[redacted]

*Proc. Instn Civ. Engrs*, Part 2, 1977, 63, Dec., 803–817

# 8047 Evaluation of a semi-confined Chalk aquifer in East Anglia

S. S. D. FOSTER, BSc, MICE, MIWES*
A. S. ROBERTSON, BSc, MIWES*

About 4000 km$^2$ of East Anglia are underlain by a semi-confined Chalk aquifer: semi-confined in the sense that it is buried beneath a variable suite of glacial deposits which, to varying degree, confine its groundwater and reduce recharge rates from infiltration. The aquifer is a major source of water supply. It exhibits outwardly unpredictable variation in borehole yield behaviour but there has been little field research into the causes. This Paper describes an investigation at a site of public water supply abstraction in south Norfolk, and has numerous implications for the development and management of groundwater resources in much of the surrounding region.

## Background

Since the early 1950s the semi-confined Chalk aquifer at Rushall (9 km east-north-east of Diss in south Norfolk (Fig. 1)) has been increasingly exploited for public water supply. Development has involved the drilling of six boreholes, and their completion as pumping wells, in a triangular site of about 800 m side; four are currently in use. All these boreholes are 400–600 mm in diameter and were completed by surge pumping and, with the exception of number 2, by acid treatment.

2. The boreholes show substantial variation in yield-drawdown characteristics (Fig. 2), numbers 3 and 5 being notably inferior. Additionally, the yields of individual boreholes have deteriorated with time (e.g. number 1 in Fig. 2). Across the region as a whole, the yields of large diameter boreholes in Chalk are normally in the range 10 l/s for 30 m drawdown to 25 l/s for 10 m drawdown.[1] Despite their close proximity and superficially similar construction, the yields of the Rushall boreholes vary from considerably below average (number 3) to well above average (number 6) (Table 1), although they do not reach the exceptional yields for small drawdowns recorded locally around Norwich and Ipswich.

## Geological setting of the Rushall site

3. The concealed surface of the Chalk of much of central East Anglia is dissected by a network of buried channels, frequently narrow and often deep.

---

Written discussion closes 15 February, 1978, for publication in *Proceedings*, Part 2. Mr Foster will give a talk based on this Paper, entitled 'The hydrogeological evaluation of Chalk aquifers' to the East Anglian Association at the Angel Hotel, Bury St Edmunds on 18 January, 1978, at 7 p.m.

* Hydrogeological Department, Institute of Geological Sciences.

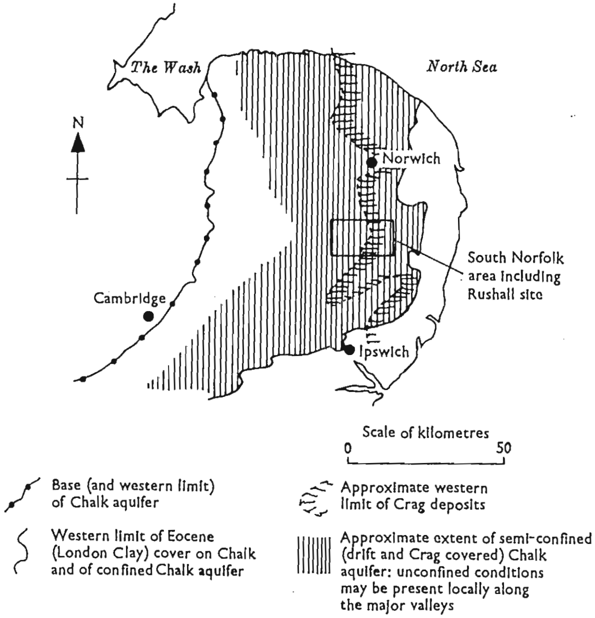


Fig. 1. East Anglia: sub-division of the Chalk aquifer

Woodland[2] described these features as 'buried tunnel valleys' and regarded them as sub-glacial in origin.

4. The Rushall site (Fig. 3) is close to the edge of a buried valley, a tributary to the Waveney system.[2] The depth of the Chalk surface varies by as much as 23 m across the site, from +9 m OD in borehole 6 to −14 m OD in borehole 3.

5. Away from the line of the buried valley at Rushall, the Chalk is overlain by 25–35 m of glacial deposits (Fig. 4), which in upward sequence comprise

(*a*) well-sorted sands and sandy gravels, probably representatives of one of the East Anglian Pleistocene crags

(*b*) a complex Boulder Clay series with rapid lateral and vertical changes in lithology, including consolidated silty clays, silts, numerous fine silty sands and rarer gravels.

The fill of the buried valley is recorded as being predominantly hard, dark grey silty clays with subordinate sand and gravel, suggesting post-Crag sub-glacial formation. About 2–3 km south-east of the Rushall site, on the limb of the East Suffolk syncline, the general level of the buried Chalk surface drops steadily and the thickness of the overlying Crag increases substantially (Figs 3 and 4).

6. At the surface the Rushall site is relatively flat, being on the broad interfluve between the valleys of the Pulham Stream to the north and the River Waveney to the south (Fig. 4).

