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THE PERMEABILITY AND STORAGE OF AN UNCONFINED CHALK AQUIFER

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ABSTRACT

In its saturated zone the Chalk, the most important British aquifer, is a dominantly fissure-flow and essentially fissure-storage formation. This paper evaluates the results of a comprehensive investigation into its hydraulic behaviour in an area of some 40 km^2 of the East Yorkshire outcrop. The hydraulics of idealized fissures are used to extend the interpretation. No strong lateral anisotropy of hydraulic properties is apparent in this area but vertical heterogeneity is very marked, with the main permeability development probably being along horizontal discontinuities in two layers of restricted thickness.

RÉSUMÉ

Dans la zone saturée de la Craie, la plus importante nappe du Royaume-Uni, l'écoulement souterraine se rencontre surtout dans les fissures, et les ressources en eau s'y contiennent aussi. Dans ce rapport on évalue les résultats d'une investigation étendue du régime hydrodynamique de la Craie dans une région de 40 km^2 de l'affleurement de l'est de Yorkshire. Pour étendre l'interprétation on fait usage de l'hydrodynamique théorique de fissures idéalisées. Dans cette zone il n'y a pas de grande anisotropie latérale des caractéristiques hydrauliques, mais une hétérogénéité verticale est bien évidente, et selon toute apparence le principal développement de perméabilité se trouve le long de discontinuités horizontales dans deux couches d'épaisseur limitée.

INTRODUCTION

Background

Since the work of Ineson (1959, 1962) there have been few publications on the hydraulic behaviour of the saturated zone in the Chalk. The Chalk Aquifer underlies a large area of lowland Britain and accounts for some 15 per cent of the national water supply. In those catchments of southern and eastern England with Chalk bedrock, the groundwater component of total river discharge frequently exceeds 50 per cent, and may reach 90 per cent. Current interest centres on the possibility of augmenting low river flows by pumping from groundwater storage; the design of such river regulation schemes requires a more precise knowledge of aquifer hydraulics than has been needed previously. This knowledge is also of relevance in predicting the movement of pollutants and in the design of deep excavations.

Ineson's work on Chalk permeability was based essentially on a statistical approach to record data for pumping boreholes. Such data may be of indifferent quality and inadequate for interpretation of aquifer confinement parameters, hydraulic boundaries and distribution of permeability and storage with depth. Of the subsequent research, that of most practical value has been the use of geophysical investigations of pumping boreholes (Tate *et al.*, 1970) to determine the levels of groundwater inflow. A disadvantage of this technique, when used in isolation, is that it is often difficult to distinguish essentially borehole conditions or processes from those in the aquifer itself.

The most direct method for investigation of groundwater hydraulics is the pumping test but reliable interpretation in a formation like the Chalk requires sound knowledge of local hydrogeological conditions, adequate observation borehole control and supporting data from other investigations. An opportunity to conduct comprehensive testing came in 1970 with the proposal to develop further groundwater production from the Etton area of the East Yorkshire Chalk (Fig. 1).

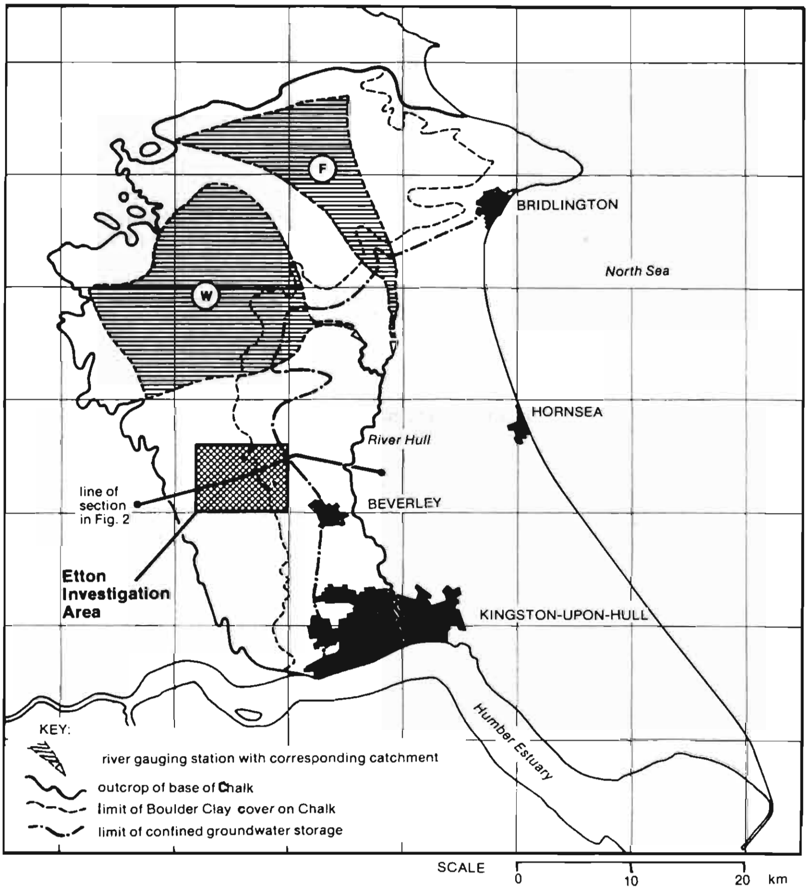


Fig. 1 — Location map of east Yorkshire.

Geohydrological Setting of the Etton Area

The Etton area is fairly typical of Chalk dip slopes and has a simple geological structure; the dip rarely approaches 5° and no tectonic disturbances are known (Fig. 2). During the deposition of the underlying Jurassic strata, structural controls dominated but only some mild influences appear to have persisted into the Chalk.

The Middle/Upper Chalk, which is the primary concern, comprises a highly-uniform, exceedingly fine-grained sequence of pure white limestones broken only occasionally by primary marls, which rarely exceed 50 mm in thickness. More frequent breaks in the sequence are associated with secondary features, particularly the ubiquitous stylolites with their associated marl seams and the flint bands. Laboratory tests on core samples of the Chalk show extremely low intergranular permeability ($< 10^{-3}$ m/day), despite moderate porosity (0·14–0·20).

