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GROUNDWATER STORAGE—RIVERFLOW RELATIONS IN A CHALK CATCHMENT

S.S.D. FOSTER

Hydrogeological Department, Institute of Geological Sciences, London (Great Britain)

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ABSTRACT

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Data from continuously monitored observation boreholes and the permanent river gauging station in the West Beck catchment of the East Yorkshire Chalk are presented and analysed. Layered hydraulic structure in the chalk aquifer is reflected in the form of and correlation between recession characteristics. A series of fairly well defined linear storage elements, each with differing coefficients of permeability and storage, appear to be present. The distribution and variation of storage and permeability with depth may be critical factors in catchments such as this, where schemes for augmentation of drought riverflows from groundwater storage are under consideration or in pilot development.

INTRODUCTORY REMARKS

The chalk formation underlies a large area of lowland Britain and is the nation's most important aquifer. In those catchments with chalk bedrock the groundwater component of total river discharge frequently exceeds 50% and may reach 95%.

In numerous chalk catchments, current interest centres on the exploitation of sub-surface storage for augmentation of low riverflows and in artificial recharge schemes (Ineson, 1970). The former involves a degree of regulation of natural aquifer discharge through the manipulation of groundwater levels with pumping boreholes.

Precise understanding of the natural groundwater storage—riverflow relationships in chalk catchments is thus of considerable practical relevance to water resources development, particularly in relation to operating conditions in drought. Moreover, the analysis of riverflow and groundwater level data can give valuable indications of the gross hydraulic characteristics of a permeable catchment, against which the results of localised pumping test investigations can be viewed.

BASIC CONSIDERATIONS

Horton (1933) and Barnes (1939) found that the components forming a discharge hydrograph, including those derived from a groundwater system, frequently each had a recession that could be approximated by simple exponential relationships of the form:

$$Q_t = Q_0 e^{-kt} = Q_0 K^t \tag{1}$$

where Q_0 and Q_t are the discharge at the beginning of the measurement period and after time t respectively and k and K are known as recession constants. When $\log_{10} Q$ was plotted against t, a straight-line relationship thus resulted for each component, in which for one log cycle of Q:

$$k = 1/\Delta t . \log_{10} e = 1/0.43 \Delta t \tag{2}$$

Clearly, in the case of the groundwater component, k will be a function of the aquifer transmissivity (T), storage coefficient (S) or specific yield (S_y), and the catchment geometry. Moreover, the total amount of groundwater storage above outlet or hydrological base-level (S_t) corresponding to a river baseflow (Q_t) will equal the total potential drainage:

$$S_t = \int_t^{\infty} Q_t \mathrm{d}t = Q_0 e^{-kt}/k \tag{3}$$

from which it follows that:

$$S_t = Q_t/k \tag{4}$$

Such a groundwater system can be termed a "linear reservoir" because its rate of natural discharge is directly proportional to its storage and storage levels. It is implicit in the Horton (1933) equation.

Using a mathematical model of simplified systems, Singh and Stall (1971) have shown that the boundary conditions to which log-linear recessions strictly relate are horizontal flow to a partially-penetrating river from a hydraulically connected large homogeneous and isotropic water-table aquifer, when variations in stream-stage are negligible in comparison to those in saturated aquifer thickness; departures occur in the case of a fully penetrating river. In practice the relationship probably holds providing hydrogeological conditions are relatively simple with one extensive, fairly uniform aquifer, negligible direct evapotranspiration of groundwater in riparian areas, absence of major groundwater development, river regulation and significant effluent discharges.

Under more heterogeneous conditions but without artificial interferences, a non-linear reservoir relationship of the form:

$$Q_t = Q_0 e^{-kt^n} \tag{5}$$

is probably appropriate, with n a variable exponent.

DATA FROM EAST YORKSHIRE CATCHMENTS

Riverflow—groundwater level recession characteristics

In the course of an analysis of riverflow data for regional hydrological study of the East Yorkshire Chalk (Foster and Milton, 1974), it became apparent that each of the recessions of the two main tributaries of the Hull river system could not be represented by any single log-linear relationship. The gauging structures on these tributaries, at Wansford Bridge (W) on West Beck and Foston Mill (F) on Foston Beck (Fig.1), are situated such that almost their entire flow (85—95%) is discharge from the undeveloped chalk aquifer. The approximate sub-surface boundaries of the respective groundwater catchments are also indicated in Fig.1.

