hydraulic gradients permit.

(viii) Since the middle of the 19th century the reduction, if not elimination, of the pollution which had entered the deposits before the introduction of main sewerage may have led to a reduced volume of recharge into the formations. This may, however, have been offset by leakages from water mains and sewers.

(ix) Variation of the chemical, bacterial and thermal pollution of the Thames has in turn varied the quality of the water infiltrating into the gravel during periods of high river stage.

(x) Alteration of the river régime will have modified the river–groundwater relation. For example, the constriction of the river by embankments will have changed the depositional–erosional balance and may have led to a rise in the height of tide levels (Bowen 1972, this volume p. 187).

Of most significance in the river–groundwater relationship is the construction of river walls which partially or completely eliminate hydraulic continuity between the two water bodies (figure 4*c*). Over sections of Kings and Lambeth Reaches, the walls act as total cut-offs with their footings set in the effectively impermeable London Clay beneath the gravels. Elsewhere, however, the walls are founded at shallower depths and hydraulic continuity is probably maintained. The structure of the walls in the old commercial-water fronts is not known in detail but is extremely variable. Throughout the Central London area, damaged and deteriorated sections of the wall are likely to exist but difficult to locate. An indication of the cut-off condition of the river walls throughout the present area is given in figure 6. Siltation of the river-bed also bears on the hydraulic continuity between the river and the groundwater body, but has not been studied in detail.

Another major man-made modification of the groundwater flow régime is the effect produced by pumping from the deposits in temporary or permanent dewatering systems used to protect civil engineering structures (figure 4*c*). Such abstraction can produce significant effects on groundwater levels and can modify the hydrochemical condition. For example, 6800 m^3/day have to be pumped continuously from the District and Circle Line underground railway to maintain effective track drainage between West Kensington and Temple Stations (Foster 1971). The result of this abstraction is that groundwater levels over much of the Flood Plain Terrace of the north bank drain to an artificial base below river level and fluctuations are largely damped out.

On the present limited evidence, artificial recharge into the gravels from leaking mains and sewers (figure 3*c*) is of lesser significance than de-watering. The current evidence for such recharge has not enabled the volume to be estimated even at an 'order of magnitude' level; this factor could be large and is undoubtedly one for which a significant allowance should be made in any urban water balance. The quality of the water which gains access to the gravels in this way would differ significantly from natural recharge in that it would not have infiltrated through a soil zone and undergone the alteration normally produced in that zone.

Groundwater levels

In civil engineering practice the level and possible fluctuations of the water table and the piezometric surface within the site boundaries control elements of foundation and basement design. Under natural conditions, groundwater levels in flood plain gravels can be expected to fluctuate in response to three principal causes – changes in river level including tides, seasonal variations in infiltration derived from precipitation and changes in barometric pressure. The rapidity of response of groundwater levels to changes in river levels is well illustrated by the tidal effect.

In the alluvial deposits of tidal rivers the propagation of groundwater tides is characterized by lateral movement of sinusoidal waves having a decreasing amplitude and increasing phase-lag with increasing distance from the river bank. The river wall cut-off in Central London has so modified the natural conditions that analysis for hydraulic properties has not yet proved possible.

The inverse relation between change in barometric pressure and change in groundwater level has already been widely observed in the present study. In the most sensitive boreholes, the effect recorded during periods of rapid barometric change has been up to 0.3 m per day. The rate of onset of the atmospheric change influences the response considerably and accurate correction of levels for this effect is not feasible. At times the changes may mask fluctuations resulting from other causes. Foster (1971) discusses groundwater fluctuations resulting from all causes in detail and the examples given below have been selected to illustrate the effects caused by man's activities.

The hydrographs (plots of water level against time) from five boreholes have been selected to illustrate artificial influences on fluctuations in water levels. The sites of the boreholes (B1, B6, B9, C3 and C7) are shown in figure 1, and relevant details in table 2. The water-level recorder charts for the period 10 to 30 July 1970 have been redrawn to a common scale and are shown in figure 5 related to Ordnance Survey Datum (O.D.).