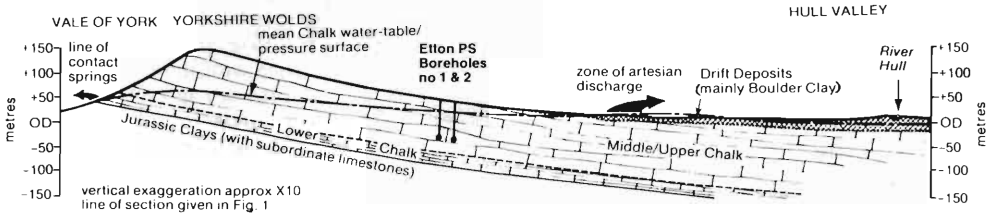


Fig. 2 — Generalized cross-section of the Yorkshire Wolds in the Etton area.

In its saturated zone the East Yorkshire Chalk must constitute an essentially fissure-flow aquifer; the same may not necessarily be true of infiltration and vertical flow through the unsaturated zone (Foster and Crease, 1974) but this topic is outside the scope of this paper. The saturated permeability will be a function of the configuration of the physical discontinuities of the rock mass (joints and less regular fissures, solution openings, fractures and cavities) with respect to the external or applied head. In the limited number of quarry exposures, the major inclined joints are normally of multi-directional aspect and high density (0·7–1·3 per metre), with the frequency of horizontal discontinuities being in the range 0·6–3·6 per metre. Their degree of persistence in depth however cannot be stated with confidence.

The Etton pumping boreholes are located in a typical shallow minor dry-valley. The stratigraphy of the site was investigated by electrical resistivity logging, using a 3 electrode 1·5 m inverse spacing considered to give the best measure of true formation resistivity (Gray, 1965). Certain features capable of local correlation were identified (*A*, *B* and *C* in Fig. 3) and indicate a dip of about 2° more-or-less due east. The resistivity logs are also a useful basis for comparison between the Etton Chalk and that in other areas.

In the Etton area the boundary between the zones of aeration and saturation seems to be as clearly defined as in intergranular-flow aquifers; on drilling boreholes the water generally rises after first being struck, but rarely more than 1 m, to the level of an apparently simple local water table. In most boreholes however, barometrically-generated water level fluctuations

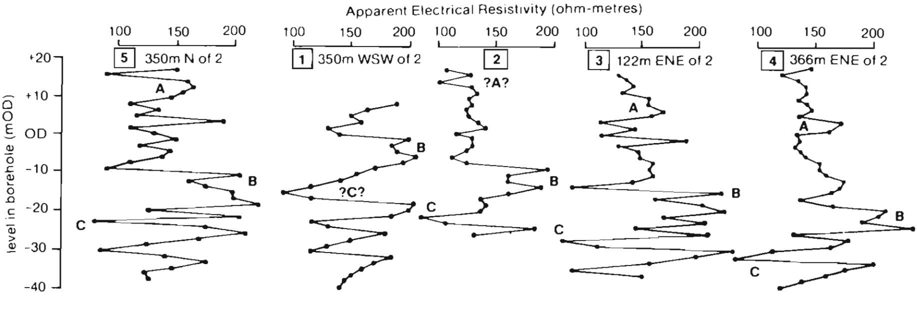


Fig. 3 — Electrical resistivity logs of the Etton boreholes.

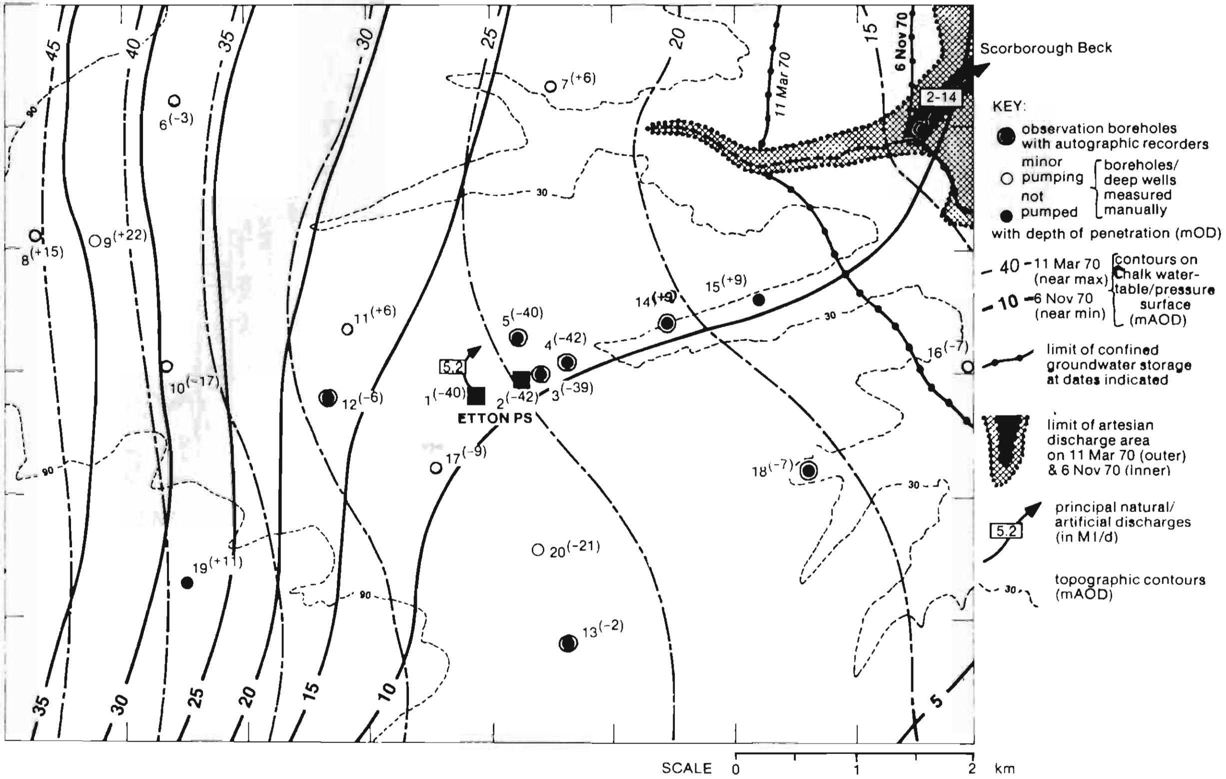


Fig. 4 — The Etton area borehole locations and groundwater level contours.

appear to occur, particularly during the rising limb of the groundwater hydrograph when the barometric efficiency may exceed 0·05.