It was also evident that the riverflow recessions could be split into a number of log-linear segments (a, b and c in Fig.2). The examination of data for other years with uninterrupted recessions corroborated this analysis. For both gauges three segments appeared to be present and in the 1962—72 data recurred in relatively closely-defined flow ranges (Table I).

The recession of groundwater levels, in the only observation borehole in the area continuously-monitored with an autographic water-level recorder (N in Fig.1), had a similar form to the riverflow recessions but included only two definite log-linear segments (x and y in Fig.2) with the trace of a third towards the end of the recession. When the riverflow data for W and F were correlated with the groundwater level data for N (Fig.3) their relationship was certainly not linear, as would be expected if the aquifer behaved as a simple linear storage reservoir. This was particularly apparent when extreme drought conditions (1964) were considered. No part of the departure from linearity could be attributed to differences between spring, summer and autumn groundwater evapotranspiration from riparian areas because their extent was far too restricted, nor to artificial interferences which were negligible.

It was apparent that a split into two linear sections, or possibly three in the case of the W—N correlation (Fig.3), was possible, the data tending to a base-level of about +15 m OD in the case of W and nearer to +16 m OD for F. Although this was perhaps stretching the interpretation, representation of a complex groundwater system by a series of linear storage elements is preferable, if at all practical. It should be noted that for the lower flow-ranges in the respective cases, the total riverflow is virtually all baseflow (i.e. chalk aquifer discharge) but at higher flows other minor components, such as surface run-off and bank storage, are also present. The position at higher flows is also complicated by minor incidents of recharge, although most of these were deliberately avoided in the choice of data analysed.

