NRA Project 128

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Groundwater Storage in British Aquifers: Chalk

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FOREWORD

The importance of the Chalk as an aquifer in England is indisputable; however its geographic location and physical properties render it susceptible to over-abstraction and pollution. Up to present, no attempt has been made to estimate the resources of this important aquifer in detail.

This project was initiated with funding from the DoE, in order to undertake such an evaluation and answer some of the pertinent questions regarding the Chalk aquifer. With the establishment of the National Rivers Authority (NRA) in 1989, the project became part of the NRA R&D Programme.

Although the project has not answered some of the initial questions, it provides a body of valuable information and insights into some of the hydrogeological processes operating; it also identifies areas where future work is necessary.

EXECUTIVE SUMMARY

The Chalk is the major aquifer in England, both in terms of areal extent, and of the quantity and quality of water abstracted from it.

This study attempted to provide estimates of the volumes of groundwater in storage between various water levels, and between those levels, and OD. This required the computation of rock volumes, based on extensive geological information; and then the computation of the products of these volumes with storage parameters appropriate to various rock types and water-table positions.

In order to validate the approach, two catchments were studied in some detail. It was found that the volume of water lost from storage between maximum and minimum water levels significantly underestimated the baseflow, which was taken to indicate the total dynamic storage. It was concluded that the most likely explanation of this discrepancy is the slow drainage of water from the unsaturated zone, which could typically represent in excess of 80% of the dynamic storage.

For each hydrometric area of the UK with a significant amount of chalk aquifer, computations were made of the rock volumes and water stored, values for the Chalk and cover being given separately. Notwithstanding the discrepancies in the catchment results, the study showed that:

- The volume of water held in the Chalk aquifer is approximately 5 x 10^9 m^3.
- The volume available in the 10 m interval below drought level was comparable with, and frequently greater than, that stored between maximum and minimum water levels.
- The contribution from storage in the cover varies greatly from one area to another but is often comparable and sometimes greater than the chalk volume.
- Elastic storage is far from negligible when compared with specific yield.

The study revealed the need for further work in order to improve estimates of the storage parameters of the Chalk and, even more importantly, to better understand the role of the unsaturated zone of the Chalk in providing dynamic storage.

KEY WORDS

aquifer, Chalk, groundwater, porosity, specific storage, specific yield, storage coefficient, water resources.

1. INTRODUCTION

1.1 Statement of the Problem

The Chalk is the most important aquifer in Britain; its extent is shown in Figure 1.1. In 1977 it provided 53% of groundwater (Monkhouse and Richards, 1982), and 18% of total water, in England and Wales (Water Authorities Association, 1986). The importance of the Chalk as an aquifer results from its occurrence in the south and east of England where: population density is high, effective precipitation is low, demand for water for industry and agriculture is large, and there is a scarcity of suitable sites for reservoirs.

The hydraulic properties of the Chalk result from the super-position of fracture porosity and permeability on fairly uniform matrix properties. The matrix has high porosity but low permeability, and the fractures contribute an additional low porosity and a very variable component of permeability. This combination means that the properties of the Chalk can vary significantly within a short distance, both laterally and vertically. Typically, the Chalk displays high transmissivities at shallow depths and in valleys and low values at greater depths and beneath interfluves.

The combination of high transmissivity and low storage coefficient results in a rapid response to recharge and abstraction. Beneath valleys the permeability may be much enhanced. Pumping from a well in the Chalk in a valley typically creates a shallow but rapidly expanding cone of depression that quickly interferes with spring flow and baseflow discharge to the river, as well as with other abstraction sources. This interference is amplified by the low storage characteristics of the Chalk.

The high permeability of the saturated zone of the Chalk also makes it vulnerable to the rapid spread of pollutants. Due to slow travel times through the unsaturated zone considerable quantities of pollutants may enter and reside in the this zone for many years. However when they arrive at the water table they may be transported relatively quickly over large distances. The false sense of security created by the slow travel time of pollutants through the unsaturated zone is enhanced by their diffusion into the relatively immobile water within the pore spaces. The history of nitrate pollution in the Chalk is a classic example of the manner in which the aquifer retained and attenuated a pollutant, which subsequently arrived at abstraction wells in relatively large concentrations.

Two questions are therefore pertinent:

- What is the volume of water contained in the Chalk that will ultimately be available either to form baseflow to rivers, streams and springs, or for abstraction from wells, and how does it compare with the annual volumes of recharge into and abstraction from the Chalk?
- What is the total volume of water in the Chalk available to dilute pollutants and how does it compare to the annual recharge?

Approximate answers to these questions can be obtained very simply, and are not reassuring. The total area of the Chalk outcrop in England, including those areas overlain by younger deposits but which nevertheless are believed to receive recharge (Monkhouse and Richards, 1982), is approximately 21,500 km^2. If it is assumed that the average thickness of the Chalk beneath this area is about 200 m a volume for the Chalk of about 4.3 x 10^{12} m^3 is obtained. With

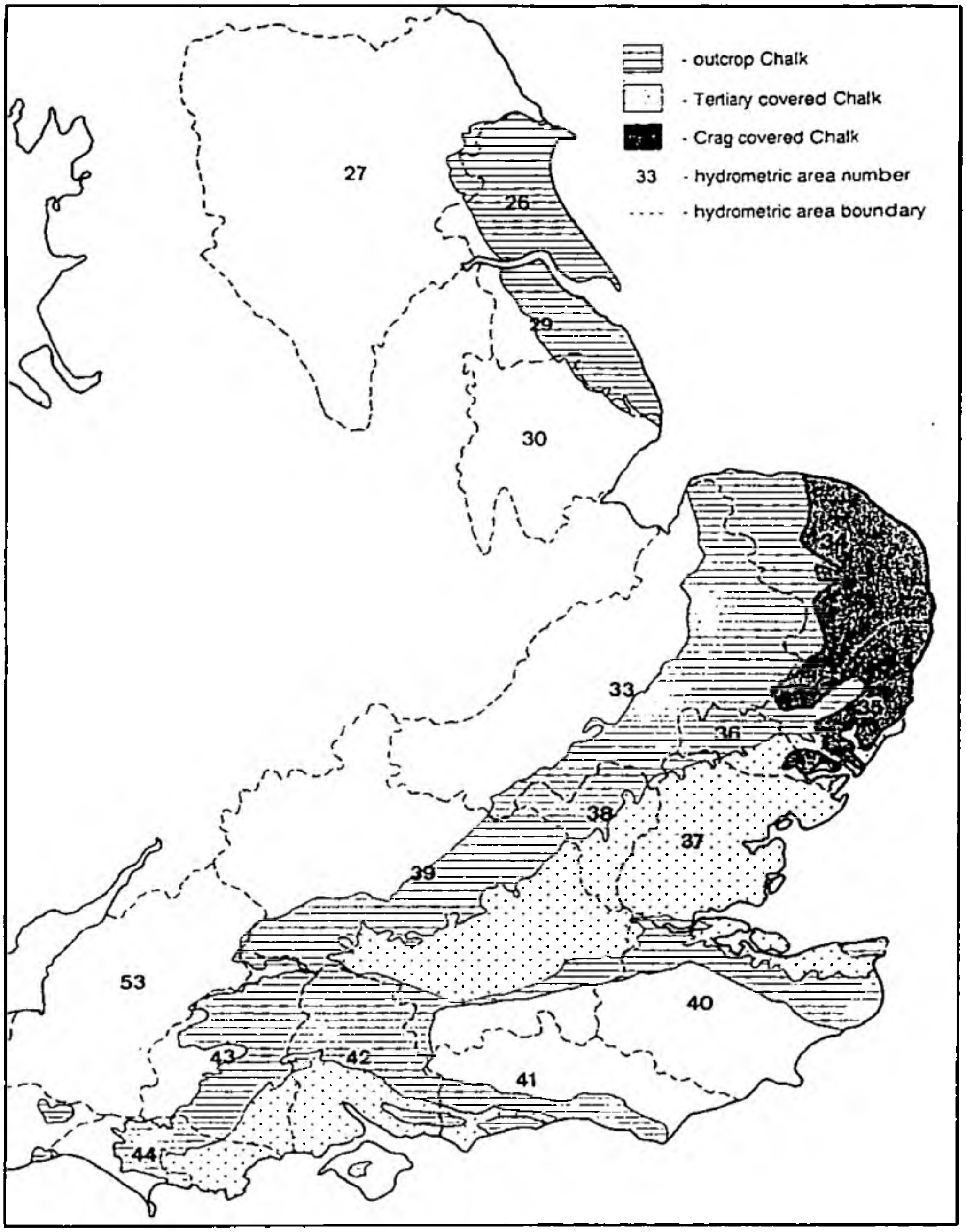


Figure 1.1 The Chalk of England with relevant hydrometric boundaries

an assumed average porosity of 35%, this would give a total chalk pore volume of approximately 1.5 x 10^{12} m^3. This total volume of pore water beneath the Chalk outcrop compares with an average annual infiltration into the Chalk outcrop of about 4.6 x 10^9 m^3 (Monkhouse and Richards, 1982), implying that the total pore volume is the equivalent of about 325 years of recharge. It is important to note that a relatively small amount (about 5 tonnes) of a pollutant such as a pesticide, organic solvent or radioactively contaminated rainfall, if evenly spread over the whole outcrop area would be sufficient to contaminate the whole of one year's recharge into the Chalk, given that the recommended limits for many such pollutants is very low. Similarly, about 1000 to 2000 tonnes of one of these substances would be sufficient to contaminate the entire volume of pore water within the Chalk beneath its outcrop. Thus contaminated, it would take an average of about 300 years for that volume of water to be flushed out by new recharge.

The usable resources of groundwater within the Chalk are of course very much less than the total pore volume. To begin with, the effective aquifer - that part of the aquifer in which groundwater is in active circulation - is typically only about 50 m thick. Further, the specific yield of the Chalk is very much less than the total porosity; most estimates place it at around 2%. With an outcrop area of 21,500 km^2, an effective thickness of 50 m, and a specific yield of 2%, the total available water in storage in the Chalk is about 2 x 10^{10} m^3. This is the equivalent of 4 years average recharge, or of about 17 years average annual abstraction. In practice, this volume may be an overestimate because not all of the upper 50 m of the Chalk saturated zone could be drained without causing a major reduction in, and in some cases the complete cessation of, river flows.

It is against this background that the present study was conceived. The work is timely because during the last 3 to 4 years infiltration into the Chalk has been very much less than average, and water levels in many parts of the aquifer are at or below the lowest values previously recorded.

1.2 Scope of the Study

This project was therefore conceived to improve the estimates outlined in Section 1.1. Volume calculations were carried out on a physical basis using digital cartography.

The objectives of the project were to determine:

- total volume of water in the Chalk
- total drainable volume of water in the Chalk
- volume of water stored in the Chalk between two different potentiometric surfaces.

This necessitated the determination of various parameters required to carry out the calculations, namely:

- volume of chalk (area and thickness)
- porosity
- specific yield and volume likely to drain
- potentiometric surface data for various dates.

It was planned to set up a system which could be used both to calculate outputs quickly and easily and be readily up-dated, by storing all the data in gridded computer files which could be used to produce contours and calculate required thicknesses and volumes with minimal effort. Using this approach, improved estimates of the above volumes could be obtained relatively easily if additional values of Chalk depths and thicknesses, or more reliable values of porosity and specific yield, become available in the future. In practice there were large numbers of unforeseen difficulties with the approach.

In order to validate the method, two catchments were studied in detail. The volume of water flowing out of a catchment between two specific dates was calculated from the streamflow recession curve. This was then compared with the calculated theoretical volume of water lost to the catchment by comparing the water levels at these dates, and used to improve estimates of specific yield. The baseflow data was also be extrapolated to calculate the total volume of water stored in the catchment above the level of the gauge.

2. DEFINING THE STRUCTURE OF THE CHALK

2.1 Chalk Stratigraphy

Towards the end of Lower Cretaceous times a major eustatic rise in sea level resulted in a global transgression that progressively covered a large part of Europe. As sea level rose, the shrinking land masses supplied decreasing amounts of terrigenous material, and the calcareous deposits which became the Chalk were formed (Kent, 1980). They were deposited under normal marine salinities at depths of between 100 and 600 m (Rawson, 1992).