The regional hydrological regime is determined by the geological structure (Fig. 2) and involves rainfall recharge to the water table throughout an outcrop area devoid of surface drainage with sub-surface flow towards the lower lying areas, primarily the Hull Valley. In the groundwater level contour data for 1970 (Fig. 4), and those of all available previous years, the hydraulic gradient at peak levels was eastnortheast towards the natural discharge area. During the annual recession (normally in July or August) the gradient swings around to the southeast as a result of heavy groundwater abstraction in the Beverley–Hull area. The most extreme hydrological conditions experienced in the last decade correspond to water table levels of +9 and +32 m OD at the Etton site, in March 1965 and February 1966 respectively.

The Scope of the Investigations

Within a radius of 4 km of the Etton production boreholes, 15 boreholes were available for water level measurement (Fig. 4) and these had been monitored monthly since 1962. To promote research into the hydraulic response of the aquifer, three narrow-diameter observation boreholes were drilled and completed to similar depth at short distances from the new large-diameter production borehole (No. 2 in Fig. 4).

This exceptional network was used for data collection during the comprehensive test pumping of both production boreholes (Nos. 1 and 2) in the autumn of 1970 under near minimum hydrological conditions (site rest water level of about +11 m OD). The observation borehole response to four periods of carefully-regulated abstraction or recovery in one or other of the production boreholes was determined, using steady pumping rates in the range 50–90 l./s for time intervals of up to 9 days. A combined yield test at a rate of 155 l./s was then carried out over 12 days. During test pumping, geophysical flow investigations were simultaneously undertaken using boreholes Nos. 1–5 (Fig. 4); some preparatory work had been done in July 1970.

It was necessary for continuity of water supply to continue abstraction from the No. 1 borehole throughout the test programme in the autumn of 1970. This complication was overcome by adopting a steady, moderate pumping rate (60 l./s) 14 days prior to commencement and sustaining it through most of the period of aquifer testing. All the water pumped was put into supply and the considerable expense of piping this water to a hydrologically-satisfactory discharge point was thus avoided.

A second phase of testing was carried out with a higher water table (+18 m OD) in April 1971; this was more limited in scope due to operating considerations and rapidly changing groundwater stage. It was based on the recovery from steady pumping at 90 l./s and recommencement at 120 l./s from the No. 1 borehole, using the No. 2 borehole as an observation well.

ANALYSIS OF PUMPING TEST RESULTS

Perhaps the more important function of a good hydrogeological pumping test is that of providing evidence on the general hydraulic response of the aquifer, its confinement and boundary parameters rather than that of obtaining accurate transmissivity (T) values. Certainly the former is more critical in predicting long-term response to pumping. Heterogeneity was a particular question in the case of the East Yorkshire Chalk, hearsay evidence suggested that groundwater flow might be largely restricted within a few random fissures.

Hydraulic Responses in the Autumn 1970 Pumping Test

The non-steady state drawdown and recovery (s) in the observation boreholes, following the onset or shut down of a constant rate (Q) of pumping in the test borehole, show a basic regularity and consistency in form (e.g. Fig. 5 A and B), after correction for various interfering factors.

These include the continuously-receding groundwater stage (falling at a rate of about 0·03 m/day) and the effects of previous pumping regimes but both are only significant for $t > 2500$ min or so (Fig. 5 A and B). In Fig. 6, comparable data for s and t have been plotted in a unified form to