Several features resulting from man's activities are illustrated. First, the hydrographs can be divided into those showing and not showing diurnal or monthly tidal effects. Secondly, a range of water levels which extends from 3.3 m below O.D. at borehole C3 to a mean level of 0.6 m above O.D. at B9. The highest tidal response (tidal ratio 0.30) also occurs in borehole B9, 24 m from the south bank of the Thames in Battersea Park and in which 2.7 m of gravel lies below the bottom of the revetment and the top of the London Clay. At a similar distance from the north bank in Chelsea, borehole B6 shows a greatly reduced tidal response (tidal ratio 0.01), as well as having a lower mean water level at 1.2 m below O.D. The lower tidal response is thought to be due partly to a lesser thickness of gravel available for hydraulic continuity and partly to artificial drainage. The level is held below O.D., and two metres or so below the mean level in the adjacent river, by pumping from underdrains beneath the tracks of the District and Circle Lines. A comparable low level is also seen in borehole B 1 to the north of the railway and too remote from the river to have a tidal response. Some 6800 m^3/day are abstracted from various drainage works between the West Kensington and Temple Station. Without these artificial effects the tidal response of borehole B6 would probably approximate to that of B9 and the water levels in gravels on the two banks would be comparable.

Table 2. Borehole details and tidal ratios

borehole	(i) depth and (ii) ground surface elevation m (i)	O.D. (ii)	distance from specified bank m	thickness of gravel below wall foundation m	tidal† ratio	river wall construction
B 1	10.9	7.4	1250 north	—	0.00	—
B 6	10.7	5.6	24 north	1.2	0.01	mass concrete and sheet piling
B 9	7.8	4.4	24 south	2.7	0.30	concrete revetment
C 3	12.7	5.0	119 north	0.3	0.00	masonry-clad mass concrete
C 7	10.4	4.0	49 south	0	0.01	mass concrete and sheet piling

† Ratio of the fluctuation of the groundwater level to that of the river in the same reach.

Similarly the water level in borehole C 3 in the Victoria Embankment Gardens was held at 2.6 m below O.D. from June until October 1969 by pumping from permanent drainage works at Charing Cross Station. Since that date the level has fallen a further 0.6 m and is now held at 3.2 m below O.D., presumably due to additional, but at present unidentified, groundwater abstraction. The hydrograph from borehole C7, located on the promenade of the South Bank in front of the Festival Hall, was also well below O.D. in July 1970. This was a short-lived condition, however, related to the de-watering of the foundation excavations for the National Theatre and for St Thomas's Hospital. Until November 1969 the mean groundwater level was at or close to O.D. but during the de-watering, which lasted for almost 12 months, it was maintained at a lower level, down to 2.4.m below O.D. This example emphasizes the the necessity of maintaining water-level observations in studies of an urban environment for as long as possible and generally for not less than a year.

Under natural conditions, replenishment of the groundwater in the gravels takes place by infiltration derived from precipitation during the winter and early spring, with the subsequent recession of groundwater levels extending into late autumn or early winter. Such conditions apply in Battersea Park where artificial disturbances to the Flood Plain Terrace is minimal. The mean level of the boreholes in the Park declined from 0.85 m above O.D. in April to 0.46 m in October 1970. In boreholes elsewhere the natural recessions were modified to a greater or lesser extent by the reduction of the surface area of the Terrace deposits exposed by infiltration.