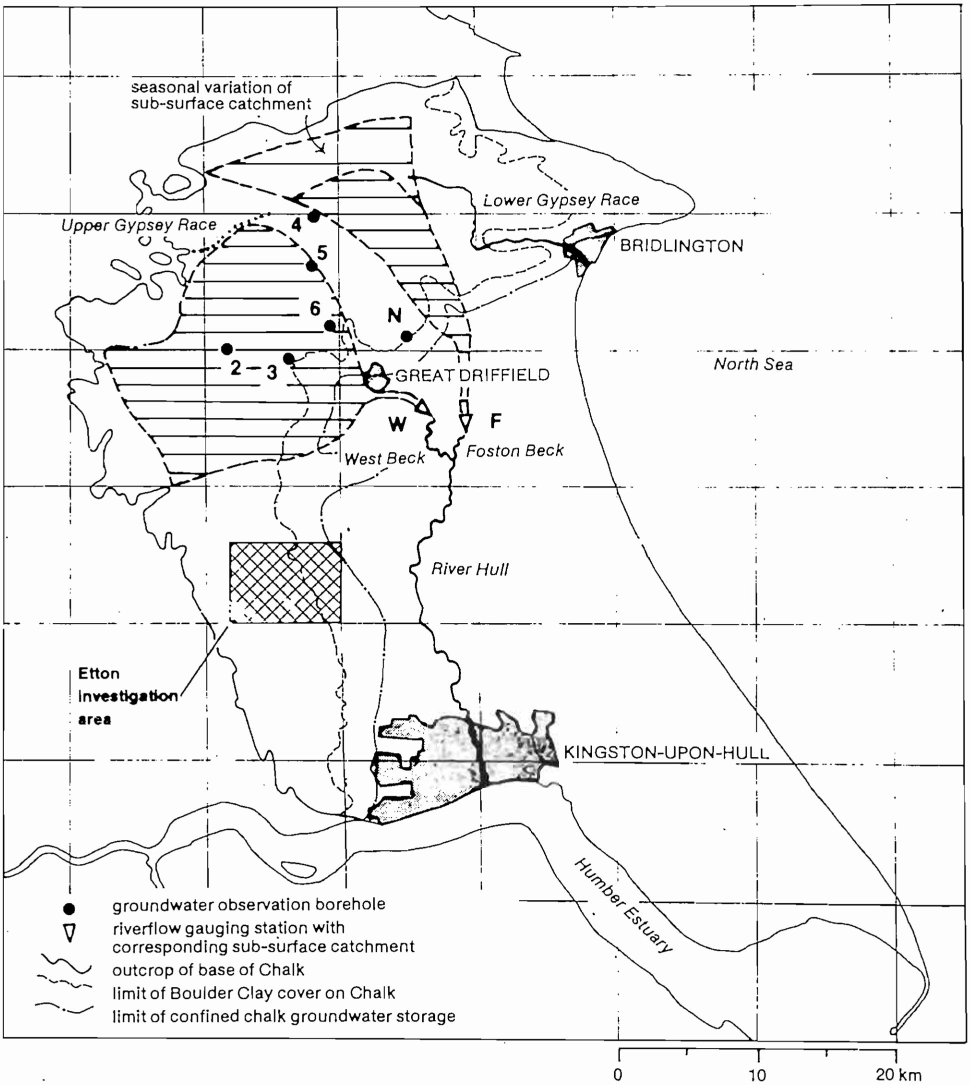

Fig.1. Location map of East Yorkshire. For explanation of symbols see text.

The Foston Beck catchment is not ideally suited to hydrological analysis because of the seasonal variability in its groundwater catchment resulting from a complex relationship with an intermittent water-table river, the Lower Gypsey Race, to the north and east (Foster and Milton, 1974). The variation in catchment area (as indicated in Fig.1) is substantial; increasing from about 50 km^2 to almost double that area, fairly early in the recession. This factor may exert some influence on the data from this gauging station for values of F in excess of about 0.7 cumecs and certainly affects those for F much above 1.0 cumecs. Hence analysis of data from this station is not pursued further.

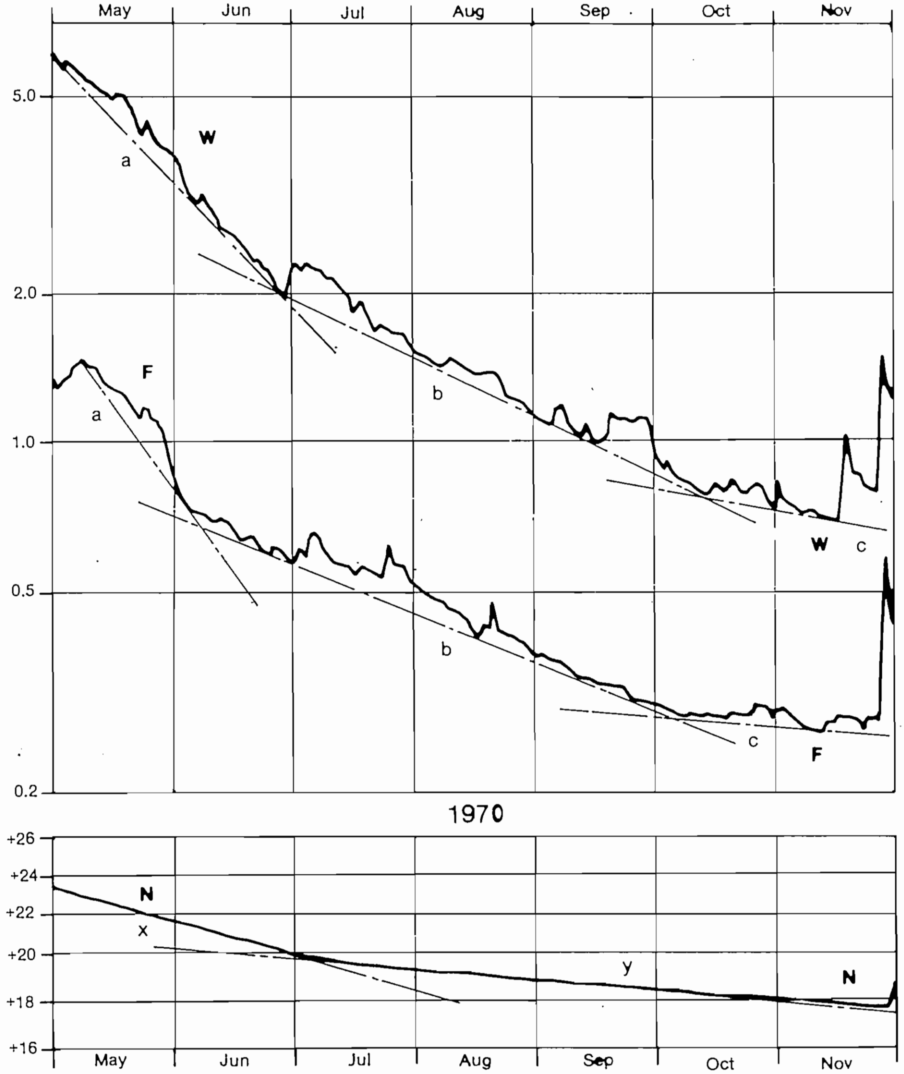

Fig.2. Riverflow and groundwater level recession characteristics. For explanation of symbols see text.