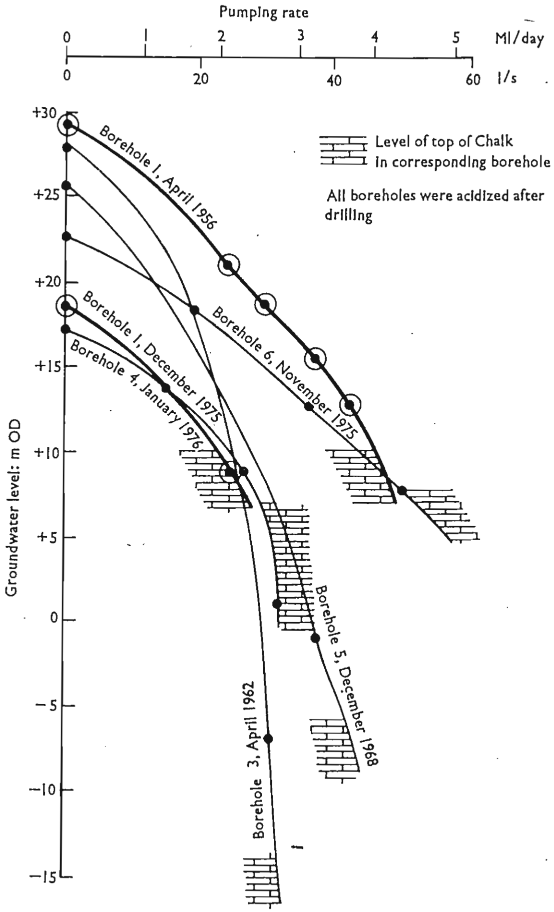


Fig. 2. Yield–drawdown characteristics for Rushall pumping boreholes

Table 1. Rushall production boreholes; drawdown comparison for yields of 25 l/s and 40 l/s

| | | Borehole 1 | Borehole 3 | Borehole 4 | Borehole 5 | Borehole 6 |
|---|---|---|---|---|---|---|
| Drawdown (in metres) for pumping rate of | 25 l/s (2·2 Ml/day) | 10 | 19 | 9 | 14 | 6 |
| | 40 l/s (3·5 Ml/day) | 17* | † | 15* | 30 | 11 |

* No longer obtainable. † Never obtainable.

## Geophysical investigation of Chalk groundwater flow

7. During 1975–76 comprehensive borehole flow logging investigations were undertaken at Rushall in some of the production diameter boreholes (numbers 1, 3, 4, 5 and 6 in Fig. 5) and in the purpose-drilled observation boreholes of 150 mm diameter (numbers 7A and 8A in Fig. 5). The methods used are described in part by Tate *et al.*[3]

8. Groundwater inflows into boreholes are normally associated with variations of electrical conductivity and/or temperature of the borehole fluid column. Such variations, although sometimes small (less than 0·01 degC and 1 $\mu$mho/cm), may be logged using sufficiently sensitive equipment.[4] The changes of the temperature/conductivity logs from the rest condition during the onset of pumping normally indicate the main levels of groundwater flow.

9. Measurements of the vertical flow rate to the pump can be made by impeller and heat-pulse flowmeters for high and low velocities respectively. Although the hydraulics of borehole flow are complex, the measurements when carefully interpreted can indicate the relative contributions from various levels