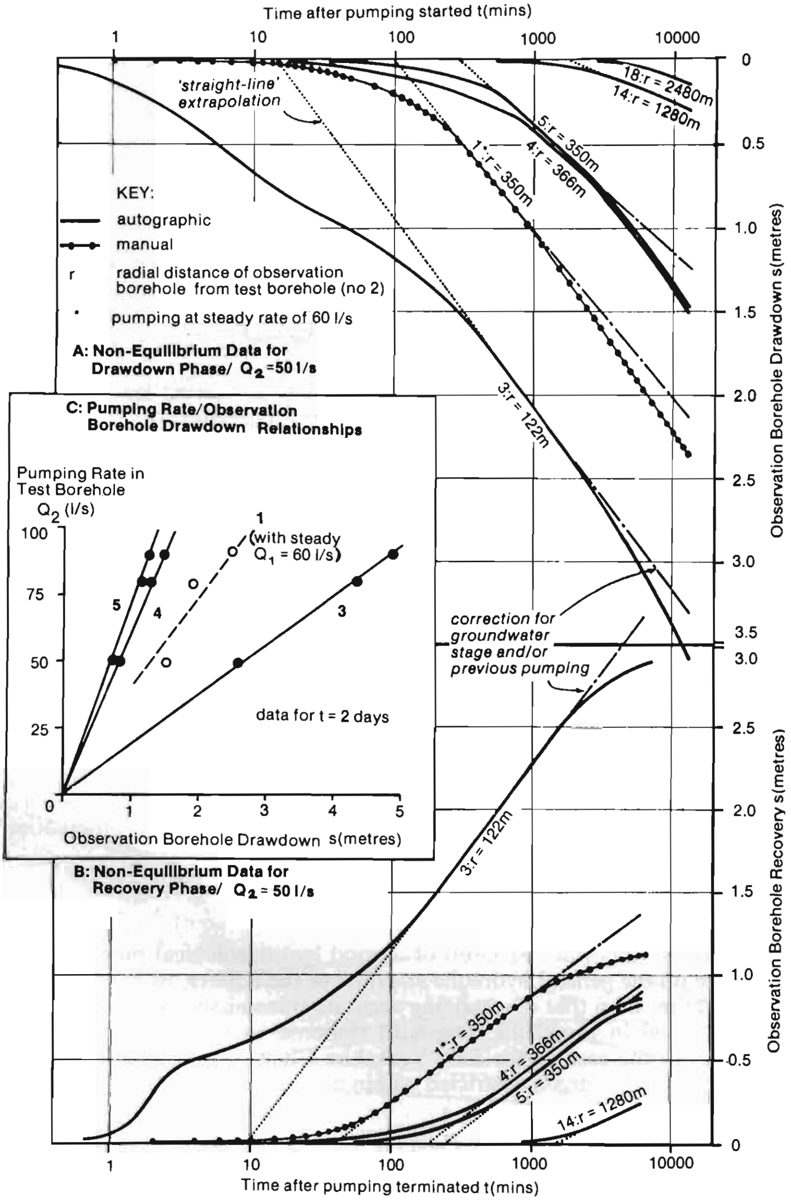


Fig. 5 — Observation borehole data from the autumn 1970 pumping test.

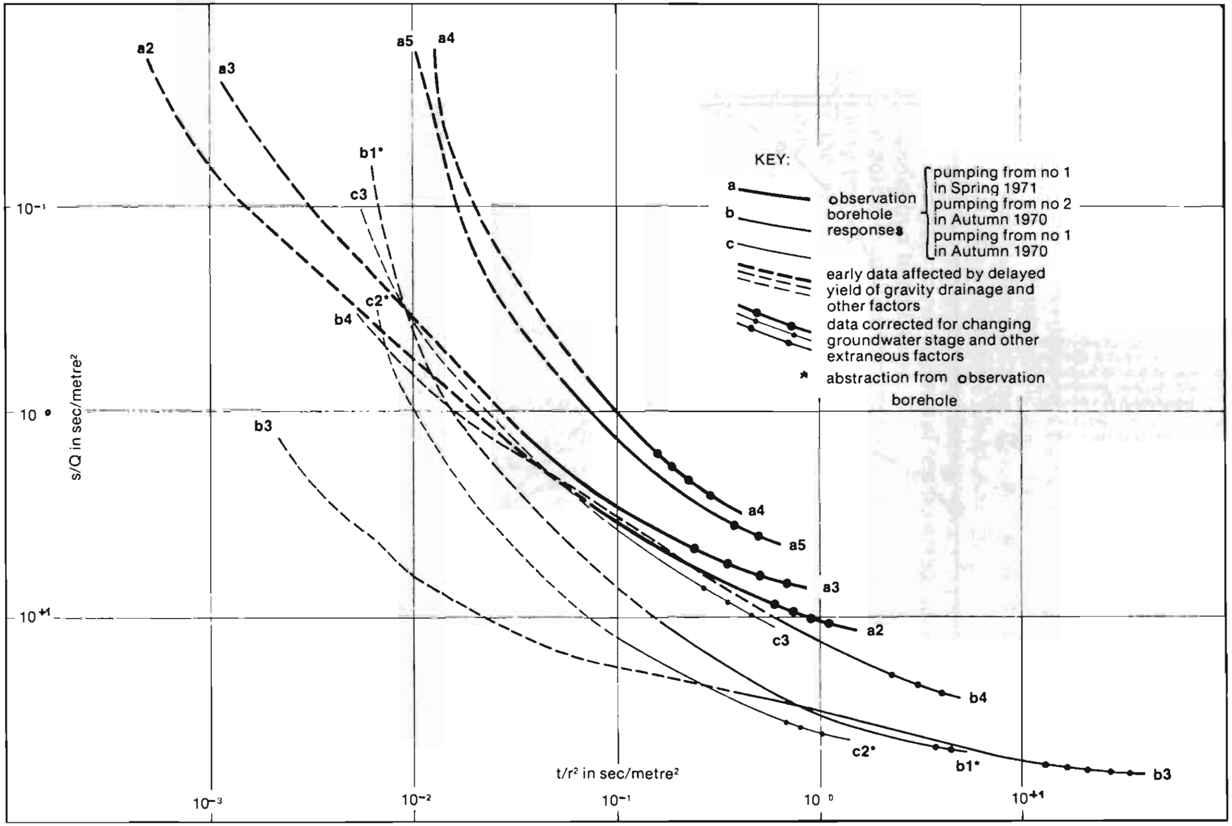


Fig. 6 — Comparative plot of time–drawdown data from autumn 1970 and spring 1971 pumping tests.