Hydrogeology of the West Beck catchment

The bulk of the flow in West Beck originates from a group of major artesian springheads to the immediate southwest of Great Driffield; although in conditions of highest water-table the increase in groundwater pressure is not fully dissipated by increased flow at the perennial springheads, and new springs and seepage areas are initiated at higher levels.

TABLE I

Summary of riverflow recession characteristics*

Segment	Recession constant *k* (days^{-1})	
	W	*F*
a	0.020	? 0.018—0.022
Inflexion (cumecs)	1.8—2.4	? 0.5—1.0
b	0.010	0.008
Inflexion (cumecs)	0.6—0.8	0.3—0.4
c	0.004	0.003

*For explanation of symbols see text.

On the basis of groundwater level contours, the flow lines to the main springheads and thus the lateral boundaries of the subsurface catchment can be defined with tolerable accuracy (Foster and Milton, 1974). They were shown to be relatively stable seasonally. The outer limits of the catchment can also be defined fairly closely although they are somewhat complicated by complex geological structure on the northwestern water-divide and by recharge from a minor semi-perched chalk watercourse, the Upper Gypsey Race, in the north. The net result is a sub-surface catchment with an area of 235 ± 15 km^2 and a small inflow (about 0.1 cumecs at maximum, decreasing to less than 0.02 cumecs at drought) across the northern boundary.

The gauging structure itself at Wansford Bridge is a compound standing-wave flume, the rating of which is occasionally affected by weed growth. Certain minor irregularities in flow are caused by the operation of a mill and non-consumptive abstraction at a trout farm, but the effluent load is negligible. There is, however, a by-pass flow in a relief drain on the southern bank which could perhaps lead to an underestimate in excess of 5% of total catchment discharge (Foster and Milton, 1974). A small buried channel underlies the gauge but the shallow underflow can be shown from first principles to be insignificant; the deep underflow in the chalk is greater but will rarely exceed 0.05 cumecs. The export and consumptive use of chalk groundwater in the catchment is also virtually negligible at present; the equivalent of less than 0.02 cumecs.

The topography of the West Beck catchment is typical of chalk outcrop country, undulating with many dry valleys; the elevation exceeding +30 m OD throughout and reaching in excess of +150 m OD in the northwestern extremities. The outcrop is freely draining and virtually devoid of surface water except for the occasional pond.