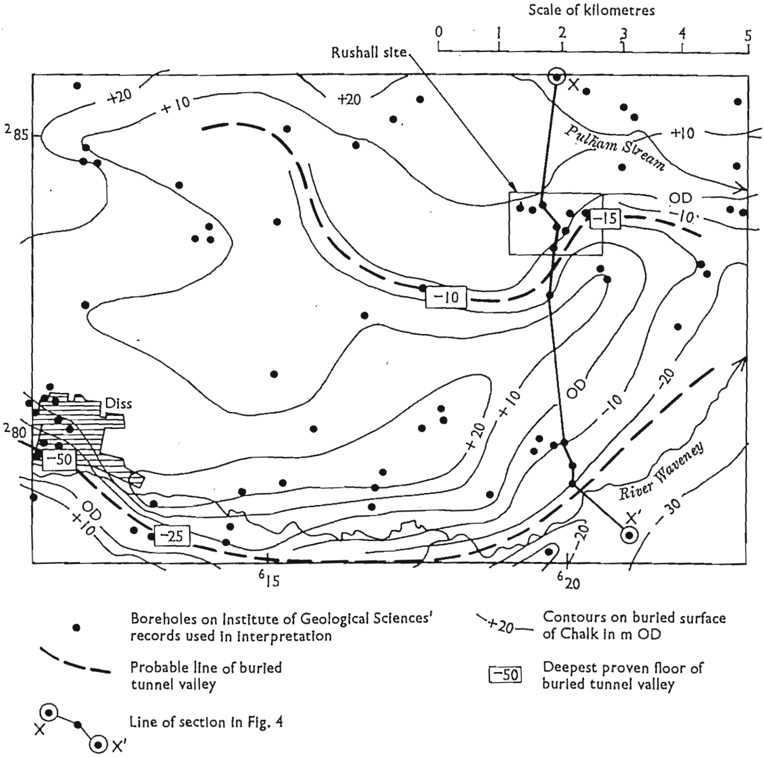
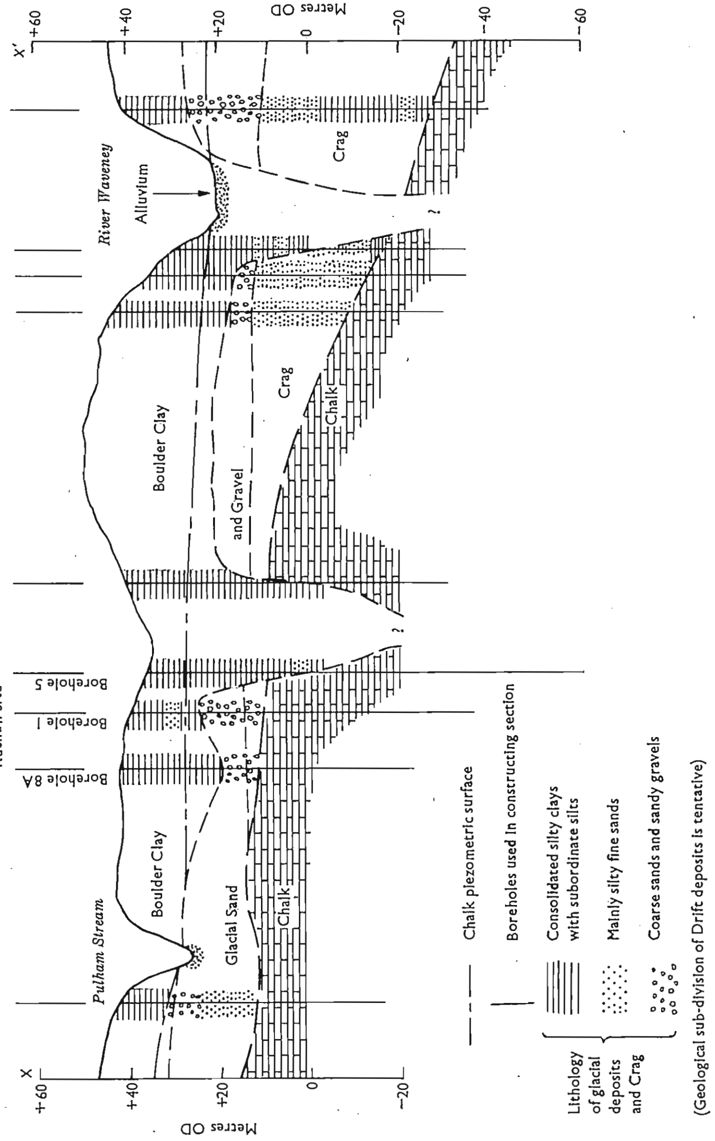


Fig. 3. South Norfolk: hydrogeological location map



(Geological sub-division of Drift deposits is tentative)

Fig. 4. Hydrogeological cross-section of Rushall site (vertical exaggeration ×45–50)

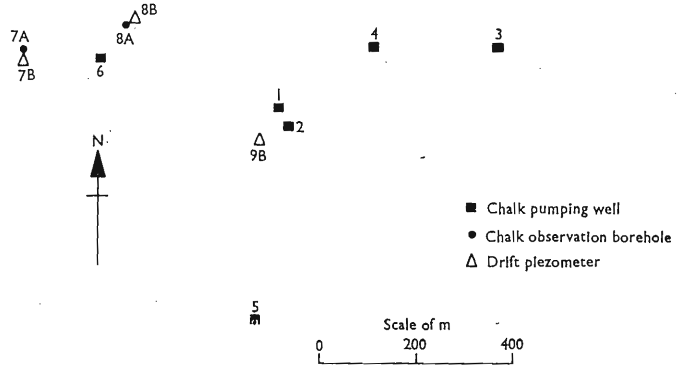


Fig. 5. Plan of Rushall site

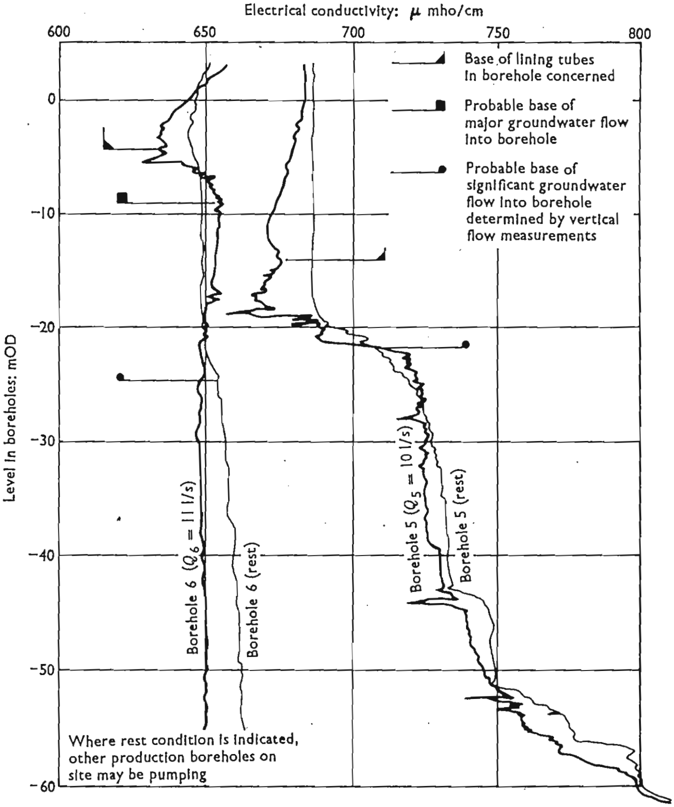


Fig. 6. Selected electrical conductivity logs of Rushall boreholes in rest and pumping conditions, boreholes 5 and 6