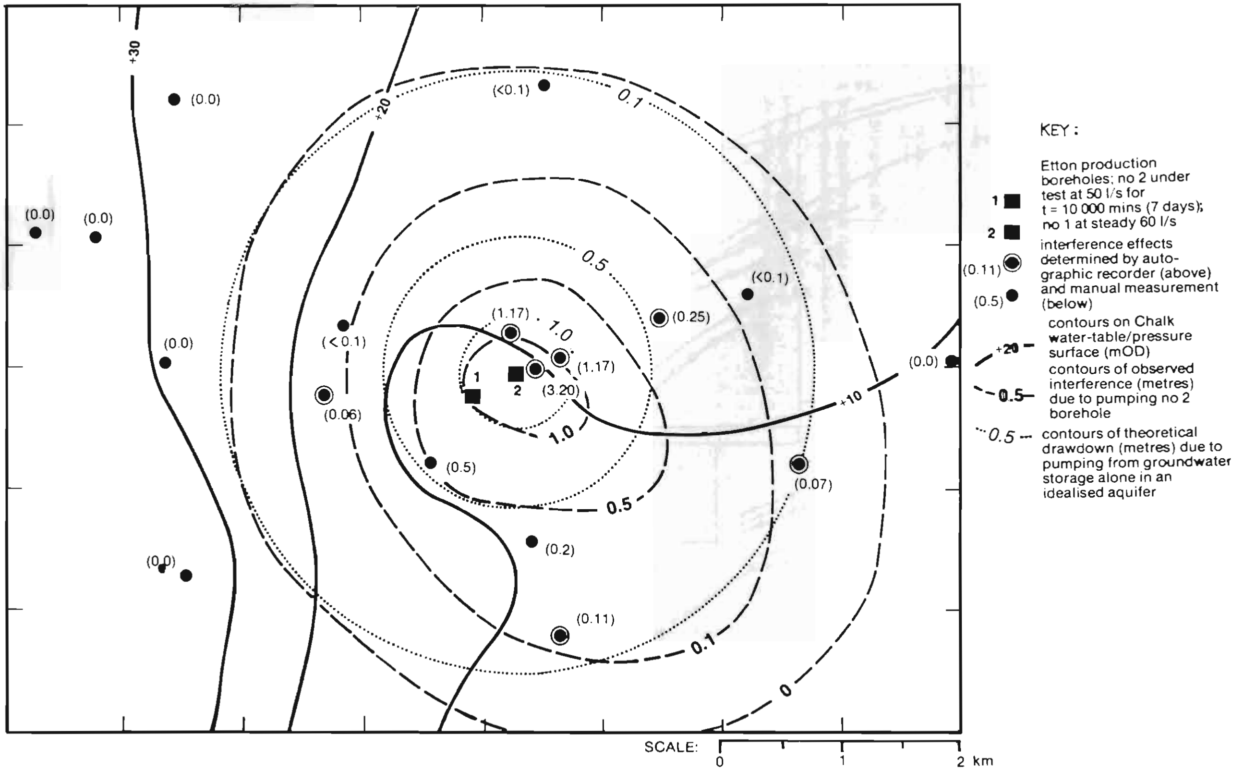


Fig. 7 — Pumping interference effects during the autumn 1970 test.

allow direct comparison of the differing aquifer responses at individual observation boreholes in the same test, and for the entire group of observation boreholes in tests at different times.

Before proceeding with any analysis it is necessary to consider the relationship between Q and s for the inner observation boreholes. This is strictly linear in all cases (Fig. 5C), confirming laminar flow at the corresponding distances from the point of abstraction under the hydraulic gradients associated with pumping rates of up to 90 l./s; an important point since it establishes that conventional groundwater hydraulics and pumping test analysis may be applied. This is not always the case in the Chalk; non-laminar flow conditions have been reported up to 260 m from a well in Hertfordshire when pumping was at 120 l./s (Ineson, 1957).

No major lateral hydraulic boundaries appear to be present in the cone of pumping depression. The general similarity in the magnitude and rate of drawdown in boreholes Nos. 4 and 5 (Fig. 5 A and B) is such as to suggest no strong lateral anisotropy in hydraulic properties, related to jointing and/or the direction of dry valleys; the reason for the differing initial response in these boreholes is not understood however. The interference effects in the distant observation boreholes (e.g. Fig. 7), resulting from the various regimes of test pumping, confirm the considerable overall uniformity of the aquifer in a lateral sense.

No observation borehole equilibrium was achieved during testing, even at a pumping rate of 50 l./s, but after long periods of time there were signs of a fall off in the rate of depletion of storage, reflecting the increasing interception of aquifer throughflow. Such effects tend to be masked by the corrections applied to the late time data.

The response of borehole No. 1, pumping at a steady rate with near equilibrium water level, to the test pumping regime in borehole No. 2 was anomalous; the rate of drawdown being somewhat greater and the magnitude of drawdown considerably greater than would be expected by comparison with the results from boreholes Nos. 4 and 5 (Fig. 5A). This can be explained by decreased efficiency in the borehole itself, associated with the further reduction in saturated thickness.

Aquifer Properties at Low Water-Table

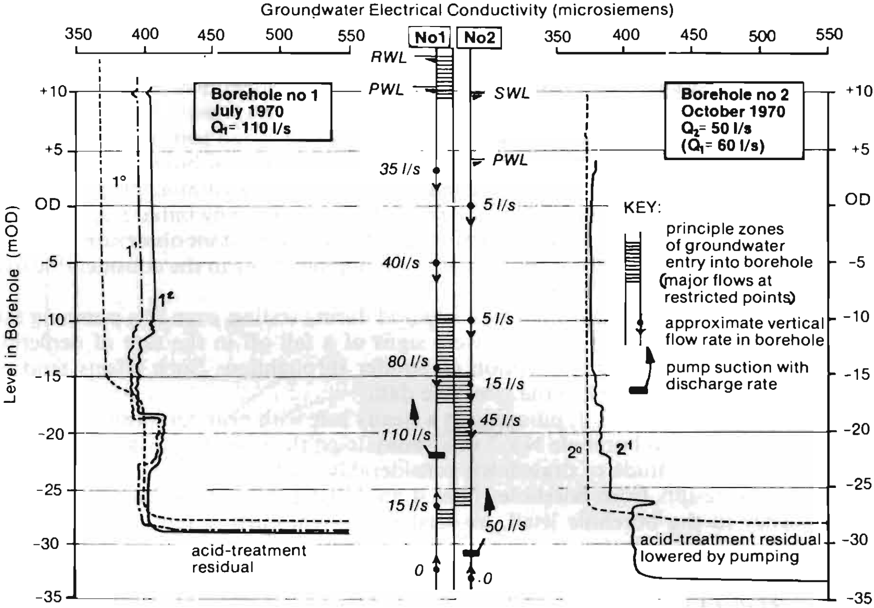
Application of the established methods of non-steady state pumping test analysis (Theis, 1935; Boulton, 1963; Prickett, 1965) on the late time data give a consistent T value of 1000 ± 300 m^2/day. The early time data for all the inner observation boreholes, particularly No. 3 (Figs. 5 A, B and 6), appear to show the characteristic relationship between instantaneous release from pressure storage and delayed yield by gravity drainage (Boulton, 1963), but this could result from other combinations of hydraulic properties (Stallman, 1965).