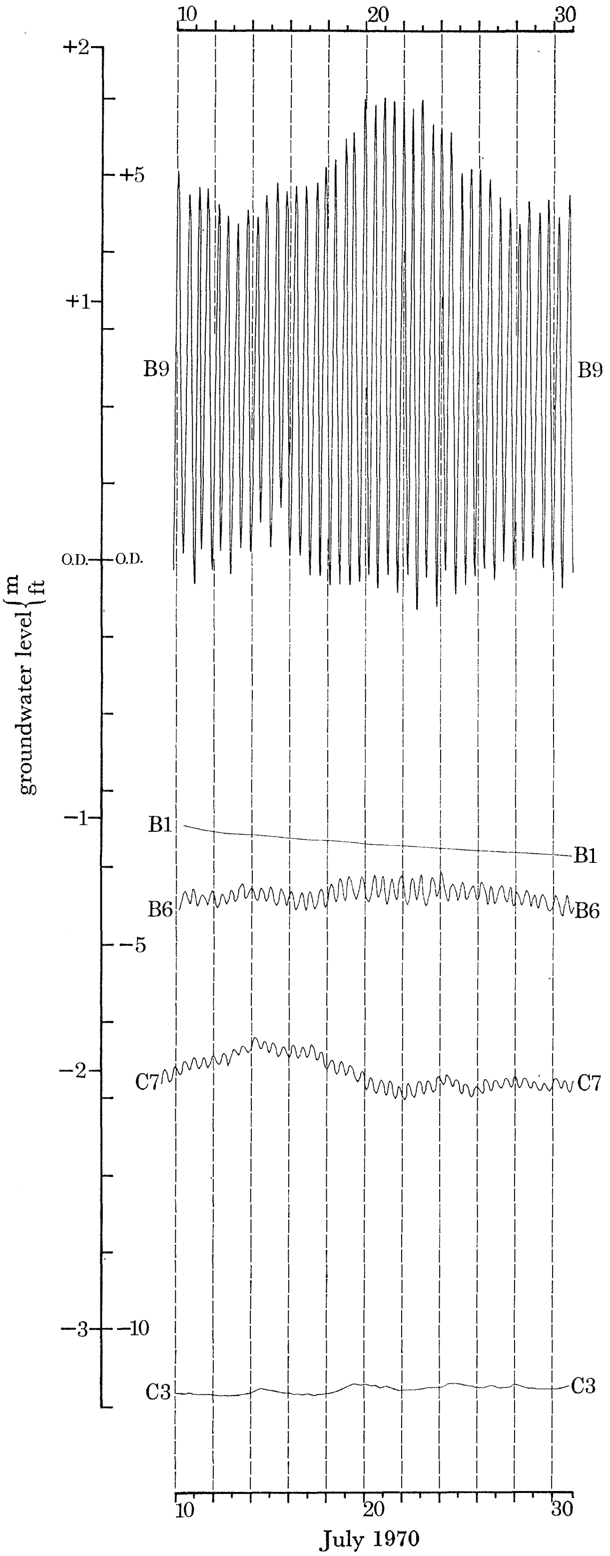

Figure 5. Selected well hydrographs from 10 to 30 July 1970.

HYDROGEOCHEMISTRY

Limited hydrogeochemical investigations were mounted to obtain a second and independent source of evidence on the river–groundwater relation and on the directions of groundwater movement. It was appreciated that the high cost and physical difficulties of arranging for temporary pumping from boreholes in an urban environment would preclude the routine sampling essential for the best results. Nevertheless, limited sampling was undertaken and the results have been described by Edmunds (in Foster 1971).

Analysis of the inorganic constituents in the groundwater samples generally showed decrease in all dissolved constituents as distance from the river banks increased, although there were some marked discrepancies. Additionally, in some embankment areas the possibility of small by-pass effects, due to damaged walls or leaking tidal flaps, is indicated. More obvious artificial effects relate to the locally heavy pollution of the groundwater samples as indicated by bacterial counts and nitrogen values.

In summary, the limited hydrogeochemical work corroborates the interchange of water between the river and the groundwater body but is not readily compatible with the concept of net mass transfer of water landward from some embankment areas.

GENERALIZED GROUNDWATER FLOW RÉGIME

A generalized flow régime, based on a summation of all available data, has been described by Foster (1971) and a simplified diagrammatic representation is shown in figure 6. Apart from the influence of the river walls, two principal man-made controls on the flow can be recognized – one on each bank.

On the north bank, the protective drainage works of the District and Circle Line cause the railway to act as an asymmetric curvilinear sink. A significant proportion of the water draining to this sink appears to be derived from the Thames.

On the south, the principal drainage appears to be towards a groundwater sink where the permeable Thanet Sand and Upper Chalk underlie the Flood Plain Terrace. Groundwater abstraction from the Chalk for water-supply purposes has led to progressive lowering of water levels in that formation (Buchan 1938). In 1965 the water level in the Chalk varied from 7.5 m above O.D. at Greenwich to 7.5 m below in the Isle of Dogs and to 45 and 75 m below at Stratford and Charing Cross respectively (R. A. Downing, personal communication). Under those conditions groundwater from the Flood Plain Gravels and water from the bed of the Thames, could infiltrate into the Thanet Sand and the Chalk; the high chloride content in Chalk groundwater in the area is not inconsistent with this view. The possibility that the flow pattern in the Flood Plain Terrace south of the Thames is also influenced to some extent by flow into underdrains beneath the low-level sewers cannot in the authors' view be entirely discounted.

The significance of the considerable track-drainage for the District Line Railway in the East End of London and for the New Cross Branch of the Metropolitan Line has not been examined in detail.