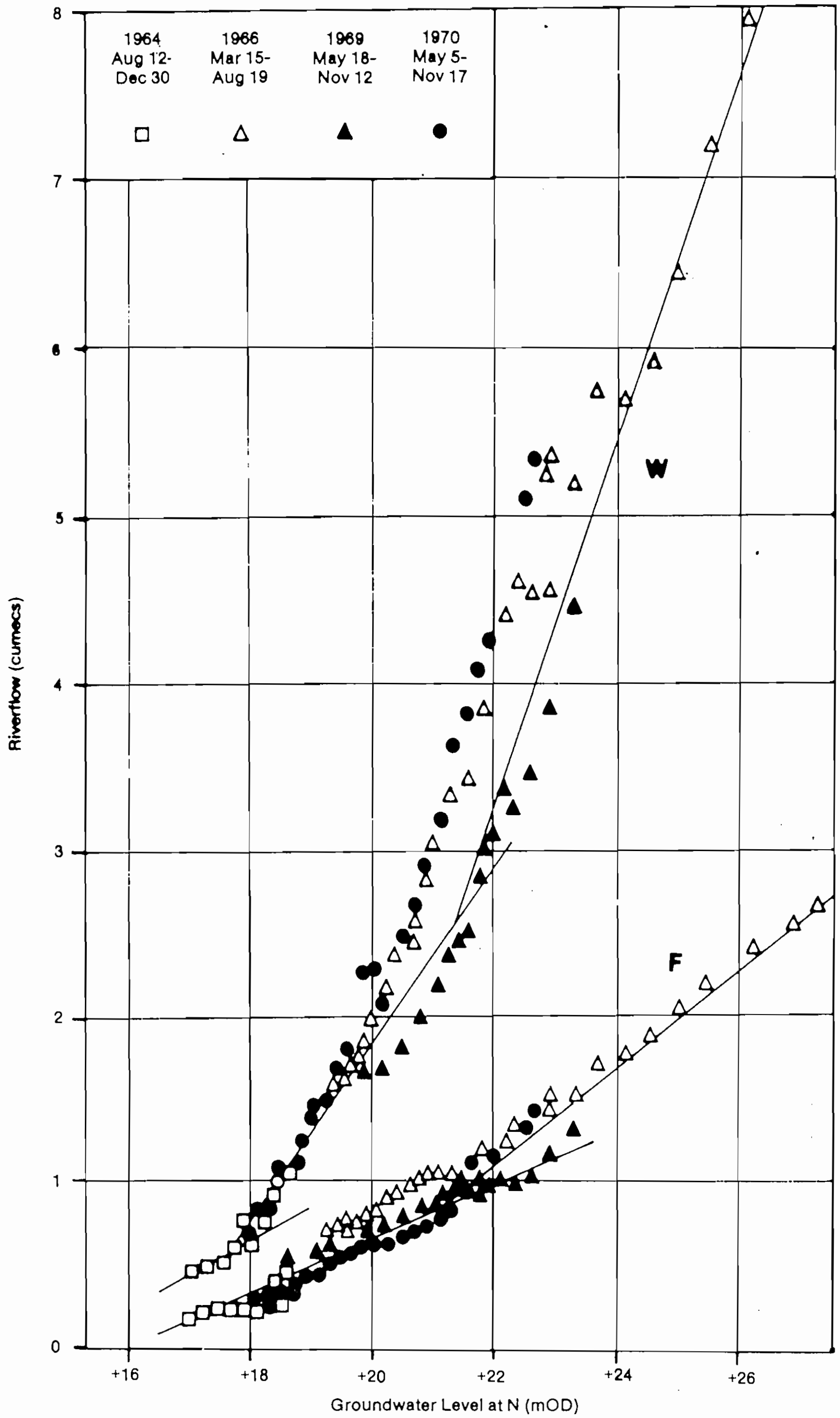

Fig. 3. Chalk groundwater level—discharge rate correlation. For explanation of symbols see text.

In its saturated zone the chalk formation is a dominantly fissure-flow and essentially fissure-storage high T—low S_y aquifer. Its hydraulic behaviour has been investigated in detail in the Etton area to the south (Fig.1) (Foster and Milton, in prep.). Within the West Bank catchment the groundwater contours or equipotential lines decrease in spacing towards the major springheads despite the converging flow in this direction. This inverse situation is interpreted as indicating steadily increasing T values down hydraulic gradient towards the discharge area, permeability development in the chalk aquifer being largely due to solution by circulating groundwater on pre-existing discontinuities. By similar reasoning the groundwater level contours indicate fairly uniform aquifer properties laterally across the catchment, but with above average T values stretching into the Wetwang area (towards boreholes nos.*2* and *3* in Fig.1).

Extension and interpretation of West Beck data

During 1971 five purpose-drilled chalk observation boreholes were completed in and immediately adjacent to the West Beck catchment (nos.*2*, *3*, *4*, *5* and *6* in Fig.1). Their water-levels have subsequently been monitored by autographic recorders.

In 1972 an extended recession commenced in late-February and continued with only minor interruptions until mid-December. For boreholes nos.*2*, *3* and *6* the recession characteristics (Table II) closely resembled those previously described for N (Fig.2).

The recession of borehole no.*5* has no distinct inflexions and has an overall k of about 0.0014 days^{-1}. That for borehole no.*4* is distinct with the recession steepening at an early stage from an initially slow rate (Table II);

TABLE II

Summary of groundwater level recession characteristics*

Segment	Recession constant k (days^{-1})					
	N (1964—70)	2	3	6	5	4
		(1972 data only)				
x	0.0030	0.0020	0.0020	0.0020	approx. 0.0014	0.0007
Inflexion (m OD)	+20	+21	+20	+22		+52
y	0.0008 –0.0006	0.0004	0.0004	0.0006		0.0012

*For explanation of symbols see text.