In general, the Chalk is a very fine-grained (less than 10 μm), extremely pure (more than 98% $CaCO_3$), relatively soft, white limestone with some marls and flints. It is formed predominantly from the detritus of calcareous algae mainly in the form of plate-like crystals, but sometimes as coccoliths or whole coccospheres. The coarser fraction (10-100 μm) includes foraminifers, ostracods, calcispheres, bryozoans, echinoid plates and bivalve fragments. It contains thin marl interbeds up to several centimetres in thickness which appear to be laterally continuous for several hundred kilometres. Some lie on erosion surfaces, others may represent altered ash as they contain Mg-rich smectite (Pacey, 1984). The flint occurs predominantly in layers parallel to the bedding either as continuous sheets or as small, scattered discrete nodules.

The Chalk Group was deposited in two lithological and faunal provinces, northern and southern, with an intermediate area across East Anglia. To clarify definitions, for the purpose of this report, the whole of East Anglia has been allocated to the southern province; Yorkshire and the area north of the Humber as allocated the 'Yorkshire' Chalk; and Lincolnshire and the area south of the Humber is allocated the 'Lincolnshire' Chalk. The northern province chalks are generally harder than their southern equivalents, due to two phases of calcite cementation, and show strong faunal links with north Germany. Those in the southern province are associated with the Paris Basin (Rawson, 1992). Typical thicknesses of Chalk sub-divisions are given in Table 2.1.

The Chalk Group of the northern province was divided into four formations in Yorkshire and Humberside by Wood and Smith (1978); these can be traced southwards through Lincolnshire into north Norfolk. The basal Ferriby Chalk Formation is about 25 m thick and defined as a slightly marly, whitish chalk with finely disseminated iron, containing no flints. The overlying Welton

Table 2.1 Typical thickness of Chalk subdivisions across England, (after Rawson et al., 1978).

	Upper Chalk	Middle Chalk	Lower Chalk
Dorset	up to 260 m	26-41 m	22-57 m
Hampshire	up to 400 m	43 m	up to 100 m
Sussex	up to 230 m	65-90 m	approx 60 m
Kent	up to 130 m	60-80 m	60-80 m
Chilterns	up to 125 m	58-76 m	50-60 m
North Norfolk	approx 320 m	46 m	18-41 m
Yorkshire	up to 300 m	approx 112 m	23-40 m

Chalk Formation consists primarily of thick-bedded massive chalks with flint nodules of the burrow-infill type; these are absent from the basal few metres. The base of the formation is defined by a pebble-strewn erosion surface (just beneath the Black Band, a distinctive marker band of variegated, occasionally laminated marls). The Burnham Chalk formation is thinly-bedded with layers of laminate chalk, and a distinctive series of tabular and semi-tabular flint bands in the lower part. The uppermost Flamborough Chalk Formation consists of over 300 m of well-bedded flintless chalk, with stylolitic surfaces and marl bands and partings (Rawson, 1992).

The southern province successions differ from those of the north; the chalk is generally softer, hardgrounds more common, and continuous tabular flints rare (Rawson, 1992). However, some marls form distinctive lithological marker bands which extend from Yorkshire to the Dorset and Sussex coasts and aid correlation between the two provinces. Although chalk remains the predominant lithofacies in the southern province, marginal sands and sandy limestones occur close to the Cornubian massif of south-west England. Hardgrounds and hard nodular chalks occur in the condensed shallower-water facies exposed along the western outcrop from the Berkshire-Chilterns Shelf to Dorset, while the rapidly subsiding Sussex Trough in south-east England accumulated over 400 m of predominantly soft chalk (Rawson, 1992).

The southern province was originally subdivided into Lower, Middle and Upper Chalk on the basis of rock bands (which were not always correctly identified) and fossils. Recently a more formal lithostratigraphic subdivision has been proposed (Mortimore, 1983; Robinson, 1986; Rawson, 1992) for Sussex and Kent using distinctive marl and flint bands for correlation (Figures 2.1 and 2.2). As this has not yet been finally correlated over the whole province, the original subdivisions have been used throughout this report.

The 'Lower Chalk' is virtually devoid of flints, the base in most areas being represented by up to 5 m of marly, glauconitic Chalk with phosphatic nodules (Glauconitic Marl). This generally has an erosive base, but locally there is a transition from the underlying Gault or Upper Greensand formations. From Hertfordshire to East Anglia, the Cambridge Greensand, a silty glauconitic marl containing a variety of pebbles and boulders, occupies a similar stratigraphic position. Above the basal beds, the bulk of the 'Lower Chalk' is marly, the marl content decreasing upwards. It has been subdivided into two units, the Chalk Marl (rhythmic alterations of marl and chalk) and the overlying, more massive, Grey Chalk. From East Anglia to the Berkshire-Chilterns shelf, they are separated by a well-marked, hard chalk with scattered phosphatic pebbles, known as the Totternhoe Stone. However this disappears towards the deeper-water areas of south-east England and cannot therefore be used as a mappable boundary between the Chalk Marl and Grey Chalk; their definition is therefore inconsistent. The highest unit of the 'Lower Chalk' is a thin sequence of alternating marls and chalks known as the Plenus Marls. These vary in thickness from 0.75 to 8.5 m, have an erosive base, and form a distinctive lithological and geophysical marker band.

The Plenus Marl Formation is overlain by the 'Middle' and 'Upper' Chalks, which are broadly similar over most of the province, consisting of flintless chalks, overlain in turn by nodular chalks with flints and smoother chalks with numerous flint bands. The lowest division is the Ranscombe Member, a flintless Chalk corresponding with all but the highest part of the former Middle Chalk. At its base is the Melbourn Rock (nodular marls and incipient hardgrounds) overlain by nodular chalks with marls which pass upwards into smoother, sometimes softer, chalks. Flints appear around the base of the overlying Lewes Member, typified by rhythmic units

NORTHERN PROVINCE		STAGE	SOUTHERN PROVINCE			
LITHOLOGICAL UNIT	ZONE		ZONE	LITHOLOGICAL UNIT		
		MAASTRICHTIAN		Sussex White Chalk Formation		Upper & Middle
Flamborough Chalk Formation 300+m	higher zones beneath drift	CAMPANIAN	*mucronata* [a]		Portsdown Member 30m	
			quadrata [a]		Culver Member 115+	
	lingua [b]		*pilula* [d]		Newhaven Member 75m	
	testudinarius [e]	SANTONIAN	*testudinarius* [e]			
	socialis [e]		*socialis* [e]			
Burnham Chalk Formation 150m	*rostrata* [d]		*coranguinum* [d]		Seaford Member 90m	
	cortestudinarium [d]	CONIACIAN	*cortestudinarium* [d]		Lewes Member 90m	
	planus [d]	TURONIAN	*planus* [d]			
Welton Chalk Formation 53m	*lata* [f]		*lata* [f]		Ranscombe Member 85m	
	labiatus [b]		*labiatus* [b]			
	geslinianum [c]	UPPER CENOMANIAN	*geslinianum* [c]	Plenus Marls Formation		Lower
Ferriby Chalk Formation 28m	*trecensis* [d]		*naviculare* [c]	Abbotts Cliff Chalk Formation 22m		
	subglobosus [d]	MIDDLE CENOMANIAN	*rhotomagense* [c]	East Wear Bay Formation 58m		
		LOWER CENOMANIAN	*mantelli* [c]			

Notes: a. All correlations are provisional because of uncertainties in the biostratigraphic scales.
b. The *geslinianum* Zone and the position of the Cenomanian/Turonian boundary are after Wright & Kennedy (1981).
c. The letters a–f against zonal indices indicate: a = belemnite; b = bivalve; c = ammonite; d = echinoid; e = crinoid; f = brachiopod.

Figure 2.1 Subdivisions and correlation of the Upper Cretaceous Chalk Group (after Rawson, 1992)

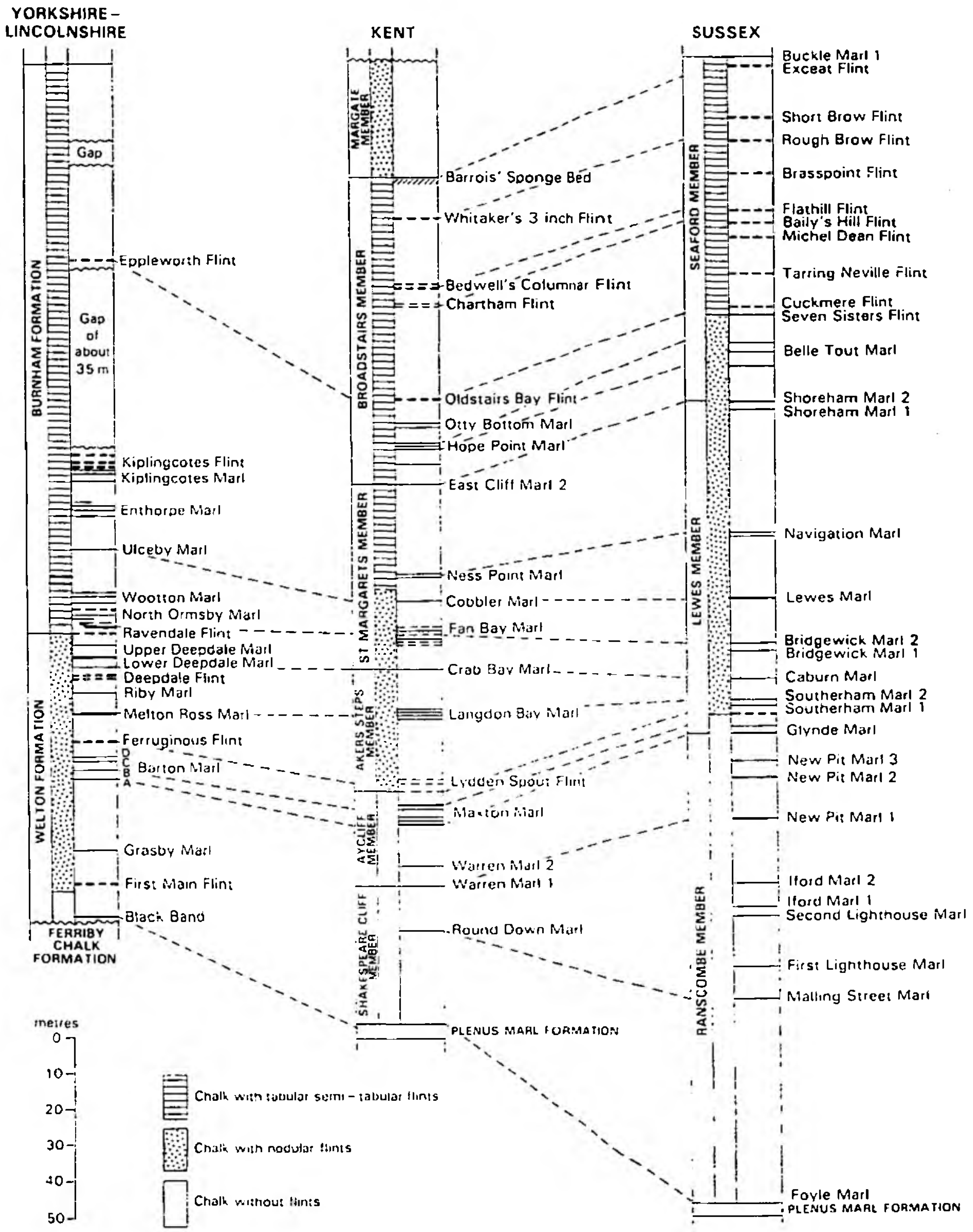


Figure 2.2 Correlation of marker bands in the Turonian and Lower Coniacian chalks of the northern and southern provinces (from Rawson, 1992)

of soft chalk passing up into nodular Chalk, and terminating with a hardground and, in places, an overlying marl band. The remaining four members (Seaford, Newhaven, Culver and Portsdown members) are predominantly soft white chalks with numerous flint bands. They are distinguished by the presence or absence of marl bands. The Seaford Member has only a few, weak marl seams, while the overlying Newhaven Member has numerous seams, with some nodular chalks.