The analysis for storage coefficient is somewhat more subjective but a value of the order of 0·005 appears to be indicated with a Boulton delay index of less than 100 min. The former probably represents the specific yield (S_y) for the Chalk in this area at low water table, but it is possible that a subsequent longer delayed yield contribution from microjoints or pores might be present or that drainage is retarded by low vertical permeability. The pumping test values of S_y relate to levels in the rock mass which will have been drained and resaturated many times during previous pumping from the No. 1 borehole in its production regime.

Transmissivity of the Zone of Seasonal Fluctuation

Subsequent test pumping in the spring of 1971, with a higher though not maximum level of saturation, also gave results capable of consistent interpretation (Fig. 6). Recharge of the water table and a rapidly changing groundwater stage however, presented some complications in the analysis. Values for T of 2200 ± 500 m^2/day are definitely indicated. An extremely high value of horizontal permeability (K_x) for the zone of seasonal water table fluctuation is thus suggested; the saturation of the basal 7 m of this zone doubling the effective T. Even higher T values are to be expected for a higher water table, but the increases would probably not be of similar proportion.

A: Groundwater Flow Regime in the Etton Production Boreholes



B: Changes in Groundwater Temperature Profiles during Autumn 1970 Pumping Test

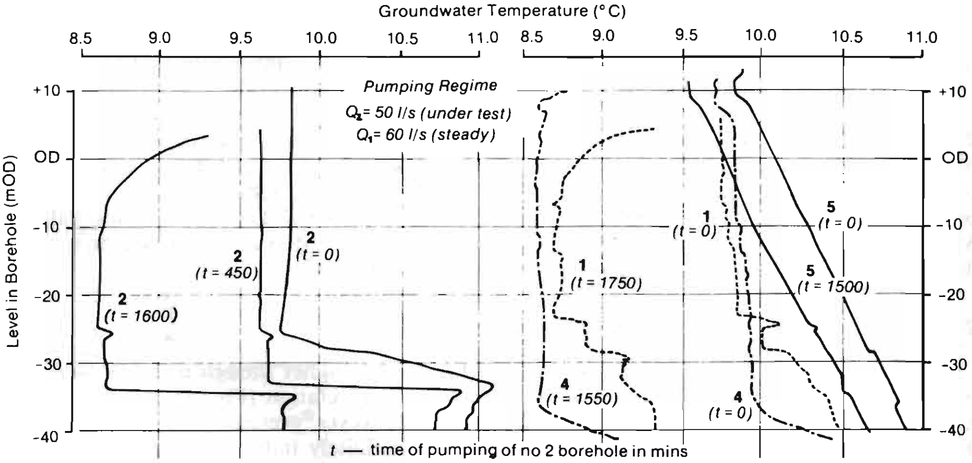


Fig. 8 — Selected results of geophysical borehole flow investigations.

In fissure-flow aquifers it is not sufficient to know only the magnitude of fissure T; the three-dimensional distribution of permeability which it represents is also required. The level and thickness of main permeability development is more important than the overall saturated thickness, since it directly relates to the heads that can be utilized in groundwater abstraction and therefore the behaviour of individual boreholes. Geophysical flow investigations (Tate *et al.*, 1970) aimed at determining this distribution were carried out in July 1970 and during the main pumping test in the autumn of 1970.

Differential electrical conductivity (Fig. 8A) and temperature logging showed the levels of groundwater entry into the Etton pumping boreholes to be restricted. Approximate vertical flow rates in the boreholes were estimated from impeller flowmeter and tracer injection detection techniques (Fig. 8A). These results must be treated with some reservation in respect of absolute accuracy because of the variable cross-sectional area of the boreholes together with the existence of eddies around certain plant and opposite some levels of entry.

In October 1970 at near minimum water levels, the bulk of the water pumped from the No. 2 borehole was derived from a 7-m-thick zone whose base was located at about −22 m OD (Fig. 8A). Investigations in the No. 1 borehole in July 1970 with a somewhat higher water table, had given similar results but with the base of the corresponding zone of permeability development at about −17 m OD and more than 30 per cent of the total discharge being derived near or above the pumping water-level (Fig. 8A). The existence of marked chloride residuals in both boreholes (the products of earlier acid treatment) suggest minimal groundwater movement from about −29 m OD to the base of the boreholes and probably below this level.

Sequences of temperature logs at the start of test pumping from No. 2 borehole showed a systematic response with cooling of the groundwater in all of the other boreholes at the Etton site (Fig. 8B); compelling evidence of their hydraulic intercommunication. One significant anomaly arises however. The temperature logs for borehole No. 5, sited on the interfluve of the minor dry valley at the site, show more positive temperature gradient and smaller response than the other boreholes. The most reasonable interpretation is that less groundwater movement occurs in this direction, though this is not compatible with the observation borehole drawdown data. Some anomalies may also be ascribed to the fact that the observation boreholes (Nos. 3, 4 and 5) were constructed only shortly before the autumn 1970 pumping test.

NATURE OF CHALK PERMEABILITY AND STORAGE

In order to extend the interpretation of Chalk permeability and storage it is of relevance to consider the hydraulic properties of idealized fissure systems.