in the borehole (i.e. the productive zones of the aquifer). The normal configuration for flow logging is with the pump at the minimum depth necessary to sustain a low pumping rate, and at a depth which does not conflict with anticipated flow levels. Under such conditions in 500–600 mm dia. boreholes, pumping rates of more than about 2 l/s should produce, in their upper sections, vertical flows characterized by Reynolds numbers of over 4000 and with blunt rough–turbulent velocity distributions. For boreholes of 150 mm diameter the corresponding pumping rate will be about 0·6 l/s. In the lower sections of boreholes below the major inflows, laminar vertical flow with parabolic velocity distribution is likely to prevail. When both flow regimes are uniform, semi-quantitative interpretation of flow logs is possible with some confidence, but a major complication arises opposite, and for some diameters above, major groundwater inflows where grossly non-uniform vertical flows may develop.

10. At Rushall the conductivity log proved to be the more diagnostic for flow investigation; selected results are given in Figs 6 and 7. In borehole 6 (Fig. 6) the onset of pumping gives rise to a strong inflow of slightly lower conductivity water from near the base of the solid lining tubes (−4 m OD) down to −7 m OD, with indications of minor inflows below the latter depth. Measurements of vertical flow to the pump, operating at 11 l/s and situated within the solid lining tubes, showed a sevenfold decrease in velocity by about −7 m OD and a further fourfold reduction by about −22 m OD, strongly suggesting that the bulk of the yield is derived from above the former level and that probably no more than 5% originates from below the latter. Borehole 1 behaved similarly (Fig. 7).

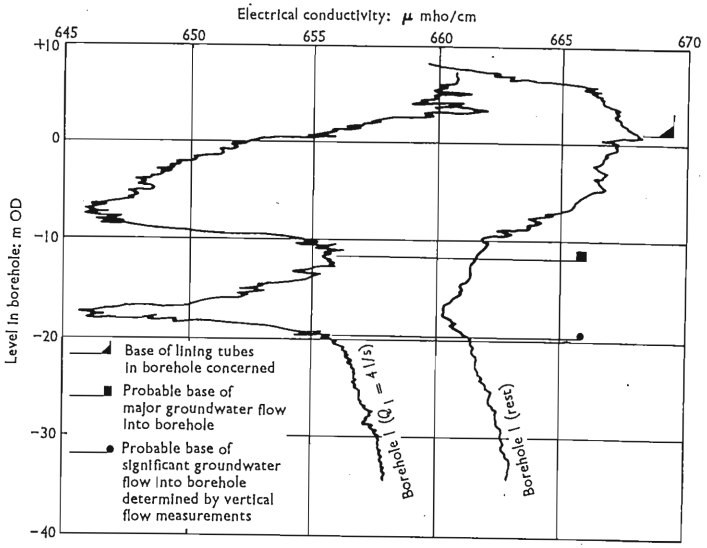


Fig. 7. Selected electrical conductivity logs of Rushall boreholes in rest and pumping conditions, borehole 1