2.2 Base of Lower Chalk

The base of the Lower Chalk in the northern province coincides with the base of the Upper Cretaceous Series and the base of the Cenomanian Stage. This is easily identified by the characteristic geophysical log signature of the Red Chalk. The definition differs from that of Wood and Smith (1978) who include the Red Chalk in the Ferriby Chalk Formation (Evans et al., 1990). The 'base of Chalk' surface used therefore shows the position of the base of the Lower Chalk (top of Red Chalk) and not the base of the Ferriby Chalk Formation. They are based on those shown on the hydrogeological maps of Lincolnshire and East Yorkshire (Institute of Geological Sciences, 1967; 1980).

In East Anglia the distinctive basement bed, the Cambridge Greensand, also has a distinctive geophysical log signature. Further south, the base of the Chalk is represented by a basal glauconitic siltstone; this hard band gives rise to a prominent gamma ray peak and an associated sonic peak (Evans and Penn, 1990). Thus the base of the Lower Chalk can be accurately located in borehole logs over the whole country.

2.3 Base of Middle Chalk

In Yorkshire and Lincolnshire, the boundary between the top of the Lower Chalk and the base of the Middle Chalk is at the top of the Black Band; this is approximately equivalent to the Plenus Marl beneath the Melbourn Rock in the southern province. The boundary between the Ferriby Chalk Formation and the Welton Chalk Formation, however, lies just below the base of the Black Band. Over the entire area, this discrepancy equivalent to the thickness of the Black Band, is no more than a few metres. As with the base of the Lower Chalk, characteristic gamma-ray and sonic responses and resistivity logs are associated with the base of the Middle Chalk, i.e. top of the Black Band (Figure 2.3).

Further south, the Melbourn Rock which marks the base of the Middle Chalk, gives rise to high sonic velocities and low gamma-ray values when compared with the gamma-ray peak and low sonic velocity of the subjacent Plenus Marls at the top of the Lower Chalk (Evans and Penn, 1990). The marly nature of the Lower Chalk compared with the overlying Middle Chalk, gives rise to overall higher gamma-ray values, which decrease upwards (Figure 2.4).

2.4 Tectonic history of the Chalk

Alpine tectonism in the Oligocene-Miocene affected all early Palaeogene and older formations, (including the Chalk), to varying extent. South of a line extending from the Mendips to the Thames Estuary compressional movement deformed the rocks into monoclines and periclinal folds. North of this line, the rocks are flexed, domed, tilted and fractured by movements which are probably of mid- or end-Cretaceous rather than Alpine age. As a result, the Chalk generally

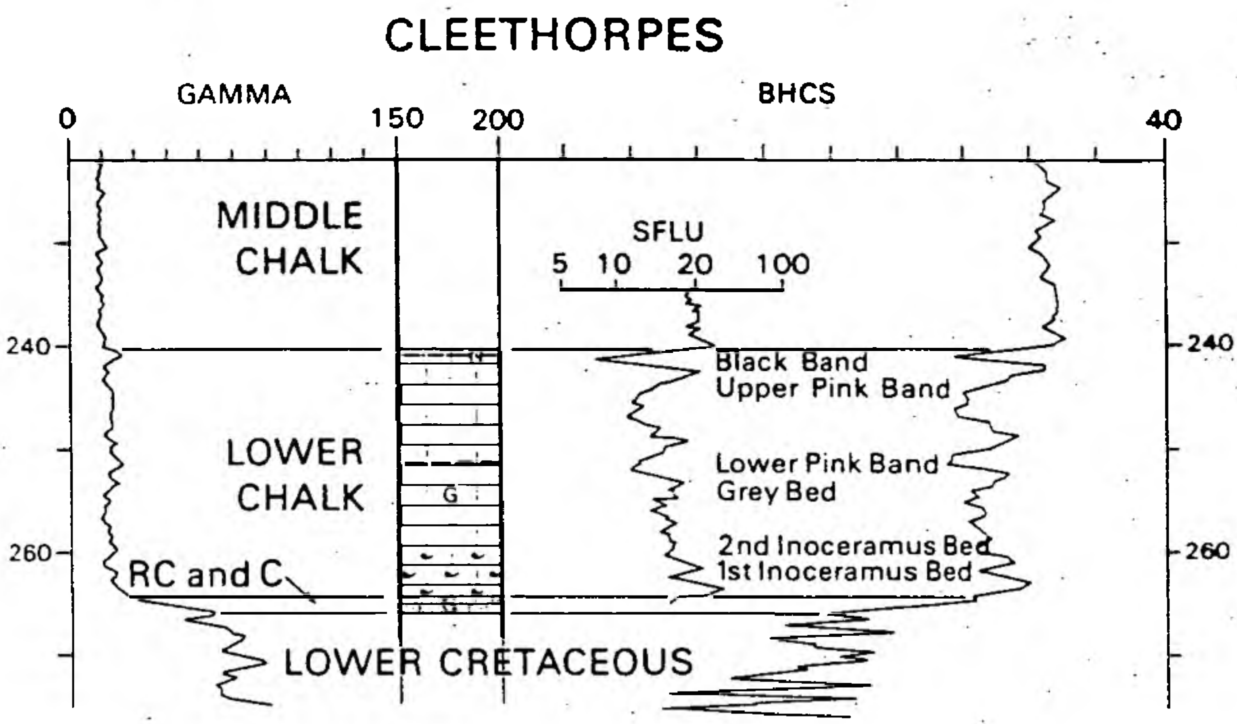


Figure 2.3 Log signatures from the base of the Lower and Middle Chalk in the northern province (after Whittaker et al., 1985)

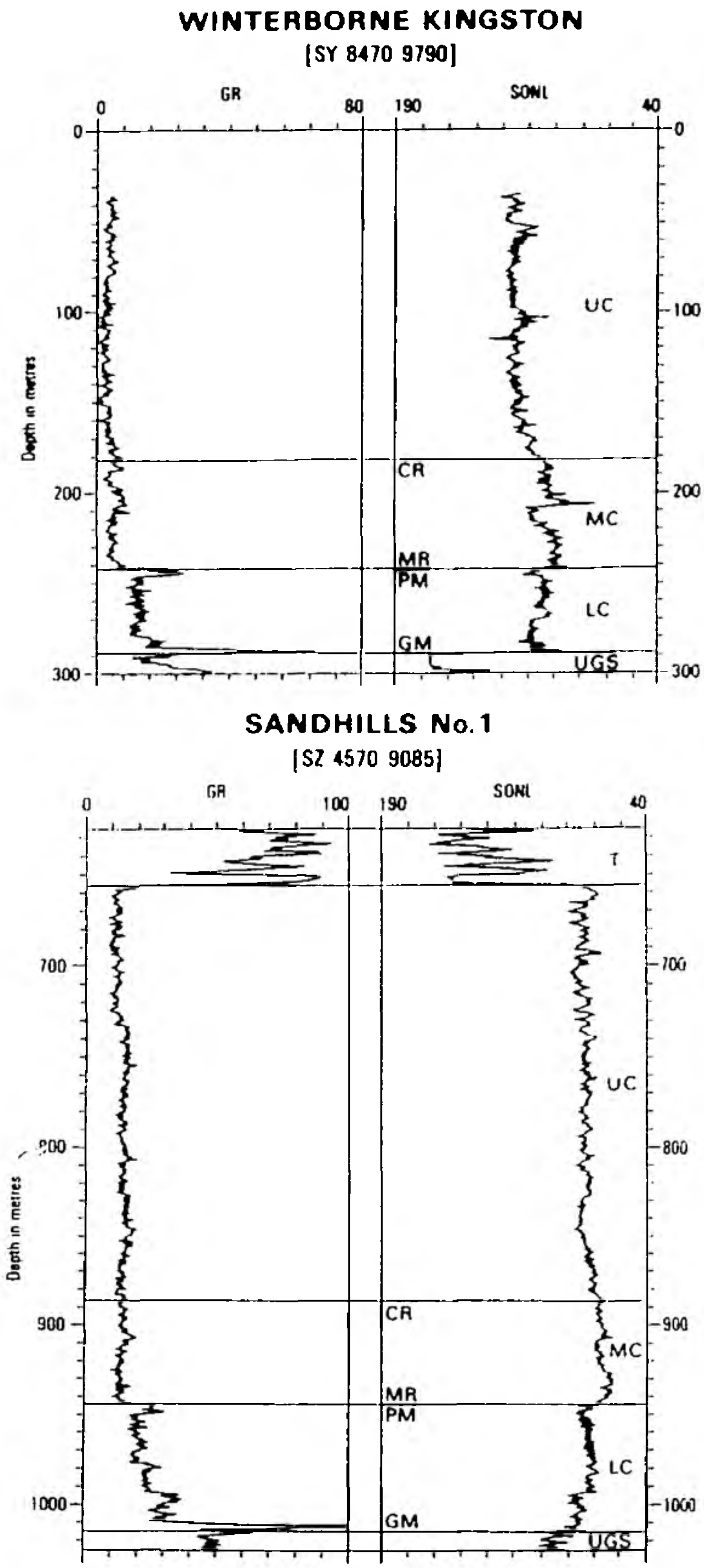


Figure 2.4 Log signatures from the base of the Tertiary, Upper, Middle, and Lower Chalk in the southern province (based on Whittaker et al., 1985)

dips east or south-eastwards north of the Thames.

Tectonic movement was responsible for the development of the basic fissure system in the Chalk, though some very fine fractures are associated with stylolites (Foster and Milton, 1974; Price et al., in press). Generally there are three sets of fissures, one set being parallel to the bedding and the other two approximately perpendicular to both this set and to each other.

3. PREVIOUS WORK

This section introduces various hydrogeological concepts, and reviews previous work that has investigated the properties of the Chalk aquifer.

3.1 Hydrogeological Parameters

Relevant hydrogeological parameters are defined in the following section.

3.1.1 Hydraulic Conductivity, Intrinsic Permeability, and Transmissivity

Hydraulic conductivity, K [LT^{-1}], is defined as the quantity of water that will flow through a unit area of rock in unit time, under unit hydraulic gradient, measured perpendicular to the direction of flow. Transmissivity, T [L^2T^{-1}], is the product of the average hydraulic conductivity and the saturated thickness of the aquifer.

Intrinsic permeability, k [L^2], represents the capacity of a rock to transmit water, and is independent of fluid properties. It is related to K by:

$$k = K\mu / \rho g \tag{1}$$

where μ is the dynamic viscosity, ρ is the density of the contained water, and g is the acceleration due to gravity.

3.1.2 Specific Storage and Storage Coefficient

The volume of water released from elastic storage in a unit volume of aquifer in response to a unit decline in head is termed the specific storage, S_s [L^{-1}]. Specific storage can be expressed in terms of the properties of the water and rock matrix by the equation:

$$S_s = \rho g \alpha + \rho g n \beta \tag{2}$$

where n is the effective porosity, α is the compressibility of the rock, and β the compressibility of the water. The first term on the right hand side of the equation represents the water released from elastic storage by compaction of the aquifer framework: the second term represents the water released as a result of the expansion of the water itself.

In the case of a fractured aquifer, the equation can be expanded to:

$$S_s = \rho g\ (\alpha_f + \alpha_m + n_f\beta + n_m\beta) \tag{3}$$

where α_f represents the compressibility of the aquifer framework resulting from the presence of discontinuities, α_m represents the compressibility of the unfractured matrix, n_f is the porosity contributed by discontinuities, and n_m is the matrix porosity.

The storage coefficient of a confined aquifer, S, [dimensionless] is the volume of water an aquifer releases from storage per unit surface area of the aquifer per unit change in groundwater head. Specific storage is related to the storage coefficient, by the expression:

$$S = S_s b \qquad (4)$$

where b is the aquifer thickness.

3.1.3 Specific Yield

The specific yield, S_y [dimensionless], of an unconfined aquifer is the volume of water released from storage per unit surface area of the aquifer for a unit decline in the water table.

The term storage coefficient, when applied to an unconfined aquifer, includes both elastic storage and specific yield.

Under unconfined conditions, the majority of water drains from the aquifer by gravity, and the amount of water released from elastic storage is generally negligible. Hence in an unconfined chalk aquifer the specific yield is virtually equal to the storage coefficient. In this report, the term specific yield will be used when referring specifically to unconfined aquifers.

3.1.4 Porosity

Porosity, n [dimensionless], can be defined in different ways:

- absolute (total) porosity, is the ratio of total pore volume to bulk volume
- interconnected (sometimes referred to as 'effective') porosity is the proportion of the bulk volume occupied by interconnected pore space.