Permeability of Idealized Fissured Media

The theoretical hydraulics of fluid flow in fractured media (Serafim and del Campo, 1965; Snow, 1969) develop from classical Navier-Stokes and Hele-Shaw parallel-plate hydraulics, in which the velocity distribution (v), for laminar steady-state flow of a viscous incompressible fluid in an idealized semi-infinite smooth parallel-walled opening of aperture b, is shown to be parabolic:

$$v = -\frac{1}{2\mu}\cdot\frac{\mathrm{d}p}{\mathrm{d}x}\cdot(bz - z^2) \tag{1}$$

where $\mathrm{d}p/\mathrm{d}x$ is the pressure gradient in the plane of the opening and μ is the dynamic viscosity of the fluid. Now $v_{\max}$ occurs when $z = b/2$ and the mean velocity (V) is $2v_{\max}/3$ thus

$$V = -\frac{b^2}{12\mu}\cdot\frac{\mathrm{d}p}{\mathrm{d}x} \tag{2}$$

From whence the discharge (Q) from a parallel series of such fissures over a width W_y in the direction of the plane of opening and perpendicular to that of the flow (x) is given by

$$Q = \frac{\gamma}{12\mu}\cdot I_x W_y \cdot \Sigma b^3 = \frac{g}{12\upsilon}\cdot I_x W_y \cdot \Sigma b^3 \tag{3}$$

where γ and υ are the specific weight and kinematic viscosity of the fluid respectively and I_x the hydraulic gradient or component of the hydraulic gradient in the plane of the opening. From (3) it can be seen that the equivalent transmissivity (T_x) of such a system is

$$T_x = \frac{g}{12\upsilon}\cdot\Sigma b^3 = 54\,\Sigma b^3 \text{ m}^2\text{/day} \tag{4}$$

taking $\upsilon = 1{\cdot}3 \times 10^{-6}$ m^2/s for groundwater at 10°C and with b in millimetres.

The importance assumed by relatively minor changes in b, due to solution or variations in fluid pressure for example, should be noted. Just one fissure of 5 mm effective opening in the plane of the hydraulic gradient would contribute over 6000 m^2/day to the T of an aquifer; giving an idea of the order of heterogeneity and anisotropy that its presence would introduce. In this context the relatively isotropic radial response of the Chalk at Etton accompanied by its high T, probably indicate that development of solution permeability is concentrated along horizontal discontinuities. In the presence of a high density of multi-directional inclined jointing, this explanation is not unique.

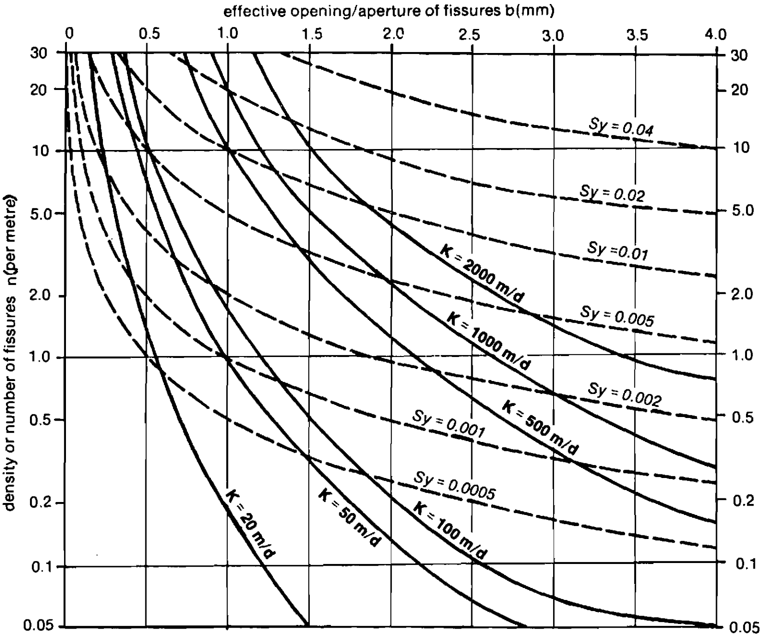


Fig. 9 — Permeability and storage of a rock mass with a single parallel system of idealized fissures.

If within a limited thickness (m_z), a rock mass has a series of equal, parallel fissures with uniform separation ($1/n$) then (3) can be written

$$Q = \frac{b^3 n}{12} \cdot \frac{g}{\upsilon} \cdot I_x W_y m_z$$

The equivalent permeability (K_x) of the system is given by

$$K_x = \frac{b^3 n}{12} \cdot \frac{g}{\upsilon} = 54 b^3 n \text{ m/day} = 0{\cdot}063\, b^3 n \text{ cm/s} \tag{5}$$

expressing b in millimetres and $1/n$ in metres. For such idealized media, a family of curves relating K_x, b and n can be constructed (Fig. 9).

The idealized fissure will, in almost all cases, be departed from in practice in respect of planarity (because of briding and constriction) and wall roughness, producing tortuosity in the flow path. The departures may not be so gross in the case of bedding-plane discontinuities in Chalk as in some other formations. It has been shown in laboratory tests on irregular rough-faced tension joints in an igneous rock with openings of 0·2–1·5 mm, that the exponent of b in equation (3) was reduced to 2 or less, even for laminar flow (Sharp and Maini, 1972).

Implicit in the development of the above equations is the assumption of laminar flow. The theoretical validity of this assumption can be examined by consideration of Reynolds number criteria. For the idealized parallel-plate model $R_b = Vb/\upsilon$; substituting from (2) and taking the lower critical value as 1000, it can be shown that the critical hydraulic gradient below which laminar flow is inherently stable is about $2/b^3$ (b in millimetres). Non-planarity, face roughness and tortuosity of flow path have a major effect on the onset of turbulence however (Sharp and Maini, 1972), and may reduce the lower critical R_b and hydraulic gradient by even two orders or more. It would still be unlikely for non-laminar flow to develop in fissures with an effective b of less than 2–3 mm under most natural groundwater flow conditions, but the possibility of turbulence deserves careful consideration in the siting of observation boreholes for test pumping in fissure-flow formations and in their interpretation.

Fissure Storage

Of equal interest to permeability is the theoretical storage capacity of fissured media. The specific yield (S_y) of the idealized fissure system used in the development of equation (5) is simply the product bn and a series of curves relating S_y, b and n have been included in Fig. 9. For this purpose it has been assumed that the effective opening (b) is equal to the mean opening and that pressure storage and surface retention are both negligible.