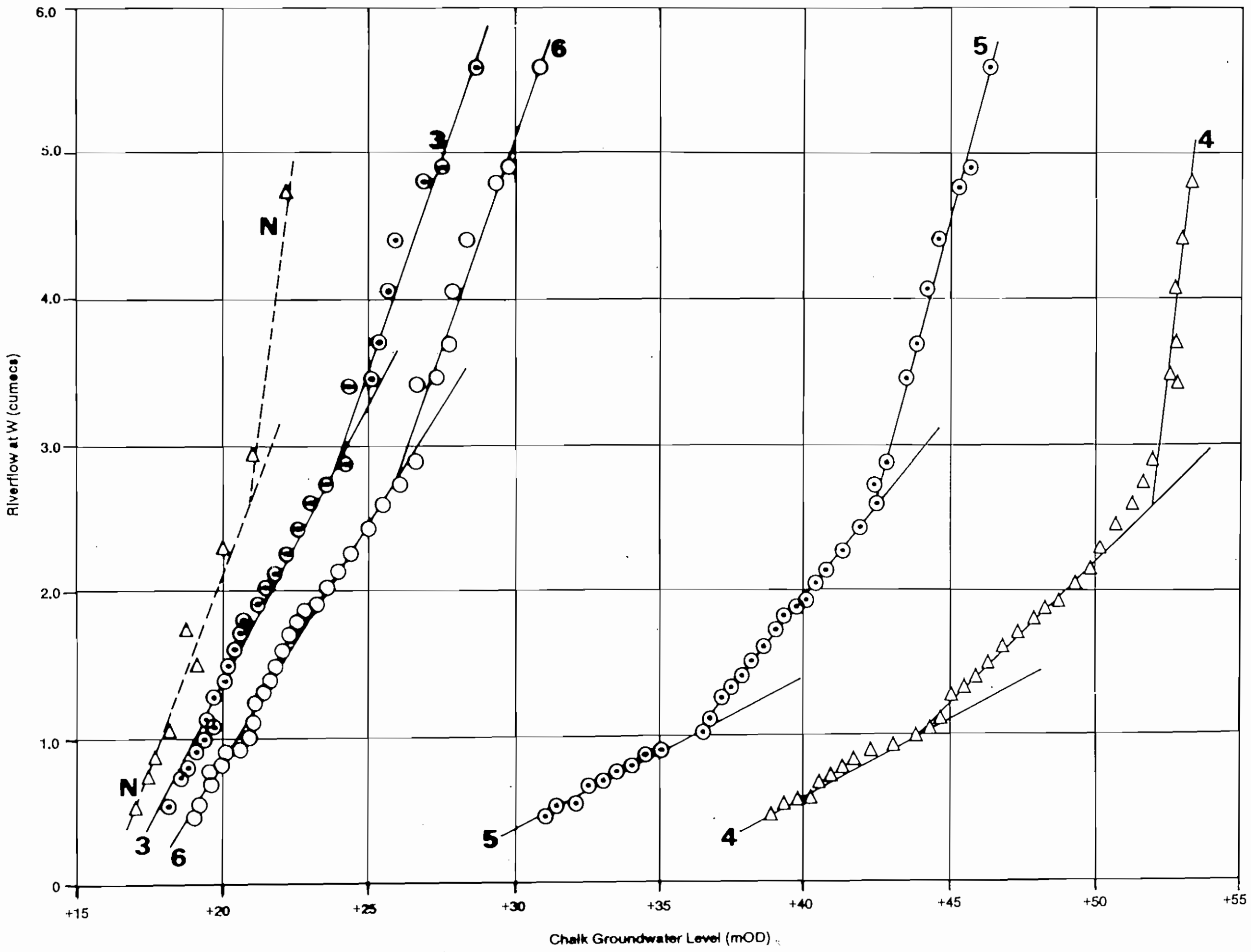

Fig.4. Groundwater level—riverflow relations for West Beck catchment during 1972 recession. For explanation of symbols see text.

this could be due to the influence of recharge from the Upper Gypsey Race or to local differences in aquifer properties.