The term 'porosity' used in the context of this report refers to the interconnected porosity.

3.2 Chalk Hydraulics

The Chalk is frequently described as a dual-porosity aquifer, in which the matrix pores provide the bulk of the porosity, and the fissures provide permeable pathways. In reality, the hydraulics of the Chalk aquifer is more complicated than this. It is widely accepted that aquifer properties vary vertically, laterally, and with stratigraphic age. The following sections outline the factors that control the transport and storage of water in the Chalk, and the ways in which storage coefficient, porosity, and hydraulic conductivity may vary throughout the aquifer.

The depositional, diagenetic and tectonic history of the Chalk have created an unusual dual-porosity reservoir rock. The shape and composition of the coccolith particles that make up much of the matrix give rise to high porosities, typically in the range 20 to 45 per cent. The small size of the pores and interconnecting pore-throats results in a low matrix permeability, typically between 0.1 to 10 mD, corresponding to a hydraulic conductivity of around 10^{-4} to 10^{-2} m d^{-1}. Consequently the hydraulic conductivity of the matrix makes little or no contribution to the transmissivity of the aquifer (Alexander, 1981; Wellings, 1984). The small pore size also means that the majority of stored water is held in the pores by capillary and molecular forces, and very little can move under the influence of gravity (Price et al., 1976).

Fissures account for much of the groundwater movement in the saturated Chalk. The fissures, even when apparently closed, may increase the hydraulic conductivity of the rock mass by an order of magnitude (Price et al., 1977). At shallow depths, a combination of factors can lead to their enlargement, either individually or in layers or zones. It is this enlargement that is responsible for the majority of the high transmissivity that is typical of the Chalk; the spacing, opening and orientation of fissures exerting a major control on aquifer characteristics.

There is some confusion about the use of the words 'fissure' and 'fracture' when describing discontinuities in the Chalk. In general, fractures are considered to be tectonic discontinuities, that is, joints or fault planes. For the purpose of this report, unless referring to a specific example, the word 'fissure' will be used.

In order to distinguish their origin, Price (1987) described undeveloped, closed discontinuities as primary fissures, and the more open ones as secondary fissures. Other workers (e.g. Reeves, 1979) have instead taken a purely descriptive approach, using the terms microfissures and macrofissures, dependent on fissure opening, frequency and spacing. Whichever nomenclature is adopted, it should be understood that there is probably a continuous range from tight fissures to greatly enlarged, even karstic, openings. In at least some localities, evidence points towards the concentration of secondary fissures at a few discrete horizons (see Section 3.4).

The propagation of changes in hydraulic head in an aquifer is governed by the hydraulic diffusivity, the ratio of transmissivity to storage. The diffusivity for the fissures is much greater than that for the matrix, therefore the fissures respond much faster to pressure changes. Under pumping stress, this leads to a pressure differential between the fissures and matrix, which causes water to move from the matrix into the fissures.

Similar values of storage and hydraulic conductivity may be derived from an infinite number of combinations of matrix properties, and primary and secondary fissures. Foster and Crease (1974) suggested that the combination of hydraulic properties at Etton in Yorkshire ($K = 150\text{-}200\ m\ d^{-1}$, $S_y = 0.005\text{-}0.01$) could be generated by a single set of high density fissures (approximately 10 per metre) with effective openings of 0.5-1 mm. Alternatively four or five larger conduits of approximately 2 mm opening could be contributing the bulk of the hydraulic conductivity, although not all of the storage. Reeves (1979) stated that a unique solution could only be found if the gravity drainage characteristics were also known.

The derived values of storage coefficient are a composite of the contributions from matrix, primary and secondary fissures. The contribution to storage from the matrix will vary according to the diameter of the pores and pore throats. It is generally accepted that gravity drainage does not occur at pore-water suctions greater than 5 m of water. Thus, pores with a diameter of less than 10 μm will not drain under gravity (Price et al., 1976) and so cannot contribute to specific yield. Pore size distribution curves given by Price et al. (1976) for the Upper Chalk suggested that, on this basis, less than 3% of the Chalk pore space i.e. approximately 1% of bulk volume represents useful storage (Figure 3.1). The Lower Chalk, and that from the Northern Province tend to have lower porosity than southern and younger Chalk, due at least in part to smaller pore diameters (Price et al., 1976). Foster and Milton (1976) suggested that the water released from the matrix of Yorkshire Chalk under gravity was of minor importance, and that additional storage was provided by the high density system of inclined microfissures.

The storage values derived from pore size distribution curves should be used cautiously. Examination of the curve (Figure 3.1) indicates that the method is very insensitive to determining the percentage of pores greater than 1 μm diameter. Thus the figure of approximately 3% of pores with diameters greater than 10 μm should be considered as an absolute maximum; in reality the figure could be very much lower. In addition, there may be some contribution to

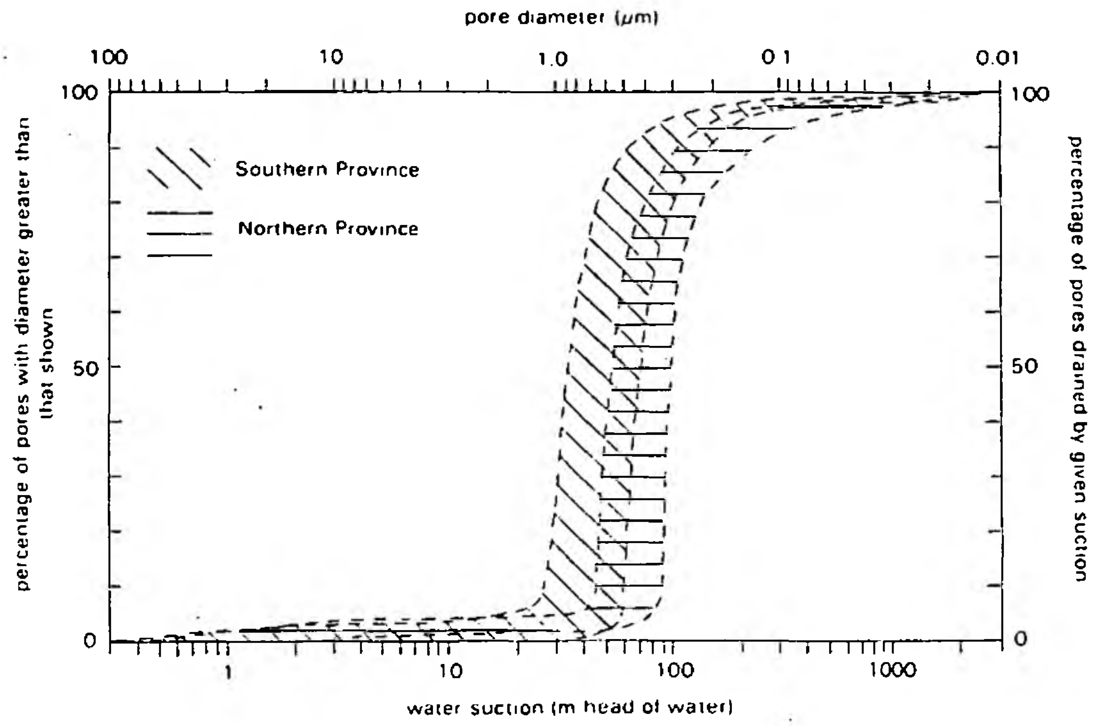


Figure 3.1 Pore size distribution curves for the Upper Chalk (after Price et al., 1976)

drainage from primary fissures. As 'microfissure' spacing has been stated to between 0.5 and 3 mm (Reeves, 1979), and the maximum sample size used in these analyses was approximately 5 mm, the contribution from primary fissures is likely to be minimal.

The relative contribution to specific yield from the matrix, primary, and secondary fissures has not been quantified, although it will depend on the relationship between the pores and fissures. The contribution from primary and secondary fissures will in turn be dependant on their frequency and openness. Reeves (1979), basing his work on data provided by Snow (1968), suggested that storage is largely provided by the secondary fissures, and that the low laboratory values of permeability and specific yield arise from the fact that they are only including the contribution from primary fissures. It should be noted that the interstitial component of specific yield will be more evenly distributed throughout the aquifer, and hence available at all groundwater stages, than the fissure storage, which will tend to be concentrated at specific levels (Price et al., 1976). It would appear that fissures, both primary and secondary, account for much of the specific yield, the contribution from the matrix frequently being less than 1% (Table 3.1).

Although elastic storage is generally insignificant when compared to gravity drainage, the volume released may become relatively important as specific yield decreases with depth. Price (1987) suggested that most of the water released from elastic storage in confined Chalk is derived from compression of the fissures, with expansion of water in the matrix pore space also playing a significant role. Table 3.2 shows his calculations for a site in the Middle Chalk of Norfolk:

The low specific yield of the Chalk may lead to large seasonal water table fluctuations (20 to 30 m) in areas remote from discharge zones. If the effective aquifer is only 50 to 60 m thick, this has a significant bearing on the available water reserves. Downing et al. (1981) showed that in the Upper Thames Valley, the volume of water remaining in storage in the Chalk under drought conditions was approximately equal to the average annual recharge.

3.3 Development of the Chalk Aquifer

Although it is the geological setting that determines the existence of the primary fissures, it is the solution potential of meteoric water that determines their development.

On average only the upper 50 m or so of unconfined, saturated Chalk functions as an effective aquifer because of the lack of open fissures below this depth (Woodland, 1946; Price, 1987; Rushton et al., 1989). This is probably about the same thickness that contributes to useful storage (Price, 1990).

Table 3.1 Suggested contribution to specific yield from matrix and fissures

	Average porosity (%)	Maximum percentage of porosity contributing to Sy (from PSD curves)	Inferred Matrix Sy	Observed Sy	Fissure Sy
Upper Chalk	35	3%	10^{-2}	0.20 - 7 x 10^{-2}	0 - 6.0 x 10^{-2}
Middle Chalk	30	2%	0.6 x 10^{-2}	0.01 - 3 x 10^{-2}	0 - 2.4 x 10^{-2}
Lower Chalk	25	2%	0.5 x 10^{-2}	0.01 - 1 x 10^{-2}	0 - 0.5 x 10^{-2}

Table 3.2 Compressibility characteristics of the Middle Chalk, Norfolk (from Price, 1987)

	Porosity	Compressibility of rock (m^{-1})	Compressibility of water (m^{-1})
Matrix	0.29	7.9 x 10^{-7}	1.4 x 10^{-6}
Fissures	0.01	4.9 x 10^{-6}	4.8 x 10^{-8}

3.3.1 Geological Setting

The geological and tectonic history of an area controls not only the properties of the rock matrix, but also the spacing, orientation and tightness of the primary fissures. Work by Carter and Mallard (1974) indicated that the strength and compressibility characteristics of chalk outcrop samples could be related to stratigraphic horizon, with the Upper Chalk tending to exhibit a higher void ratio (and hence porosity), and lower strength and compressibility than lower horizons. Foster and Milton (1976) also demonstrated different ranges of porosity for outcrop samples of Upper and Middle Chalk from Humberside. Edmunds et al. (1973) indicated that porosity tended to reduce with depth, although they could not determine whether this was because of sedimentological differences or diagenetic changes.

Porosity tends to decrease with age, and to the north. Bell et al.(1990) explained the reduced values for the Yorkshire Chalk and the Lower Chalk by diagenesis, in particular pressure solution and reprecipitation of calcium carbonate. As a result of this, up to 50% of the voids in the Yorkshire Chalk may be filled with cement. This contrasts with the Upper Chalk of south-east England, where cement is only usually present at grain contacts. Price et al. (1976) suggested instead that the decrease in porosity was related to decreasing pore size distribution.

The primary fissure characteristics are controlled partly by the matrix properties, and also by the tectonic history of the rock. It has long been observed that high hydraulic conductivity of the Chalk is frequently associated with tensional structural features such as domes and anticlines, these causing radial fracturing of the rock and a high number of primary fissures (Woodland, 1946; Ineson, 1962). However, this is not always the case; examination of borehole records for the Candover Groundwater Scheme (Southern Water Authority, 1979) indicated lower yields and hydraulic conductivities along anticlinal axes, than along synclinal axes. The explanation in this case could perhaps be attributed to the fact that synclines are more likely to be associated with river valleys, where fissures would be expected to be developed by groundwater solution.