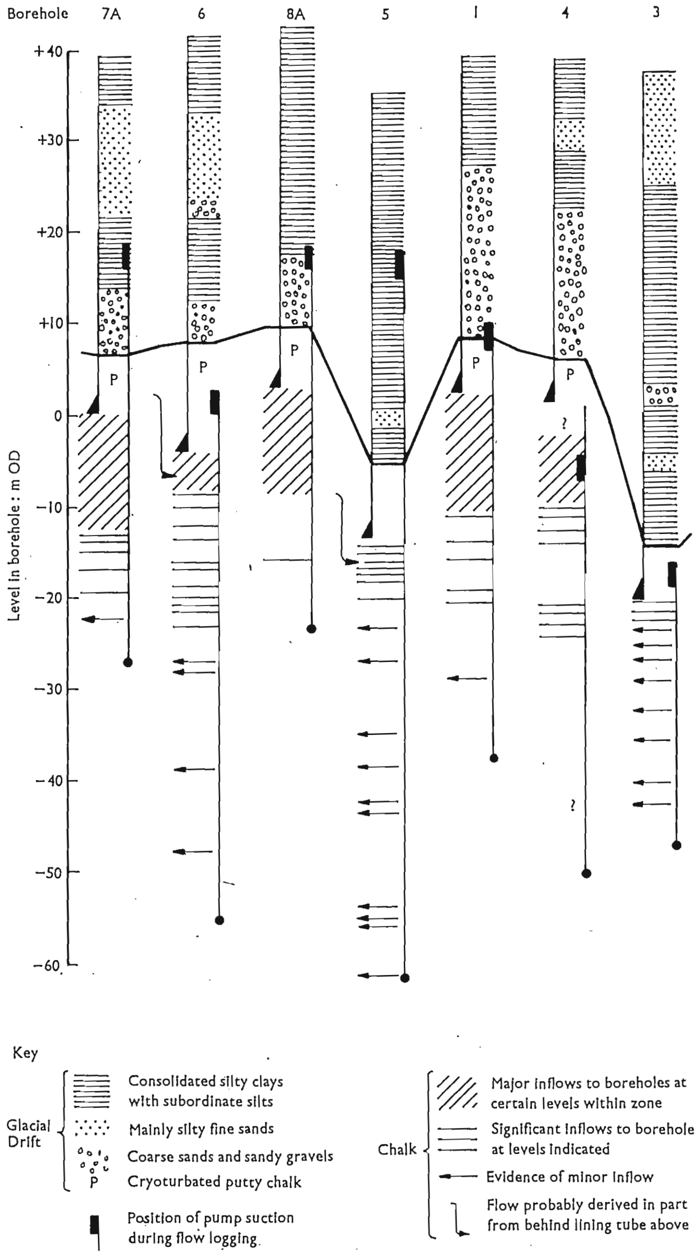


Fig. 8. Rushall boreholes: summary of Chalk groundwater flow levels and glacial drift lithologies

11. Borehole 5, on the edge of the buried valley, has a distinctive conductivity log (Fig. 6), with more saline (higher conductivity) groundwater at depth. The flow levels are again clearly marked by conductivity changes with the onset of pumping, but in this case the flow logging suggests that the minor inflows below −21 m OD are proportionally more important than in boreholes 1 and 6.

12. The overall results of the geophysical investigation of groundwater flow are summarized in Fig 8. Although the Upper Chalk alone is estimated to be over 200 m thick at the Rushall site and many of the boreholes penetrate to −40 m OD or more, the bulk of the groundwater flow to Chalk boreholes is concentrated above −20 m OD and largely above −10 m OD. Although the distribution of groundwater inflow to boreholes may be influenced to a degree by the positioning of pumps, it is suggested also that the bulk of the permeability development in the Chalk is above −10 m OD, with no highly permeable horizons below −20 m OD. Recently, the fact that substantial thicknesses of the Chalk aquifer have very low in situ permeability has been independently demonstrated at sites in Hampshire using water injection tests in cored boreholes.[5] The inferior yield–drawdown characteristics of boreholes 3 and 5 at Rushall thus appear to be due to the absence or erosion of most of the highest permeability chalk in the buried valley. The implication is that the development of high permeability, presumably due to the solution on near-horizontal discontinuities of the rock mass by naturally circulating groundwater,[6] must in substantial part geologically pre-date the formation of the buried tunnel valley.

## Interpretation of aquifer test pumping

13. Systematic pumping tests were carried out in November–December 1975 by pumping boreholes 6 and 2 in turn and observing the aquifer response by monitoring the water levels in all other boreholes in Chalk. Three piezometers in the glacial deposits (7B, 8B and 9B in Fig. 5) were also measured regularly throughout the tests. Steady pumping rates of 18 l/s, 37 l/s and 49 l/s were used in the case of borehole 6 and 24 l/s was used for borehole 2. In order to satisfy the operational needs of Rushall pumping station, boreholes 3 and 4 were pumped at a steady combined rate of about 55 l/s (4·7 Ml/day) from some weeks before the start of test pumping until some weeks after its completion. This is not believed to have significantly affected the aquifer testing.

14. An example of the data collected is given in Fig. 9. The most prominent feature of all the test data is a rapid trend to equilibrium caused by marked recharge effects. The non-equilibrium observation borehole responses, for the test around borehole 6 (Fig. 9), conform tolerably to the leaky confined model[7,8] and suggest aquifer properties of about the following magnitudes: transmissivity 500 $m^2$/day, storage coefficient $10^{-3}$ and leakage factor 600 m.

15. The regional groundwater flow in the Chalk is known to be directed generally eastwards under a hydraulic gradient of less than 0·003% and is therefore unlikely to exceed 1·5 Ml/day per 1 km of flow frontage. It thus could not be the major source of rapid recharge observed in the high rate (49 l/s, 4·2 Ml/day) pumping test. The recharge is interpreted as induced downward leakage from the overlying Crag sands. The confining bed appears to be the 2–5 m thick layer of putty chalk (a glacial cryoturbation product) between the base of the Crag sands and the main body of the Chalk formation (Fig. 8). The existence of leakage is corroborated by the behaviour of a piezometer in the Crag (8B),