CONCLUSIONS

The original concept of a flood-prevention structure across the Thames included consideration of a fixed barrage as well as of a removable barrier. Half-tide control of the removable barrier selected for construction has been advocated to improve the amenity in Central London by

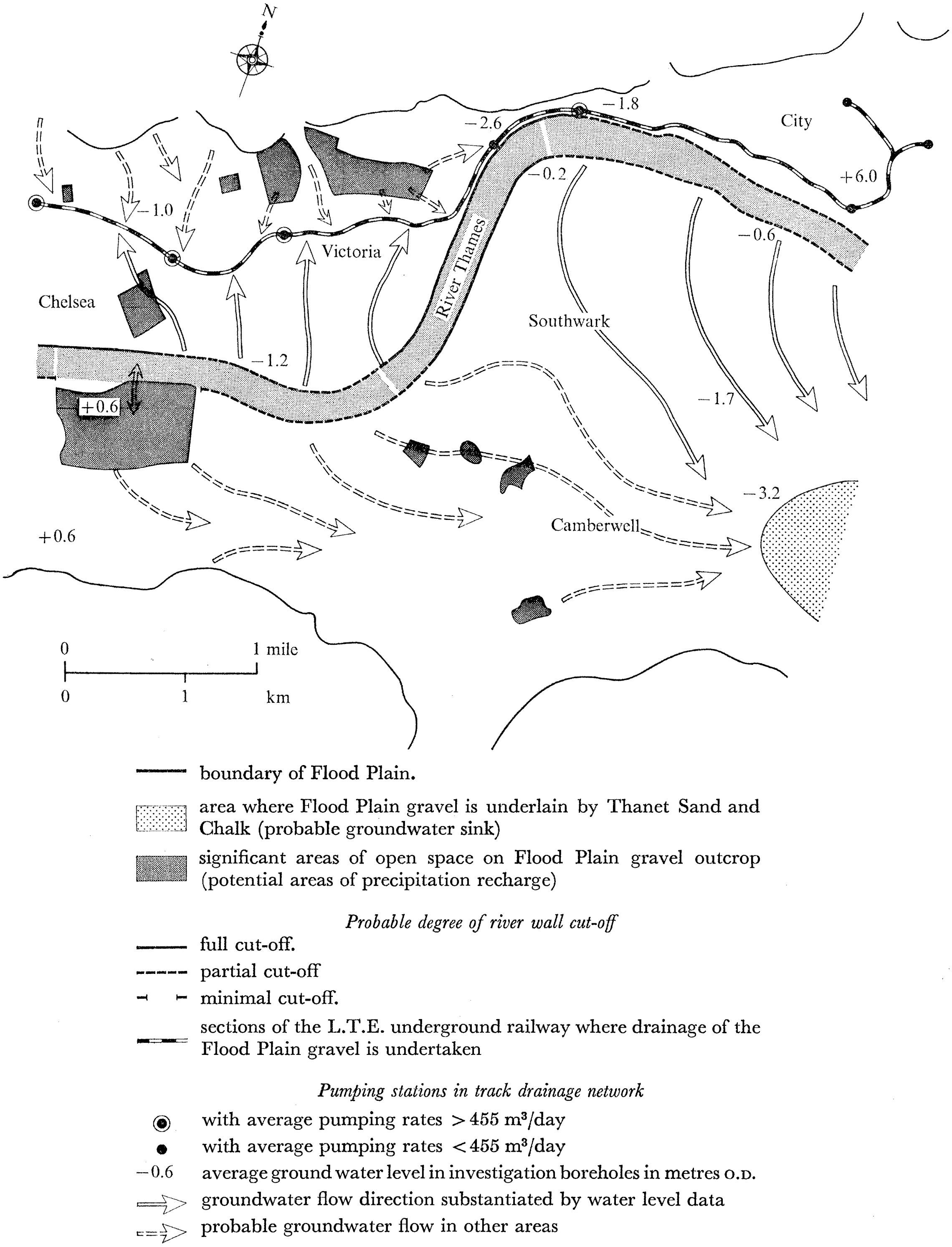

FIGURE 6. Generalized groundwater flow régime in the Flood Plain deposits.

permanently submerging at least part of the inter-tidal flats. A fixed barrage would have led to a rise in groundwater levels throughout the Flood Plain Terrace, as well as in lower reaches of the Lea Valley. The effect of half-tide control of the removable barrier would be similar over much of the area. Prediction of the amount of the general rise in water level which would follow half-tide control formed an integral part of the study and has been undertaken.

The results of the study indicate that the groundwater conditions in the Flood Plain deposits have been and are greatly influenced by man. The Thames barrier to be erected in the Woolwich Reach could be operated in such a way that these influences would be modified appreciably. It follows that current drainage practices might require alteration, that major problems might arise due to increased uplift on basement floor-slabs and that minor interferences on shallow foundation stresses could occur.

The authors conclude that it is incumbent upon the promoters to determine the existing conditions and the probable effects on those conditions of the proposed method of operation of the barrier (Gray & Foster 1971). A fuller understanding of man's influence on the groundwater conditions and the interaction of individual influences would assist in the planning and implementation of many future civil engineering activities in the Thames Valley.