Throughout the Chalk sequence, hard, well-cemented bands have developed. Pumping test results from Thames Water indicate that these hard grounds, (e.g. the Chalk Rock, Melbourn Rock, and Totternhoe Stone), have consistently good yields, even when buried at depth. This is thought to be due to the nature of the rock: although the bands usually have low porosity and storage, their hardness and good cementation render them susceptible to fracturing, therefore providing a thin but highly transmissive zone.

The presence of drift and Tertiary cover may strongly affect hydrogeological conditions in the Chalk in some areas, because of the way in which it controls flow to and from the aquifer. Boulder clay, where present, may confine the Chalk and restrict ground water movement to valley areas (Lloyd and Hiscock, 1990). However, its hydrogeological behaviour has not been unequivocally established. Lloyd et al. (1981) estimated values of permeability for the boulder clay of 10^{-4} to 10^{-6} m d^{-1}, although locally along the margins of this cover, sand and gravel lenses may allow significant recharge (Lloyd and Hiscock, 1990, Spink, personal communication). Bonell (1972) suggested values of 10^{-2} m d^{-1}, the higher values being due to weathering and the presence of patches of sand and gravel. Similarly, work on the Yorkshire Chalk (Yorkshire Water Authority, 1985) suggested that weathered till and gravel lenses along the flanks of the Yorkshire Wolds could allow significant recharge to occur.

The concentration of acidic runoff at the edge of the Tertiary cover may have promoted the development of fissures (Price et al., *in press*). Such runoff is thought to have been a significant factor in the creation of rapid flow systems such as at Bedhampton in Hampshire (Atkinson and Smith, 1974) and in Hertfordshire (Water Resources Board, 1972).

3.3.2 Glacial History

The glacial history of an area affects the aquifer properties in a number of ways. Locally fissures were enlarged by solution from groundwaters moving beneath glaciers and permafrost (Lloyd and Hiscock, 1990). In the Middle Thames Valley, permafrost is thought to have restricted much of the groundwater movement to the talik (unfrozen) areas beneath major river channels, with flow being concentrated under these channels (Younger, 1989). Permafrost under smaller channels and interfluve areas would have prevented groundwater circulation for much of the year.

In periglacial areas, regular alternations between freezing and thawing of interstitial water during the Pleistocene caused near-surface weathering and fracturing of the Chalk (Hancock and Price, 1990). While the persistence of this type of weathering is frequently restricted to depths of 5-6 metres, some opening of pre-existing joints and bedding planes to depths of up to 20 to 30 m has been suggested (Higginbottom and Fookes, 1970; Williams 1987). In the Middle Thames Valley this freeze-thaw action produced a horizon of low permeability, 'putty chalk' at the surface (Younger, 1989). The putty chalk locally confines the Chalk, preventing hydraulic continuity between it and the overlying gravels. As a result, in this area, fissure development was limited and borehole yields are disappointing. Younger also suggested that the lack of association between river valleys and high hydraulic conductivity in Humberside is the result of this area being overlain by glaciers during the Quaternary.

The formation of tunnel valleys at the time of glaciation may also affect the present day groundwater flow, with either high hydraulic conductivity zones because of in-filling with sands and gravels, or local flow boundaries caused by in-filling with clays (Woodland, 1946; Foster and Robertson, 1977; Lloyd and Hiscock, 1990).

3.3.3 Solution Potential of Groundwater

Two factors strongly affect the enlargement of primary fissures:

- The solution potential of meteoric water. The development of secondary fissures is due to solution by water containing carbon dioxide (Woodland, 1946; Price, 1987). It has been suggested (Connorton, 1976) that the partial pressure of carbon dioxide in chalk groundwater decreases as the water moves through the unsaturated zone. Therefore, where the unsaturated zone is thick, the water is less able to dissolve carbonate at the water table, and fewer fissures are developed. Even so, water containing carbon dioxide in solution does reach the saturated zone at depth, particularly at times of the year when rapid infiltration occurs through the unsaturated zone (Pitman, 1978).
- The flux of groundwater through any particular volume of aquifer (Rhoades and Sinacori, 1941; Reeves, 1979; Price, 1987). This is in turn controlled by the influence of overlying deposits, the hydraulic gradient, and the proximity to the topographic watershed.

The above factors affect the development of the Chalk as an aquifer, both vertically and laterally. However, due to variations in lithology, hardness and the tectonic history of the rock mass, the

Chalk would not have been perfectly homogeneous and isotropic initially. Some of the primary fissures would have been more open and permeable than others with solution being concentrated along these at the expense of the less permeable openings (LeGrand and Stringfield, 1971; Price et al., 1987).

3.4 Variation of Storage Coefficient and Transmissivity

The way in which the Chalk has developed as an aquifer implies that storage coefficient and transmissivity will vary, both laterally and with depth. Any attempt to determine storage coefficient and transmissivity will be affected by both components.

3.4.1 Variation with depth to the saturated zone

Previous work has indicated that aquifer properties decrease significantly with decreasing groundwater head (Foster and Milton, 1974; Rushton and Chan, 1976b; Connorton and Reed, 1978; Owen and Robinson, 1978; Southern Water Authority, 1979; Headworth et al., 1982; Rushton et al., 1989). As high storage and transmissivity generally coincide with zones of fissure development, the identification of such horizons would help to understand the variation of these properties with depth.

Work has been carried out using borehole logging and injection techniques to identify major contributing fissures (Tate et al., 1970; Headworth, 1972a; Foster and Milton, 1974; Foster and Robertson, 1977; Price et al., 1977; 1982; Connorton and Reed, 1978; Owen and Robinson, 1978; Southern Water Authority, 1979). This has produced evidence that active fissures tend to be concentrated at particular levels, with much of the saturated thickness of the Chalk having low total hydraulic conductivity. For example, Foster and Milton (1976) identified two horizons of increased hydraulic conductivity at a site in Humberside; one, in the zone of water table fluctuation was approximately 7 m thick. A lesser contributing horizon, 8 m thick, was located 35 m below the first. On the basis of injection test results at a site in Hampshire, Price et al. (1977; 1982) concluded that more than 99% of the transmissivity was contributed by a total of 12 m (17%) of the saturated thickness, although primary fissures were present throughout the thickness of the aquifer.

Although large fissures are present at great depths, they may not be in hydraulic continuity with the effective aquifer. For example, logging as part of the Candover Pilot Scheme (Southern Water Authority, 1979) suggested that fissures were present to a depth of 88 m below ground level, although the majority of inflow occurred at depths less than 46 m. Borehole logging by Thames NRA has indicated major contributing fissures at depths of up to 110 m below ground level, although the majority were at less than 50 m depth. Non-contributing fissures were identified at depths of up to 170 m.

Although flow logging has greatly enhanced understanding of the vertical development of the Chalk, it has been suggested (Headworth, 1972b; Rushton and Chan, 1976b; Rushton, Pers. Comm) that the results of geophysical logging and packer testing to identify 'active' fissures be used with caution. Although they indicate fissure development in the locality of the borehole, this may be strongly affected by pumping and the development of the borehole and consequently results may not be applicable at any distance. Rushton and Chan (1976b) illustrated this point when attempting to model drawdown and recovery using a vertical distribution of hydraulic conductivity and storage based on the results of geophysical logging. They failed to relate the vertical variation of aquifer properties to fissure distribution, and eventually attained a good fit between actual and predicted drawdown by assuming a highly permeable zone between 5 and 15 m below ground surface.

As part of the Thames Groundwater Scheme, Connorton and Reed (1978) plotted the number of fissures per one metre interval against depth below ground level for a number of boreholes (Figure 3.2). The resulting distribution was considered to be similar to the decline in storage and transmissivity with depth derived from pumping test analyses at different initial water levels. That is, the decrease in aquifer parameters was being caused by the loss of major yielding fissures.

The variation of aquifer properties with depth is very important when attempting to model groundwater flow and storage in the Chalk. If transmissivity and storage coefficient are assumed to decrease linearly with depth, errors will occur. During recharge periods when the high water table is high, water would be unable to move a sufficiently high rate through the aquifer and predicted groundwater heads would be too high. Conversely, at times of low groundwater head, the models would allow too much water to be stored in the aquifer. For example, Headworth et al. (1982) were unable to model both spring flow and groundwater levels using constant storage and transmissivity. However, by assuming a linear decrease in the parameters across the zone of water table fluctuation a reasonable fit was achieved. Rushton et al. (1989) proposed that models should incorporate a coefficient, c, to allow for the change in transmissivity with groundwater head. An estimate of the order of magnitude of this parameter could be acquired from pump test analyses, the distribution of values throughout the aquifer being deduced by the calibration and verification of the models.

Work on the Yorkshire Chalk (Yorkshire Water Authority, 1985) showed that aquifer response varied according to the assumed degree of layering of the aquifer properties. More pronounced layering resulted in more localised drawdown. This in turn led to a greater chance of problems with well yield due to the increased possibility of dewatering major fissures in the vicinity of the well.

Because of the lack of detailed evidence regarding the vertical variation of storage and hydraulic conductivity, the use of regional models to simulate proposed abstraction regimes may be limited, particularly as water levels fall during drought conditions.

3.4.2 Regional Variation

It was noted in Section 3.3.3 that hydraulic conductivity is enhanced beneath valley areas, and reduced in interfluves. Owen and Robinson (1978) related yield to topography and identified a pattern of distribution of transmissivity that appeared to correlate with relief. Values were a maximum around the heads of main flow concentration valleys and principal dry valleys, and decreased rapidly away from them, with values ranging from 50 to 2500 $m^2 d^{-1}$. Plots of log (T) against distance from main flow valleys showed a very good straight line correlation (Robinson, 1975), the deviant boreholes all occurring in large dry valleys close to the main valleys. However, similar plots for storage coefficient indicated less correlation.

A number of conceptual models have been developed to explain the spatial distribution of aquifer properties. One of the earliest (Ineson, 1962) suggested that the increase in hydraulic conductivity associated with river valleys was due to increased fracture density in these areas.

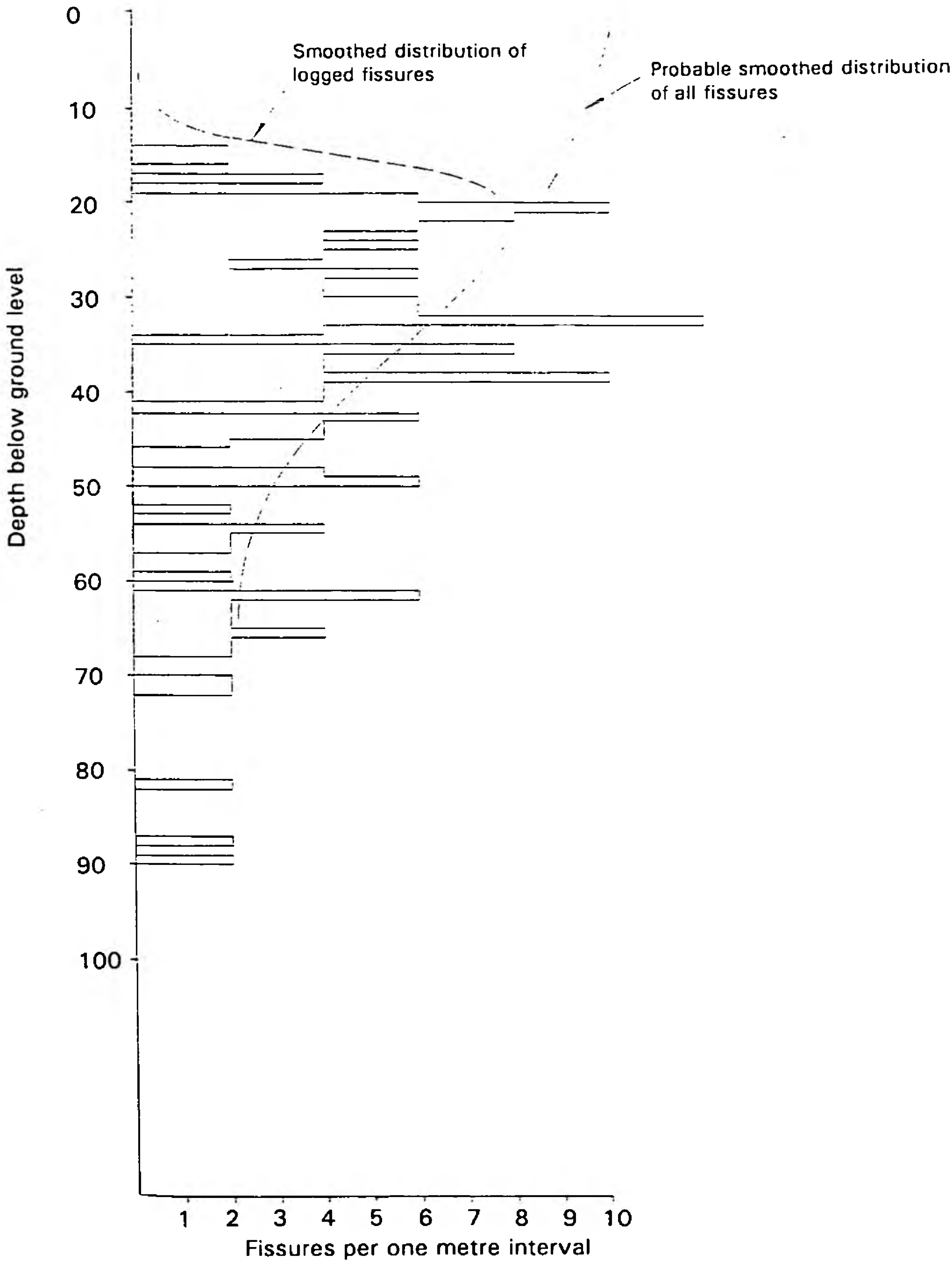


Figure 3.2 **Histogram of fissure distribution in the Stage I unconfined boreholes, Thames Groundwater Scheme (from Owen et al., 1976)**