The correlation of the 1972 water-level data from the new observation boreholes with the corresponding riverflow at W (Fig.4) corroborates and considerably extends the results presented in Fig.3. The separation into two linear storage elements corresponding to flows at W of greater and less than 2.5—3.0 cumecs is consistent. A third element is present in the data from boreholes nos.*4* and *5*, for W less than about 1.0 cumecs. In extreme drought it is probable that a third segment would be revealed in the data from boreholes nos.*3* and *6* and for borehole no.*2* (not illustrated in Fig.4), whose plot is almost coincident. All the data must trend to a catchment base-level of about +15 m OD for $W = 0$.

The data in Fig.4 are interpreted as strong evidence of the overall layered hydraulic structure of the chalk aquifer in the West Beck catchment. Each storage element will have a distinct combination of T and S_y values. Those for the specific yield (S_y) will correspond directly to the particular element undergoing drainage but the T values will be the total transmissivity of the saturated aquifer and will decrease progressively, and probably in quite marked steps, during the recession. The location of the three storage elements in depth would appear to be as indicated by *1*, *2* and *3* in Fig.5.

The analysis can be extended to compute catchment average values of S_y for each storage element from consideration of the area of the sub-surface catchment, the total volume of baseflow during a defined period and the corresponding mean groundwater level recession over the catchment; the main source of error in the present case being estimation of the last of these factors. Values for S_y of 0.010—0.015, 0.015—0.020 and 0.005—0.010 were obtained for the elements *1*, *2* and *3* in Fig.5, respectively, from analysis of the 1964—72 data. Furthermore, if the existence of a single linear element of aquifer storage between extreme drought groundwater level and hydrological base-level is assumed, it is possible through applying eq.4 to make an estimate of its average S_y. A value of about 0.002 was obtained, significantly less than that of the overlying elements.

The layered hydraulic structure of the outcrop chalk aquifer in East Yorkshire has been independently verified at one site at least. Detailed investigations at Etton, to the south of the West Beck catchment (Fig.1), showed an effective transmissivity of about 1,000 $m^2 day^{-1}$ and S_y of 0.005 at minimum water-table but the saturation of the basal 7 m of the zone of seasonal water-table fluctuation added 1,200 m^2 day^{-1} to the total T (Foster and Milton, in prep.). The former values would appear to correspond to element *1* in Fig.5 and the latter to element *2* (the upper zone of major permeability development).

Geophysical borehole flow investigations at Etton showed that at minimum water-table the bulk of the flow and the total T was contributed by an 8 m thick layer with its base at around −20 m OD; there appeared to be negligible groundwater flow (and presumably restricted storage) below about −30 m OD. This factor together with the exceptionally high permeability of the chalk in