The extensive assistance in the field and the office provided to the staff of the Institute of Geological Sciences by the staff of the Director of the Greater London Council's Department of Public Health Engineering is gratefully acknowledged. Thanks are also due to the Chief Civil Engineer of the London Transport Executive for access to records and to the representatives of the several organizations serving on the Groundwater Working Party. The paper is published with the permission of the Director of the Institute of Geological Sciences.

REFERENCES (Gray & Foster)

Anon. 1964 Effects of polluting discharges on the Thames Estuary. Thames Survey Committee and Water Pollution Research Laboratory. Water Pollution Research. Technical Paper No. 11. D.S.I.R.

Barton, N. J. 1962 *The lost rivers of London*. Phoenix House Ltd, London and Leicester University Press.

Berry, C. S. & Dean, A. C. 1937 *Min. Proc. Inst. civ. Engrs* **81**, 34–51.

Bowen, A. J. 1972 The tidal régime of the River Thames; long-term trends and their possible causes. *Phil. Trans. R. Soc. Lond.* A. **272**, 187–199 (this volume).

Buchan, S. 1938 Water supply of the County of London from underground sources. *Mem. Geol. Surv.* H.M.S.O.

Dewey, H. & Bromehead, C. E. N. 1921 The geology of South London. *Mem. geol. Surv.* H.M.S.O.

Edmunds, F. H. 1931 *Sum. Prog. Geol. Surv.* Pt. II, for 1930, pp. 18–24.

Foster, S. S. D. 1971 Appendix 6. Pt. I. In *Thames flood prevention barrier project: second report of studies*. Greater London Council.

Gray, D. A. 1969 Appendix 4. In *Thames flood prevention barrier/barrage project: first report of studies*. Greater London Council.

Gray, D. A. & Foster, S. S. D. 1971 Appendix 6. Pt. II. In *Thames flood prevention barrier project: second report of studies*. Greater London Council.

Glossop. R. & Collingridge, V. H. 1948 *Proc. 2nd Int Conf. Soil. Mechanics*. IIXa, 3.

Higginbottom, I. E. & Fookes, P. G. 1971 *Q. Jl Eng. Geol.* **3**, 85–117.

King, W. B. R. & Oakley, K. P. 1936 *Proc. Prehist Soc.*, N.S., Vol. **2**, pp. 52–76.

Leggett, R. E. 1962 *Geology and engineering*. New York: McGraw-Hill.

Mather, J. D., Gray, D. A. & Houston, J. F. T. 1971 Distribution of the Flood Plain Deposits of the Thames between Chiswick and Beckton. *Inst. Geol. Sci. Wat. Supp. Pap., Res. Rep.* no. 4.

Perlmutter, N. M. & Soren, S. 1963 Effects of major water table changes in King's and Queen's Counties, New York City. *U.S. Geol. Surv. Prof. Pap.* 420–E.

Stamp, L. D. 1947 Britain's structure and scenery. London: Collins.

Wilson, G. & Grace, H. 1942 *J. Instn civ. Engrs* **19**, 100–127.

IGURE 2. Oblique aerial photographs illustrating typical building and structures in the lower Thames Flood Plain. (Courtesy Aerofilms Ltd). (*a*) Kings Reach – Westminster – Waterloo (SV 10120). The narrow strip of Flood Plain on the north bank in the Central London area and the ground slope associated with its boundary is shown. The foreground includes the artificial lake in St James's Park and the complex of historic buildings in Westminster, whose original foundations and basements in general are probably shallow and thus potentially affected by changes in groundwater conditions. The modern developments on the south bank have pile foundations and extensive deep basements and subways which must interrupt the continuity of the Flood Plain strata. Much of the river wall in this area is relatively modern and has a deep foundation, nearly, or completely, cutting off the gravel stratum.

FIGURE 2 (*b*). Bermondsey and Isle of Dogs (SV 997). A high proportion of the total area has roof- and paved-cover and artificial surface drainage. Old buildings, probably with shallow foundations and small basements in Flood Plain gravel, predominate with some multi-storey blocks, probably with deep-piled foundations. The variable river-wall construction of the commercial waterfront and the large area occupied by the docks is well illustrated. The railway viaduct is a dominant feature, but probably has a shallow foundation and does not cut off the gravel stratum.

FIGURE 2 (*c*). Kensington area (SV 1009). A significantly higher proportion of open space than in (*b*). Dominantly terraced houses probably with shallow foundations and invariably with small basements in the Flood Plain gravel; increasing size of building is probably accompanied by increasing depth of basement, but shallow foundations were probably still employed.