Ineson proposed that the relationship was due either to the rivers following zones of structural weakness in the Chalk, or that the removal of overburden pressure in such areas resulted in fracturing. Younger (1989) suggested there was no such increase in fracture density towards valleys, and that the enhanced permeabilities were due to the enlargement of fissures by solution.

Price (1987), basing his work on that of Rhoades and Sinacori (1941), suggested that the higher hydraulic conductivity in valley areas was due to the concentration of calcite undersaturated groundwater flow near river channels. The concentration of flow would, in turn, lead to rapid solution and the development of secondary fissures.

Once secondary fissures have developed at a certain horizon, the water table would tend to be restricted to this zone. If the water table rose above it, the increased hydraulic gradient would lead to greater flow through the fissured zone and a lowering of the water table. If the water table fell below the zone, the hydraulic gradient would decrease, the water level would rise, and the zone would be intersected again. This model offers an explanation for the high hydraulic conductivity associated with the zone of water table fluctuation. However it should not be considered that this zone has a high hydraulic conductivity because of the fluctuating water table; rather, that the water table is constrained to remain within the zone. The processes described above are dynamic. Erosion and lowering of valley floors would result in lowering of the water table, with a new zone of enhanced hydraulic conductivity developing at a level related to the new position of the valley floor. Such a model explains the development of fissures in the present unsaturated zone.

Connorton (1976) and Robinson (1976) also placed little emphasis on the view of Ineson (1962) that river valleys are zones of structural weakness. Their approach was similar to that of Price (1987), stressing instead the importance of the rate of flux of groundwater and its saturation with respect to calcite. This is illustrated in Figure 3.3 (from Robinson, 1975). Interfluve areas have a low flux of groundwater combined with a large distance from the ground surface to the water table. Overburden pressures are high and fissures are less easily opened up. In valley areas, the opposite is true, and a zone is developed of high groundwater flux with high solution potential. Consequently, fissures are more rapidly developed and hydraulic conductivity and storage are enhanced.

Younger (1989) did not discount the models suggested by Connorton (1976), Robinson (1975, 1976) and Price (1987), but proposed that those mechanisms were only operative during the warmer periods of the Quaternary. Working on the Middle Thames Valley, he suggested that the higher hydraulic conductivity of valley areas was due to increased solution in these areas during the Devensian period when the area was subject to periglaciation (see Section 3.3.2).

Whatever the underlying mechanisms, hydraulic conductivity and storage tend to be enhanced in river valleys and dry valleys, with the effective aquifer thickness being correspondingly greater in these areas. Thus there is little to be gained from attempting to abstract water in interfluve areas, and boreholes are concentrated in valleys. The nature of the Chalk will tend to favour a shallow, but extensive, cone of depression, with the effects of pumping rapidly affecting river and stream flow.

3.5 Summary of Physical Properties of the Chalk Aquifer

From the above discussion it can be appreciated that the Chalk is an extremely complex aquifer.

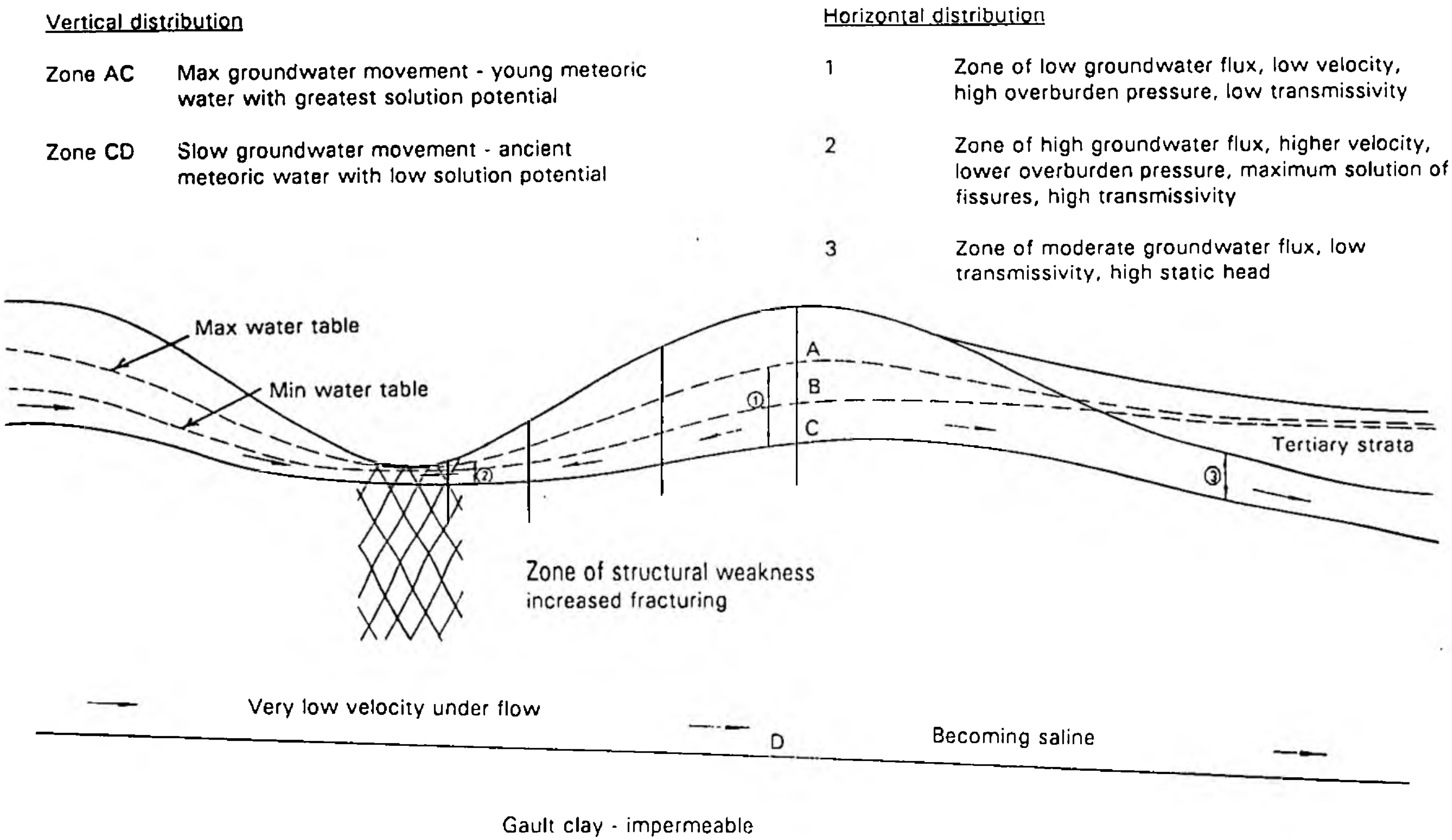


Figure 3.3 Model to explain the vertical and lateral development of the Chalk aquifer (after Robinson, 1975)

Overall, it has a high porosity, low storage coefficient, and variable hydraulic conductivity. Although the porosity is strongly controlled by the depositional history of the rock, the storage coefficient and hydraulic conductivity are influenced by the way in which the rock has since been subjected to diagenesis, tectonic, and solution processes; such processes include fracturing and glacial and periglacial effects. The result is an aquifer with properties that very both laterally and vertically, the storage coefficient and hydraulic conductivity tending to decrease with depth and away from main flow concentration valleys.

The hydraulic conductivity relies on the development of secondary fissures; the storage coefficient (or specific yield) is controlled by a combination of matrix properties, and primary and secondary fissures. The relative importance of each component will vary according to the size of the pores and pore throats, and the spacing, frequency, and openness of the fissures. Therefore hydraulic conductivity and storage coefficient will be enhanced in horizons where secondary fissures are developed, although the storage will be less dependant on these zones.

From an understanding of how storage is controlled by the matrix and fissure properties, and how these fissures actually develop, it can be appreciated that aquifer properties will tend to be enhanced in certain areas and/or horizons, principally:

- close to river valleys
- at outcrop or under permeable cover
- at shallow depth
- in the Upper and Middle Chalk compared with the Lower Chalk
- in the southern province compared with the northern province.

Although the bulk of pore water is immobile, the interaction between the primary fissures and the matrix is of great importance with respect to the movement of pollutants (Foster, 1975).

3.6 Determination of Storage Coefficient

There are two main approaches to the determination of storage coefficients: water balance calculations based on measured fluctuations of the water table in response to estimated recharge or discharge, and analysis of time-drawdown data from pumping tests.

3.6.1 Determination from Groundwater Fluctuations

Headworth (1972) proposed that groundwater head fluctuations in a well unaffected by pumping could be used to assess aquifer parameters. The premise of the method is that, as the storage coefficient represents the amount of water required to cause a unit rise in groundwater level, it should be possible to determine the specific yield by comparing groundwater level fluctuations with infiltration.

As groundwater flow has both lateral and vertical components, the rate of natural groundwater recession must first be estimated. The specific yield may then be calculated as:

$$S_y = \frac{\text{rainfall - evaporation}}{\text{change in water level + groundwater recession}}$$

Errors may occur due to extended periods of rain, and loss to soil moisture deficit or evaporation.

Using this approach, Headworth obtained an average specific yield for unconfined Chalk wells in Hampshire of 2.5×10^{-2}, with a range from 0.9×10^{-2} to 7×10^{-2}.

There appears to have been little application of Headworth's proposed techniques. Alexander (1981) considered the methodology to be ambiguous, and was unable to follow the method to calculate storage from well hydrographs in Dorset.

3.6.2 Comparison of aquifer volume dewatered and stream baseflow

Approximately 90% of the flow in chalk streams is baseflow derived from groundwater (Headworth, 1972a). In general, groundwater levels tend to reach a peak value in March and a low in October. By collecting maximum and minimum water level data from wells across a region, groundwater contour maps can be constructed, and the volume dewatered calculated. The specific yield of the aquifer can then be calculated as:

$$S_y = \frac{\text{volume of baseflow}}{\text{change in volume of storage}}$$

Using this approach, Headworth (1972a) derived values of storage coefficient of 3.3×10^{-2} for the Test catchment in Hampshire (1968) and 3.4×10^{-2} for the Itchen (1967).