Interpretation of Hydraulic Properties of the Chalk

It is now possible to consider further the hydraulic properties of the lower part of the zone of seasonal water table fluctuation at Etton; $T = 1200$ m²/day for $m = 7$ m, $K_x = 170$ m/day, $S_y = 0{\cdot}005$–$0{\cdot}010$. Interpolating in Fig. 9, it would appear that such a combination of properties could be generated by a single set of fissures of high density (n about 10 per metre) with effective openings of 0·5–1·0 mm. It is more probable however that a much smaller number of horizontal master conduits (perhaps four or five in total) of greater opening (say 2 mm) contribute the bulk of the permeability development, although these would be unlikely to contribute all of the S_y also.

The bulk of the particles in the fabric of the Chalk are of the order of 1 μm diameter (Hancock and Kennedy, 1967); most of the pore diameters are even smaller and unlikely to drain under suctions of less than 3 atmospheres. This factor, confirmed by the results of centrifuge specific yield tests on core samples from the East Yorkshire Chalk (mean $CS_y = 0{\cdot}002$ with maximum values of around 0·005), suggests that pore-water drainage under gravity will be of only minor significance, the greatest part of the saturated porosity (0·14–0·20) constituting physically inert storage. It must be suspected therefore that additional gravity storage is present in a high density system of inclined microjoints.

There are few descriptions of the state of the discontinuities in the Chalk at depth. At a site in Norfolk (Ward *et al.*, 1968), horizontal 'separation planes' open in places to as much as 10 mm were described just above the water table during the direct inspection of the walls of large-diameter boreholes. At the same site it was observed (R.W. Gallois, personal communication) that deeper than a maximum of about 14 m bgl most of the discernible inclined joints were closed tight; the far greater density of inclined joints in the core from an adjacent borehole suggests that *in situ* many must be microscopic, perhaps less than 0·2 mm aperture.

Implications

It is not a primary aim of this paper to draw implications from the hydraulic behaviour of the Chalk. In the context of groundwater storage development and management they have been fully discussed elsewhere (Foster and Milton, in press). Some of the more important points are worthy of mention here.

A high-T/low-S_y water table aquifer such as this, will have a much more rapid hydraulic response than that of most unconfined systems. Actual groundwater flow rates will be relatively fast, though less fast than for karst systems. Even under natural hydraulic gradients they could reach 200 m/day; a significant factor in the spread of pollution, should pollutants reach the water table. High flow rates were confirmed by the movement of the products of acid treatment from the No. 2 to the No. 1 borehole at Etton, a distance of 350 m. The first arrival, peak and mean travel times were measured at about 6, 15 and 27 h respectively for a pumping rate of 30 l./s and overall hydraulic gradient of about 1/150.

The large seasonal variation in T has a number of implications; pumping interference effects will show major seasonal variation and the natural aquifer throughflow will vary in much greater proportion than the associated hydraulic gradient. There will be profound seasonal differences in the yield–drawdown characteristics of pumping boreholes. At Etton, the yield for a 5-m drawdown in the No.1 borehole varied between 56 l./s in November 1970 and 98 l./s in March 1971, and the limiting yield at low saturation was strongly influenced by the level of the main lower zone of permeability development. It should thus be evident that considerable care is needed in the planning of groundwater investigations, if reliable evaluations of drought behaviour are required for major schemes.

CONCLUDING REMARKS

The Chalk Aquifer in the outcrop area around Etton forms a layered, high-T/low-S_y, laminar fissure-flow, unconfined system. Although some anomalies exist, laterally its properties are relatively isotropic; in depth however permeability development is localized in two main layers of limited thickness, not distributed through the entire thickness of the formation. It is probably associated with a small number of horizontal discontinuities which have experienced a degree of preferential solution.

The uppermost of the two layers of permeability development constitutes the lower part of the zone of seasonal water table fluctuation; the other is located significantly below local hydrological base level. It is tempting to attribute the former to solution during long-term circulation of fresh groundwater to the existing base level (with the T values increasing down the dip slope towards the natural discharge areas). A similar conclusion has been drawn in the studies of a number of carbonate systems (le Grand and Stringfield, 1971) and appears to be due to the fact that the gross long-term circulation is often volumetrically greatest at this level. The lower zone of permeability development could well be attributable to a similar process operating to a much lower base level, perhaps in Pleistocene times, although there is also a suggestion of stratigraphic control, since it may be associated with feature *C* of the resistivity logs (Fig. 3).

The layered hydraulic structure of the East Yorkshire Chalk has been corroborated in part, and the properties of the zone of seasonal water table fluctuation elucidated, through analysis of groundwater level recession and river flow data in the West Beck and Foston Beck catchments (*W* and *F* in Fig. 1) to the north of the Etton area (Foster, 1974). Moreover the hydraulic uniformity of the dip slope of the aquifer appears to be confirmed by the similarity of groundwater level recessions throughout the region.

It is not the intention to suggest that the Etton area is necessarily typical of the unconfined Chalk Aquifer in all the extensive tracts of wold and down which form its outcrop. Similar conditions probably persist southwards from East Yorkshire into Lincolnshire but variations probably occur further south, associated with changing relief and hydrological discharge regime, geological structure, stratigraphy and lithology. Only the harder 'chalk rock' beds of south-eastern England have a comparable porosity to that of the bulk of the East Yorkshire Chalk; perhaps introducing a greater likelihood of stratigraphic control over joint and permeability development. Nevertheless there will be many features in common.

The simple theoretical permeability and storage relationships for idealized fissured systems presented, are probably not of direct practical application in the prediction of formation properties because of the formidable difficulties in field measurement of the parameters involved, particularly the effective fissure opening. They have however considerable relevance in the physical interpretation of results of *in situ* testing, which is essential if such results are to be meaningfully employed in the evaluation and management of water resources stored in fissure-flow formations.

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