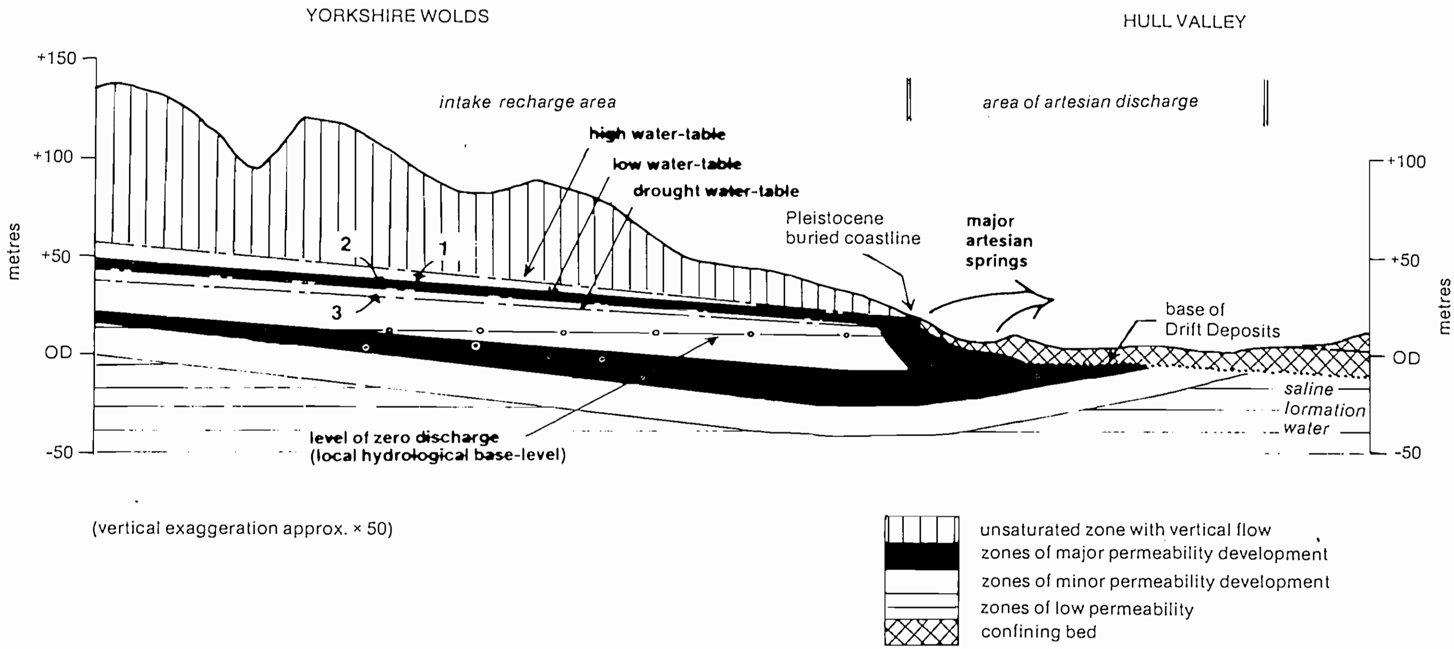

Fig.5. Schematic interpretation of the hydraulic structure of the chalk aquifer in East Yorkshire. For explanation of symbols see text.

the vicinity of the Pleistocene buried coastline along the perimeter of the Hull valley, proven at Haisthorpe (Foster and Milton, 1974), have been used in the interpretation of aquifer structure in Fig.5; uniformity perpendicular to this section across the catchment and throughout the East Yorkshire dip slope being reflected by the form of groundwater level recessions throughout the region. The two layers of principal permeability development may be attributed to solution during long-term groundwater circulation, the upper to the existing base-level and the lower to a previous much lower and probably Pleistocene base-level.

DISCUSSION AND CONCLUSIONS

It is clearly inadequate to assume a uniform distribution of permeability and storage with depth in a carbonate aquifer such as the chalk. A fairly well-defined layered structure appears to be present in East Yorkshire. In such an aquifer it is to be *expected* that borehole yields, borehole yield-drawdown characteristics and the spread of pumping interference effects will show major or significant variation with groundwater level. Considerable caution is thus required in the interpretation of, and extrapolation from preliminary investigation and pilot operation for river augmentation schemes, which ultimately at full-scale will involve the manipulation of aquifer storage located below drought groundwater level or even below hydrological base-level.

In relation to the rate and magnitude of propagation of interference effects from "remote" pumping centres to distant springheads and surface-water features, the variation of S_y is particularly important. For example, variation in S_y between 0.020, 0.005 and 0.002 would cause marked differences in the drawdowns at 5 km radius from a pumping centre in a $T = 1{,}000\ \mathrm{m}^2\ \mathrm{day}^{-1}$ aquifer after 50 days abstraction at 20 Ml day^{-1}; the drawdowns corresponding to these S_y values being less than 0.1 m, about 1.0 m and in excess of 2.0 m, respectively, and implying contrasting diminutions in flow of springs discharging against heads of say, 0.5—3.0 m.

It is also *essential* that hydrogeological conditions and aquifer properties should be carefully considered before attempting to synthesise or extrapolate drought hydrographs in permeable catchments containing this class of aquifer.

Finally, there arises the question of how typical is the West Beck catchment of other areas of the English chalk. Clearly significant variations are to be expected with changes in relief, discharge regime, geological structure and overlying strata as well as with those in chalk stratigraphy. It is, however, interesting to note that Ineson and Downing (1964), after examining numerous graphs of the logarithm of discharge against time, suggested that "for many British (Chalk) rivers no single linear plot can be constructed". Some of the examples quoted from East Anglia have a comparable form of recession with that of West Beck. Headworth (1972) in a study of the Hampshire Chalk indicated that several log-linear sections are present in some riverflow and groundwater-level recessions in that region also.

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