Owen et al. (1976) determined specific yield as part of the Thames groundwater scheme investigations by dividing the net gain to river flow by the volume of aquifer drained (obtained by areal integration of the drawdown levels), and obtained values of between 0.8×10^{-2} and 1×10^{-2}, the values decreasing with duration of pumping, as the lowering of the groundwater head caused dewatering of major fissure zones. A similar approach in the Candover Pilot Scheme (Southern Water Authority, 1979) indicated that storage coefficients increased from 0.7×10^{-2} to 2.6×10^{-2} over 130 days of pumping, the increase being attributed to the fact that, as the cone of depression gradually expanded, it drew on parts of the aquifer with higher water levels and hence higher values of storage.

It is suggested that the relative contribution from low and high storage zones will vary according to the shape of the cone of depression. Parts of the Chalk with higher transmissivity would be expected to produce a shallow but rapidly expanding cone when subjected to pumping. This would draw on the upper, high storage regions of the aquifer. Conversely, a steep sided, deep cone of depression would be expected in areas of low transmissivity. This would expand relatively slowly, and limit the proportion of water contributed from the upper zones.

A drawback to the calculation of specific yield from volume calculations is that they assume there is no recharge to the aquifer during the period of analysis. In reality, drainage through the unsaturated zone may continue months after the end of the 'recharge' period; for example, at the Fleam Dyke lysimeter, drainage was observed through to september in some years (Shearer, personal communication). The magnitude of this effect does not appear to have been assessed.

3.6.3 Pumping Tests

The most widely used method of estimating aquifer properties is pumping test analysis. Normally an abstraction well is pumped at a constant rate for a predetermined time, and the effects observed in both the pumped well and surrounding observation boreholes. Where there are no observation boreholes, it is difficult to estimate the storage coefficient because of the problem of identifying the effective radius of the drawdown (Walton, 1970).

Analytical solutions have been derived for a number of situations; by comparing field results with these analytical solutions using curve matching techniques, values for the aquifer parameters may be derived. The most frequently used method of pump test analysis is based on that proposed by Theis, and is applicable to non-steady state conditions. Strict application of the Theis equation requires adherence to a number of conditions, namely:

- radial flow to the pumping well
- uniformly thick aquifer
- homogeneous, isotropic aquifer of infinite extent
- no well losses
- no delayed yield
- no well storage

Although adequate matches are often achieved for early time data, deviations from classical behaviour are frequently observed over longer periods, due to one or more of the above conditions not being met.

An alternative to the traditional approach of curve matching is the utilisation of a discrete space and time numerical model, in which, various aquifer characteristics may be incorporated (Rushton and Chan, 1976a; Connorton and Reed, 1978; Rushton and Redshaw, 1979). The models additionally allow an investigation of the effects of changing the magnitude of the aquifer parameters; and so determine which factors dominate the aquifer response. Using this technique Rushton and Chan (1976a) illustrated the importance of including the effects of delayed yield, well storage, and variations in hydraulic conductivity, on the response of the Chalk aquifer.

3.6.4 Accuracy of Estimates of Storage Coefficient

There may be numerous sources of error in the estimation of storage coefficients from pumping tests, as a consequence of problems with data quality or the validity of the adopted models. In practice, observations are usually distorted by errors, including inaccurate measurement of groundwater head, inaccurate pump discharge measurement, pump breakdown, and the influence of other abstracting wells in the area. Rushton and Howard (1982) considered that flow between horizons with different groundwater heads in open observation wells was likely to cause difficulties in analysing many pumping tests. Errors are also introduced if the natural groundwater recession /recovery is not correctly characterised.

The violation of the assumptions imposed by the method of analysis may mean that the experimental curves do not conform to the type curves. This is a particular problem with the Chalk which fails to conform to the assumption of homogeneity and isotropy, in both the vertical and horizontal direction. Due to the vertical variation in aquifer parameters, the initial water level will also affect the results of any pumping test analysis.

Toynton (1983) employed multiple regression analysis to the results of pumping tests in order to measure the influence of several factors at various sites across northern Norfolk. No single variable, or group of variables, could be shown to significantly influence the transmissivity or storage coefficient. This implies that either the variables chosen (depth of well, casing of well, stratigraphy, and aquifer conditions) were not those controlling the aquifer response or that they were operating in conjunction with other factors.

The above discussion leads to the question of how accurate and reliable is the value of the storage coefficient derived. There generally appears to be little evaluation of the accuracy of values of storage estimated from pump test results or from regional baseflow calculations. Comparison of the two methods however, shows that storage coefficients calculated on a regional basis are greater than those derived from pumping test analyses (Headworth et al, 1982; Rushton and Howard, 1982; Nwankwor et al., 1984; Neuman, 1987). For example, Rushton and Howard (1982), working on the Permo-Triassic sandstone of the Lower Mersey Basin, suggested regional values of 1×10^{-1} to 1.5×10^{-1}, compared with 0.4×10^{-3} to 1×10^{-3} from pumping tests. Similarly, for the Candover catchment, Headworth et al. (1982) found that regional estimates provided values of 5×10^{-2} to 7×10^{-2}, compared to pumping test values of 0.4×10^{-2} to 3×10^{-2}. In addition, long term pumping tests in the Candover catchment, and similar tests on sand and gravel aquifers (Wenzel, 1942), suggested that the apparent storage coefficient in unconfined aquifers commonly increases with duration of pumping.

There are three possible explanations:

- long time periods allow for the full gravity drainage of the zone above the falling water table. Nwankwor et al. (1984) suggested that the duration of many pumping tests was probably less than the time necessary for complete drainage from above the water table. As the time required for complete gravity drainage increases with decreasing grain size (Stallman, 1971), this is likely to be a particular problem in the Chalk.
- a significant amount of water may be released from storage beyond the observed cone of depression, although drawdowns in these areas may be imperceptible. This would give the impression of increasing storage with time as the pumping test progressed (Neuman, 1987).
- in the Chalk, the way in which the cone of depression intercepts the zone of water table fluctuation will affect the estimated storage coefficient, and the way in which storage changes with time.

Ultimately the confidence that can be placed on the calculated storage coefficient is determined by the governing equation. Sensitivity analysis has been carried out (McElwee and Yuckler, 1978; McElwee, 1982) to determine the sensitivity of aquifer models to variation in storage coefficient and transmissivity. The results may be used to indicate the accuracy of pump test-derived storage coefficients, and to help understand the sources of error. An interesting conclusion from McElwee's work is that the calculation of storage coefficient is dominated by dh/dt i.e. the instantaneous change in groundwater head with time. This implies that the storage coefficient derived for areas with large groundwater fluctuations will be more accurate than that for areas with more moderate changes in groundwater levels.

Barker and Herbert (1989) produced a series of nomograms to determine storage coefficient and transmissivity for large diameter wells. The nomogram shape highlights the difficulty of accurately determining storage coefficients, particularly when the coefficients are small. Herbert and Barker (1990) analysed data from large-diameter wells by automatically fitting analytical solutions; this technique yielded confidence limits on the resulting parameters. In particular, the 50% confidence limit for the storage coefficient was found to span two orders of magnitude.

This type of result underlines the insensitivity of pumping test analysis to estimate storage values. It is suggested that confidence figures must be routinely produced as part of the analysis if the aquifer parameters derived are to be meaningful.

3.6.5 Summary of the determination of storage coefficient

There are two main approaches to the determination of storage coefficient:

- volume calculations based on groundwater level fluctuations (local or regional values)
- pumping test analyses (local values).

Most pumping test analyses are subject to numerous errors including inaccurate observation data, inaccurate characterisation of the natural groundwater recession, integration of different groundwater heads, and violation of the assumptions of the analyses. Some of these problems may be overcome by numerical modelling of pumping test results, rather than the traditional approach of curve matching. Volume calculations based on comparison of baseflow and groundwater fluctuations may also be subject to errors, including the failure to account correctly for abstraction or recharge in the catchment.

Comparison of values calculated using the two different approaches have shown that those from regional volume calculations are greater. This could be due to a number of factors:

- the volume calculation allows for full gravity drainage
- there may be a significant contribution from beyond the measurable cone of depression
- there may be a significant contribution from continuing drainage through the unsaturated zone
- the presence of a high transmissivity/storage zone near the surface may affect different techniques in different ways.

Limited sensitivity analysis and calculation of confidence intervals for the values of storage coefficient suggest that pumping test results should be used with caution.

All the methods of determining storage coefficient described have one major disadvantage when estimating the amount of water remaining in unconfined storage during a drought. That is, they all depend on estimating the volume released from storage between two positions of the water table (discounting any contribution from the capillary fringe). Unless the lower level is below the extreme drought water table - which up to present has only happened when the water table has been lowered by extreme pumping - the specific yield so derived cannot apply to drought conditions.

Relatively few values of specific yield have been derived for the Chalk from pumping tests conducted with the water levels depressed in this way. Those that have (e.g. Owen and Robinson, 1978) have suggested that both transmissivity and storage coefficient decrease non-linearly as the water table falls. This has great importance when considering the extrapolation of results from preliminary investigations and pilot studies to schemes that require the abstraction of water from beneath drought groundwater levels.

3.7 River Augmentation Schemes

3.7.1 Introduction

Since the mid-1960s various workers have explored the possibilities of developing resources in such a way that surface and groundwater could be used in combination (Ineson and Downing, 1964; Ineson, 1970; Downing et al., 1974). Research has concentrated on the inter-relationship of ground and surface water systems, and models have been used to assess the significant variables involved (e.g. Rushton and Chan, 1976b; Connorton and Reed, 1978; Rushton et al., 1989).

Groundwater resources depend on three factors:

- The amount of natural recharge,
- The rate at which groundwater can be abstracted (transmissivity),
- Underground storage (storage coefficient).

There are two ways in which groundwater storage and surface water could be used conjunctively:

- Abstraction of groundwater from wells to augment river flow during periods of low flow.
- Artificial recharge into the aquifer of river water during periods of high flow.

Various river augmentation schemes have been investigated in Great Britain (see Owen et al., 1991), and much of the evidence for the variation of transmissivity and storage in the Chalk has been provided by the results of such schemes. Three of these, the Thames Groundwater, Candover, and Great Ouse schemes, are described in the following section.

The effects of groundwater abstraction on river flow will vary according to the hydraulic continuity between the aquifer and the river (Downing et al., 1974; Rushton et al., 1989). The three cases portrayed in Figure 3.4 represent different degrees of hydraulic continuity between the river and the aquifer. In the first situation, the river bed is permeable and the river is in hydraulic continuity with the aquifer. This is the typical scenario for streams on the Chalk. In the case of an impermeable river bed, although groundwater may seep into the riparian zone, flow from the river to the aquifer is not possible. If the river bed is semi-permeable, groundwater may flow freely to the river, but reverse flow to the aquifer is restricted.

This leads to the concept of net gain:

$$\text{net gain} = \frac{\text{groundwater abstraction rate - reduction in river flow}}{\text{groundwater abstraction rate}}$$

The net gain would be low if the response time of the aquifer was short (i.e. the ratio of transmissivity to storage with respect to distance) and vice versa. Thus, the ideal aquifer for river regulation would have moderate hydraulic conductivity and high storage coefficient.

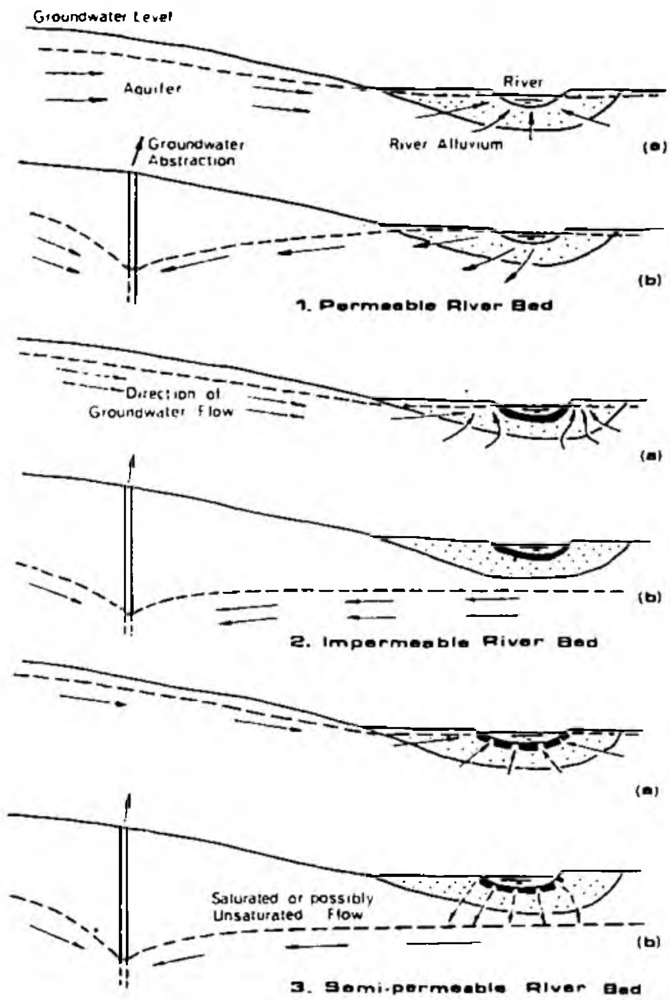


Figure 3.4 Differing degrees of hydraulic connection between aquifer and river for (a) natural and (b) groundwater abstraction conditions (from Downing et al., 1974)

3.7.2 Thames Groundwater Scheme

The Lambourn Valley pilot scheme was carried out between 1967 and 1969 to determine the yield characteristics of the boreholes, hydraulic properties of the aquifer, and effects of pumping on the aquifer/stream system. This initial assessment was followed by the investigation of the Kennet in 1979.