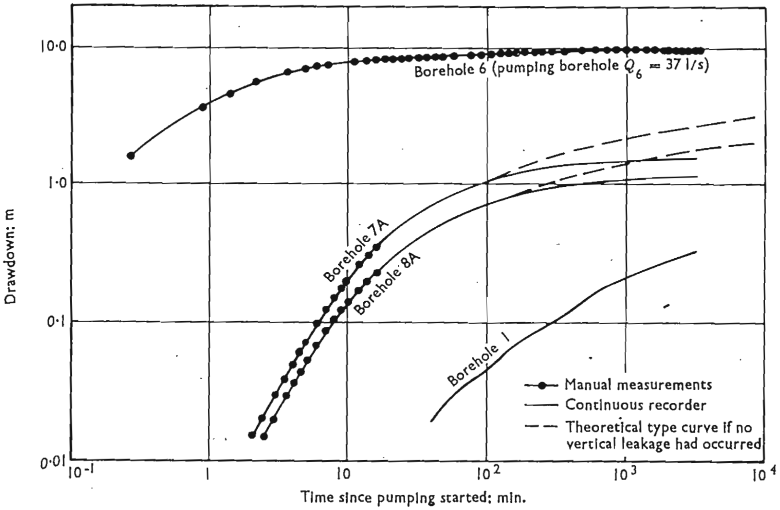


Fig. 9. Example of non-equilibrium pumping test data

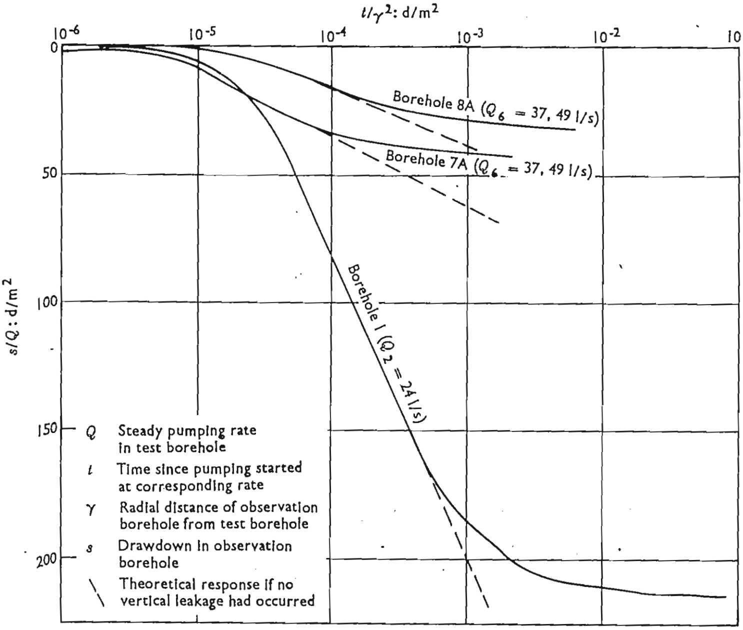


Fig. 10. Comparative plot of non-equilibrium pumping test data from Rushall site (November–December 1975)

which responded to pumping but to a smaller degree and less rapidly than in the adjacent Chalk observation borehole (8A) with the same pre-test water level. The shallower piezometers (7B and 9B) in the more sandy horizons of the Boulder Clay series recorded significantly (3–6 m) higher pre-test heads than those in the underlying Chalk, but showed no response to pumping throughout the test period.

16. The relationship between the pumping rates from borehole 6 and the corresponding observation borehole drawdowns was strictly linear, confirming a laminar flow regime in the aquifer at distances of 100 m and more from the pumping well. Similar behaviour has been observed for an unconfined Chalk aquifer.[6]

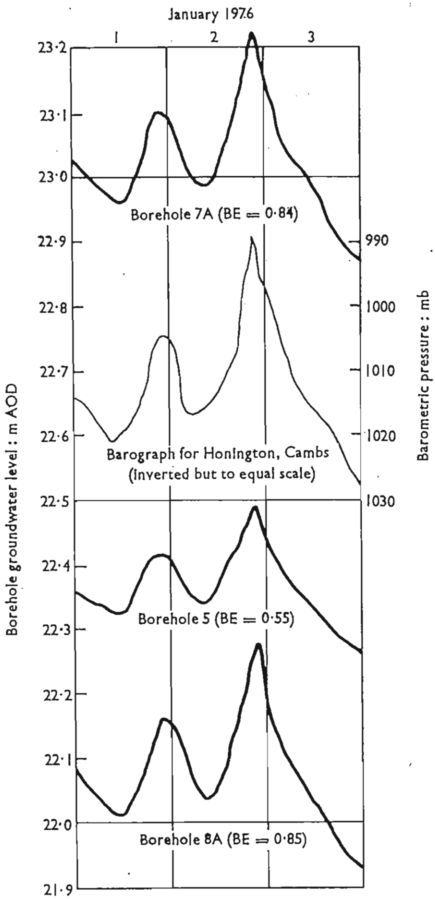


Fig. 11. Barometric response of selected Rushall boreholes (BE barometric efficiency)

17. Despite the relatively good yield–drawdown characteristics of borehole 6, evaluation of the theoretical drawdowns attributable to radial groundwater flow through the aquifer alone to a well of equal nominal diameter suggests that it may be only 55–65% efficient. The well losses appear to result mainly from the partial lining out of the most productive zone of the Chalk (Fig. 8). Slotting of the bottom 6 m or so of the solid lining tubes should have reduced losses and increased efficiency.

18. The more limited data from the test around borehole 2 have been plotted on an equal dimension basis (Fig. 10) to facilitate comparison with those from the test on borehole 6. A threefold or fourfold reduction in $T$ is apparent with a slower rate of development of induced vertical leakage. However, the possibility of turbulence affecting the observation borehole response here cannot be completely ruled out, as it is only 30 m from the test borehole and there are insufficient data to prove laminar aquifer flow. Further reduction in $T$ occurs along the centre of the buried valley, where values appear to fall well below 100 $m^2$/day.

19. As might be expected, the Rushall boreholes show marked response to barometric fluctuations (Fig. 11). Barometric efficiency is in most cases very high, but lower in the case of borehole 5; the reason is not understood. (Data for borehole 3 are not available.)

## Evaluation of vertical leakage from glacial deposits

20. The rapid equilibrium achieved in all the Rushall boreholes after the start (or re-start) of pumping was interpreted as being due primarily to induced downward leakage from the Crag sands, the interception of regional groundwater flow in the Chalk aquifer being of only minor significance in this process. (This is an important conclusion, which could easily be missed if comprehensive hydrogeological data were not collected.) However, such equilibrium will be sustained in the long-term only if the rate of recharge of the Crag from the overlying Boulder Clay series and the rate of infiltration to the latter formation at the surface are both sufficient to balance the long-term abstraction.

21. The historical record of abstraction, considered together with recovery water level data, for the Rushall site provides corroborative evidence. It shows (Fig. 12) that the Chalk piezometric surface has fallen (at boreholes 1 and 2, for example) from above +30 m OD in 1950 to +23 m OD in 1975. Moreover, shallow groundwater levels in the sandier horizons of the Boulder Clay appear, from local drainage practice, at one time to have stood at +30 m OD to +35 m OD but levels of +26 m OD and +27 m OD were recorded by piezometers 9B and 7B respectively during the present investigation. Some permanent fall in groundwater level is both inevitable and necessary for the economical development of groundwater resources, particularly in this type of hydrogeological environment, otherwise an excessive number of isolated production boreholes would be required. However, at Rushall the average rate of groundwater abstraction has increased steadily from the equivalent of only 1·6 Ml/day in 1960 to 3·4 Ml/day in 1970 and 4·5–5·0 Ml/day since 1973. It is therefore not possible to establish a trend of long-term equilibrium at any given pumping rate from the historical record. If, in the long term, abstraction grossly exceeds replenishment, groundwater levels will fall, drawdowns will increase or borehole yields reduce. Failure of boreholes would be gradual as the cone of depression

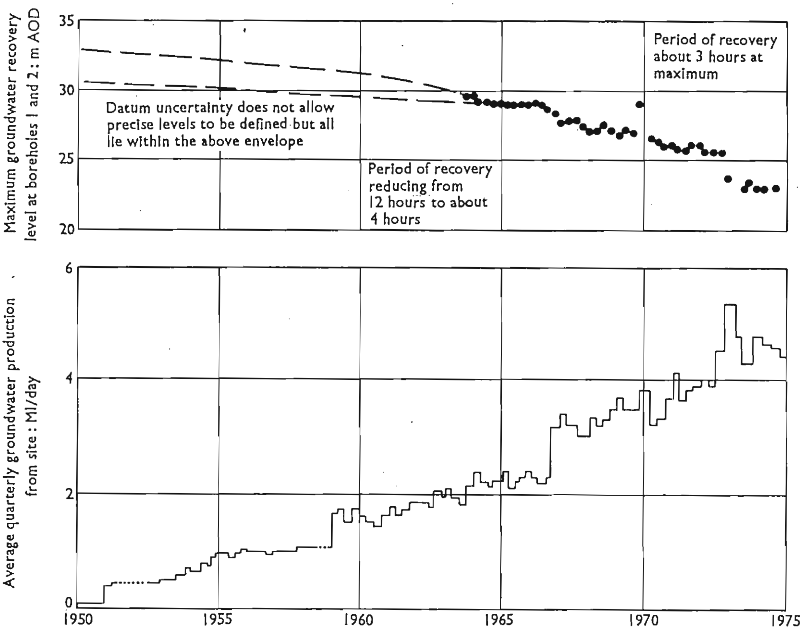


Fig. 12. Historic groundwater abstraction and recovery levels for Rushall site

would tend to expand, thus intercepting more aquifer throughflow and inducing additional leakage. Equilibrium at a reduced abstraction rate would eventually be established.

22. The fall in the Chalk piezometric surface over the years, has reduced available aquifer drawdown and the yields of individual boreholes, for example borehole 1 between April 1956 and December 1975 (Fig. 2).

23. Many approaches to the evaluation of deep groundwater recharge from excess rainfall are possible but, because of the lithological complexity of the Boulder Clay, none will be precise. From determination of the groundwater component of river flow in the Waveney at Needham, the average natural long-term recharge to the Chalk aquifer over the entire catchment was put at 40–50 mm/a.*, [1,9] The corresponding figure for excess rainfall exceeds 150 mm/a* and it is probable that additional deep recharge is thus being induced by groundwater development. Such figures give an indication of the order of resources (0·1–0·4 Ml/day per km$^2$) available in the long-term from induced downward leakage in the area considered. The extent to which these resources can be developed from a single borehole or localized source, such as Rushall, will depend on the transmissivity of the Chalk aquifer. Correspondingly higher rates of abstraction can be sustained in the short and medium term because of the very large volume of groundwater storage in the glacial deposits.

---

* This assumes, perhaps questionably, that no long-term climatic change is occurring.

## Conclusions

24. For the Rushall Chalk there is little evidence to suggest useful permeability, in the context of water supply development, below about $-20$ m OD. The zone of highest permeability appears to be 10 m and more above this level and almost directly below the formation's buried erosion surface. This condition has been observed widely in East Anglia,[10] although at many locations there is evidence of some flow of fresh groundwater down to about $-40$ m OD. In general it appears that there is little to be gained by drilling water supply boreholes deeper than $-20$ m OD. In view of the probable permeability distribution, however, it is strongly recommended that any lining tubes required for support in the Chalk should be slotted from as near the top of the formation as possible, to avoid accidental exclusion of groundwater from the zone of highest permeability.

25. In East Anglia the so-called buried tunnel valleys[2] appear to constitute poor sites for chalk groundwater development, because the zone of enhanced chalk permeability will often have been eroded during their formation; under certain circumstances it is possible that they may act as partial barriers to groundwater flow. Boreholes into such valleys are likely to provide poorer yields for higher drawdown, need to be of greater depth and require longer lengths of solid casing. However, when the fossil valleys are traced downstream their character changes radically[2] and a different hydrogeological condition almost certainly will apply. Where a true buried tunnel valley[2] directly underlies part of a major present-day valley, the position will also be more complex. Woodland[11] and Ineson[12] suggest that, in general, the Chalk was higher yielding (and thus possessed higher transmissivity) beneath major valleys than beneath the higher ground. High chalk permeability is probably associated with solution during long-term natural circulation of fresh groundwater;[6,13] thus where these valleys are the focus of major groundwater discharge permeability is likely to be highest. However, drilling water supply boreholes into those parts of present alluvial tracts underlain by buried tunnel valleys should be avoided anyway. Moreover, the transmissivity of the Chalk away from the present valleys may have been underestimated by studies of the variation in borehole yield alone, since many more well-constructed, high-demand boreholes are located, for one reason or another, in valleys, introducing a bias into statistical data.

26. The rapidity with which equilibrium is established in boreholes in Chalk at Rushall after the start, or re-start, of pumping could, in the absence of other data, easily be misinterpreted. It has been shown to be due to induced downward leakage from the basal glacial sands and gravels (the Crag, in the case of Rushall). Similar pumping test behaviour has been reported at sites in the Tas Valley to the north of Rushall[14] and is likely over large areas of the semi-confined aquifer (Fig. 1). There is strong evidence from the Rushall site that such equilibria may be relatively short-lived and that in the longer term the sustainable yield of a site will depend on the average rate of induced leakage throughout the entire thickness of the glacial deposits and their rate of replenishment from excess rainfall.

27. Despite the semi-confined conditions of groundwater storage, the hydrogeological environment should prove favourable to schemes for augmentation of river flow from groundwater storage in drought or for conjunctive use of surface and groundwater. This is because the induced leakage should

allow seasonal over-abstraction of groundwater and at the same time greatly retard the rate of spread of interference effects to the areas of groundwater discharge and, therefore, to river flow.

## Acknowledgements

28. The investigations described were carried out by the Institute of Geological Sciences in collaboration with the Anglian Water Authority to form a basis for decisions on the future operation and management of the Rushall pumping station and the development of water supplies in the surrounding area. They were suggested by Mr T. K. Tate of the Institute of Geological Sciences, Hydrogeological Department, and promoted by Mr K. Rowe, Divisional Engineer of the Anglian Water Authority, Norwich Water Division, to both of whom the Authors are most indebted. Much assistance on site was given by Mr A. M. Robinson and Mr E. Sharpe of the Anglian Water Authority and Mr M. J. Bird and Mr W. G. Darling of the Institute of Geological Sciences. This Paper is published by permission of the Director, Institute of Geological Sciences.

### References

1. East Suffolk and Norfolk River Authority. *Survey of water resources and demands*. East Suffolk and Norfolk River Authority, Norwich, 1971.
2. Woodland A. W. The buried tunnel-valleys of East Anglia. *Proc. Yorks. Geol. Soc.*, 1970, **37**, 521–578.
3. Tate T. K. *et al.* The hydrogeological investigation of fissure-flow by borehole logging techniques. *Q. Jl Engng Geol.*, 1970, **2**, 195–215.
4. Tate T. K. and Robertson A. S. Logging equipment for water boreholes. *Wat. Serv.*, 1975, **79**, 368–369.
5. Price M. *et al.* Chalk permeability—a study of vertical variation using water injection tests and borehole logging. *Wat. Serv.*, 1977, **81**, Oct., 603–610.
6. Foster S. S. D. and Milton V. A. The permeability and storage of an unconfined Chalk aquifer. *Hydrol. Sci. Bull.*, 1974, **19**, 485–500.
7. Hantush M. S. Analysis of data from pumping tests in leaky aquifers. *Trans. Am. Geophys. Un.*, 1956, **37**, 702–714.
8. Walton W. C. Leaky artesian aquifer conditions in Illinois. *Illinois St. Wat. Surv. Rep.*, 1960, **39**, 1–27.
9. Ineson J. and Downing R. A. Some hydrogeological factors in permeable catchment studies. *J. Inst. Wat. Engrs*, 1965, **19**, 59–80.
10. Tate T. K. Private communication, 1975.
11. Woodland A. W. Water supply from underground sources of Cambridge—Ipswich District. *Geol. Surv. GB*, 1946, **10**, Wartime Pamplet 20, 1–86.
12. Ineson J. A hydrogeological study of the permeability of the Chalk. *J. Instn Wat. Engrs*, 1962, **16**, 449–463.
13. Foster S. S. D. and Crease R. I. Hydraulic behaviour of the Chalk Aquifer in the Yorkshire Wolds. *Proc. Instn Civ. Engrs*, Part 2, 1975, **59**, Mar., 181–188.
14. Parvisi. Private communication, 1976.