One of the main hydrogeological problems that rapidly became apparent was the prediction of long-term yield from the unconfined aquifer. Duplication of pumping tests at different rest water levels indicated that the yields from some wells varied according to the initial rest water level (Connorton and Reed, 1978; Owen and Robinson, 1978; Rushton et al., 1989).

An effective aquifer thickness of approximately 60 m below ground level in the Kennet Valley was defined based on the identification of fissures by geophysical flow logging (Owen et al., 1976; Owen and Robinson, 1978; Robinson, 1978). This was found to be dependent on the depth below ground level, and independent of stratigraphic level. The exception to the depth control on fissure development were fissures at 80 m coinciding with the Chalk Rock (Owen and Robinson, 1978).

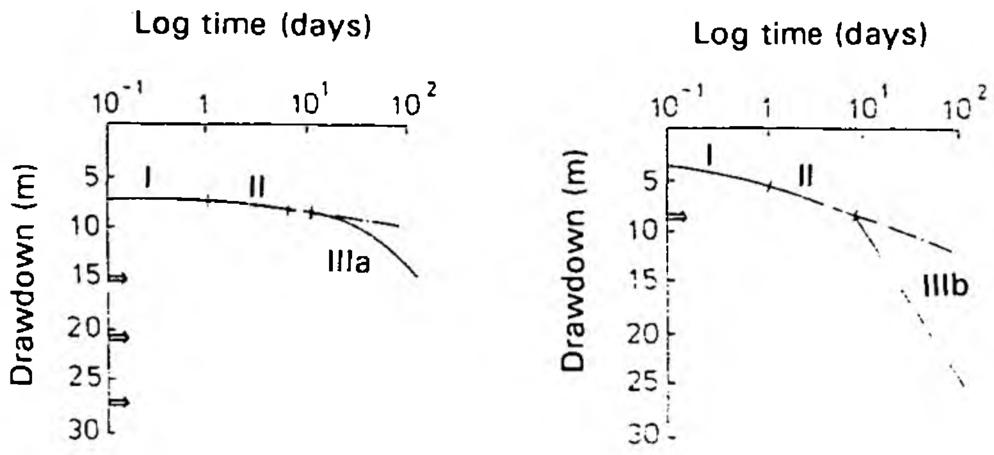
Effective aquifer thickness under the interfluves was not investigated to the same extent. Using geophysical logging, fissures were detected in some boreholes to a depth of 100 m below ground level (rest water level between 70 and 80 m depth). The greater depth to water table under the interfluves restricts the vertical extent of contributing fissures, and Robinson (1978) concluded that the effective aquifer in these areas was probably relatively thin.

Numerous approaches were used to determine the transmissivity and storage coefficient of the aquifer. Initial investigations for the pilot scheme suggested values of transmissivity of approximately 1500 m^2 d^{-1} and specific yield of 7.5×10^{-2} (Owen and Robinson, 1978). However, all the pilot scheme pumping tests were carried out at groundwater levels above the seasonal average, and much higher than would apply during operation of the scheme.

Further pump tests (including step tests, constant rate tests of up to 14 days, and long-term group tests) were carried out in 1973/74. Time-drawdown analysis of the data using standard infinite aquifer methods (Boulton, 1963; Jacob, 1947) emphasized the failure of the Chalk to satisfy conditions of homogeneity and isotropy, particularly over long periods of time. With increased duration of pumping and distance of observation wells from abstraction wells, the actual responses departed increasingly from ideal responses. Analysis of over 50 pumping tests of varying duration indicated one of two 'type' responses (see Figure 3.5) (Connorton and Reed, 1978; Owen and Robinson, 1978). The initial curvilinear part of the graph (I) represents the period prior to the delayed yield commencing, lasting typically around 1 day. The following straight line portion (II) indicates a period when the aquifer was behaving as isotropic, homogeneous, and infinite in areal extent, that is, it corresponds to the expected response of an 'ideal' aquifer (Cooper and Jacob, 1946).

The straight line section was subsequently replaced by either a gradual downward departure (IIIa) or an abrupt 'breakaway' (IIIb). The timing of these departures varied between boreholes depending on the hydrogeological conditions at each site.

The basic type IIIa response was modelled by using a lateral decrease in transmissivity and



Key

I	period of delayed yield
II	period of homogeneous, isotropic infinite aquifer response
IIIa	gradual downward departure due to effect of lateral decrease in aquifer parameter values
IIIb	abrupt breakaway departure due to the dewatering of a major yielding fissure
⇒	major yielding fissure

Figure 3.5 Pumped well 'type' responses derived from constant rate pumping tests (from Connorton and Reed, 1978)

storage coefficient, assumed to be associated with topographically higher areas. Further adjustment was obtained by allowing for vertical variation in the same parameters (Connorton and Reed, 1978; Owen and Robinson, 1978).

The type IIIb response was assumed to be a result of dewatering of major yielding fissures in the immediate vicinity of the well. Again, modelling confirmed this, the basic shape of the curve being controlled by the vertical distribution of transmissivity and storage coefficient (Connorton and Reed, 1978; Owen and Robinson, 1978)

The vertical distribution of aquifer properties was further investigated by plotting the results of pumping tests conducted at increasingly lower water levels (Owen et al, 1976; Connorton and Reed, 1978). The results are shown in Table 3.3a. Figure 3.6 (Longacre) indicates that both transmissivity and storage coefficient reduce non-linearly at this site with falling water level, the trend appearing to be asymptotic to the depth axis.

Although this pattern of variation in aquifer properties appeared quite consistent, there were exceptions. Mile End, conformed least to the general pattern. Figure 3.7 shows the almost linear decline of storage coefficient with depth, whilst transmissivity remained almost constant over the same range. Other boreholes deviated from the 'trend' to varying degrees. The data set was based on very limited data (5 boreholes, each with four or five different water levels), and it was felt (Owen et al, 1976) that this prevented the extrapolation of the trends. Each sample point could represent very different local geological conditions, particularly with respect to fissuring.

Test pumping carried out in connection with Stage I and preliminary Stage II investigations had been on large diameter boreholes situated in dry valleys. The data available suggested there was a variation in aquifer properties, dependent on topography and depth to groundwater level. No pump test data were available to confirm this trend for the interfluves. To amend this deficiency, pumping tests were carried out in 1978 in interfluve areas. The results showed a relatively poor correlation ($r = -0.59$) between log T and distance from main valleys, compared with a value of -0.85 for the stage I abstraction boreholes.

Limited testing of the confined aquifer (7 wells) indicated much less variation in transmissivity and storage coefficient, reflected in much more consistent yields. Although transmissivity again showed a slight tendency to reduce with increasing depth of burial, storage exhibited no such trend (Owen and Robinson, 1978).

It was concluded that the total quantity of water that could be obtained during a period of drought operation would depend both on the duration of pumping and the initial aquifer conditions.

3.7.3 The Candover Pilot Scheme

The Candover Pilot Scheme investigated the feasibility of augmenting flows in the River Itchen by groundwater abstraction from the headwaters of its tributary catchments.

Three pairs of production boreholes, 17 observation boreholes and 5 riverside tube boreholes were constructed, and added to a network of 50 existing wells and boreholes, and over 50 artesian boreholes. All these were monitored fortnightly from 1972.

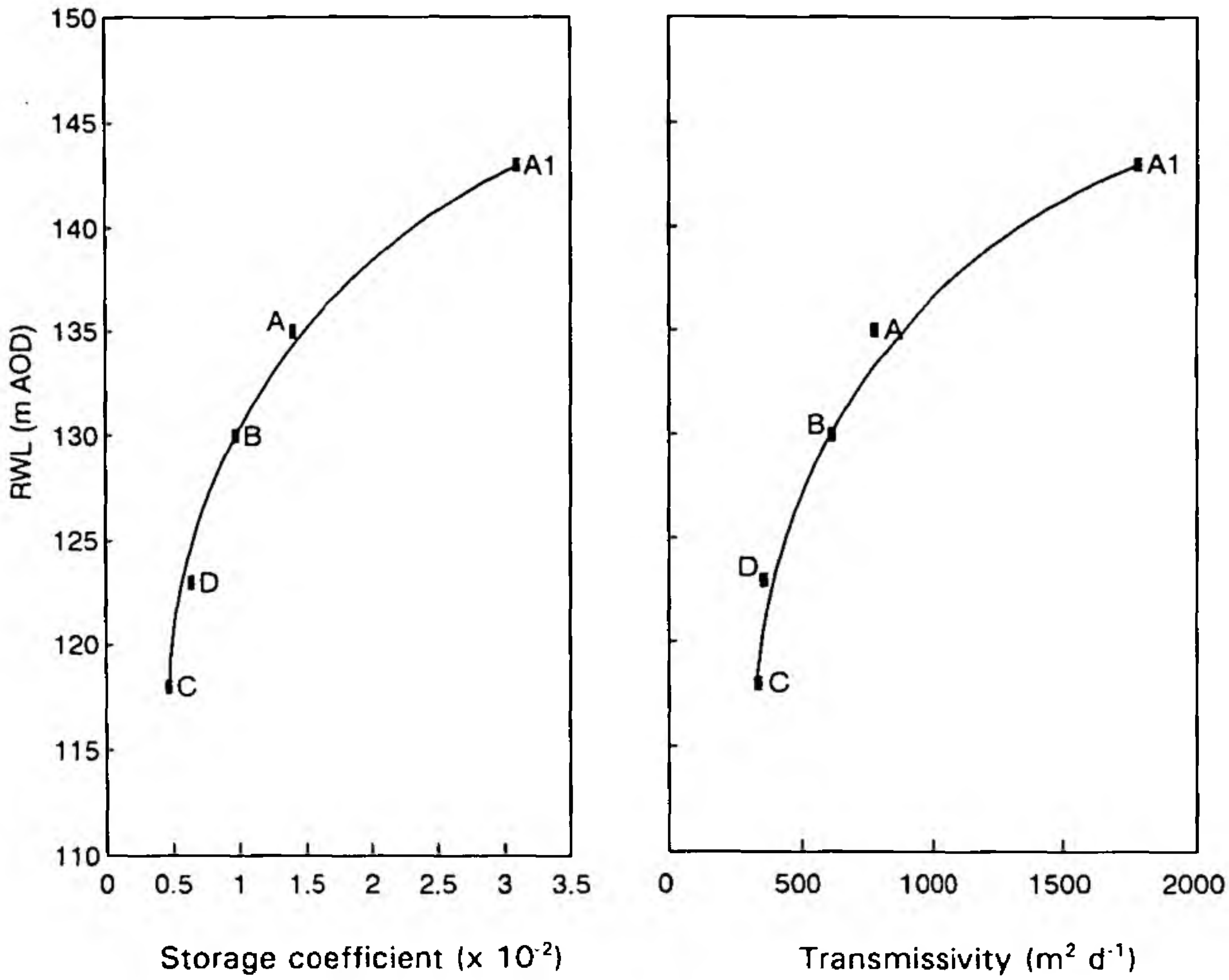


Figure 3.6 Transmissivity and storage coefficient variation for differing rest water levels, Longacre (after Owen et al., 1976)

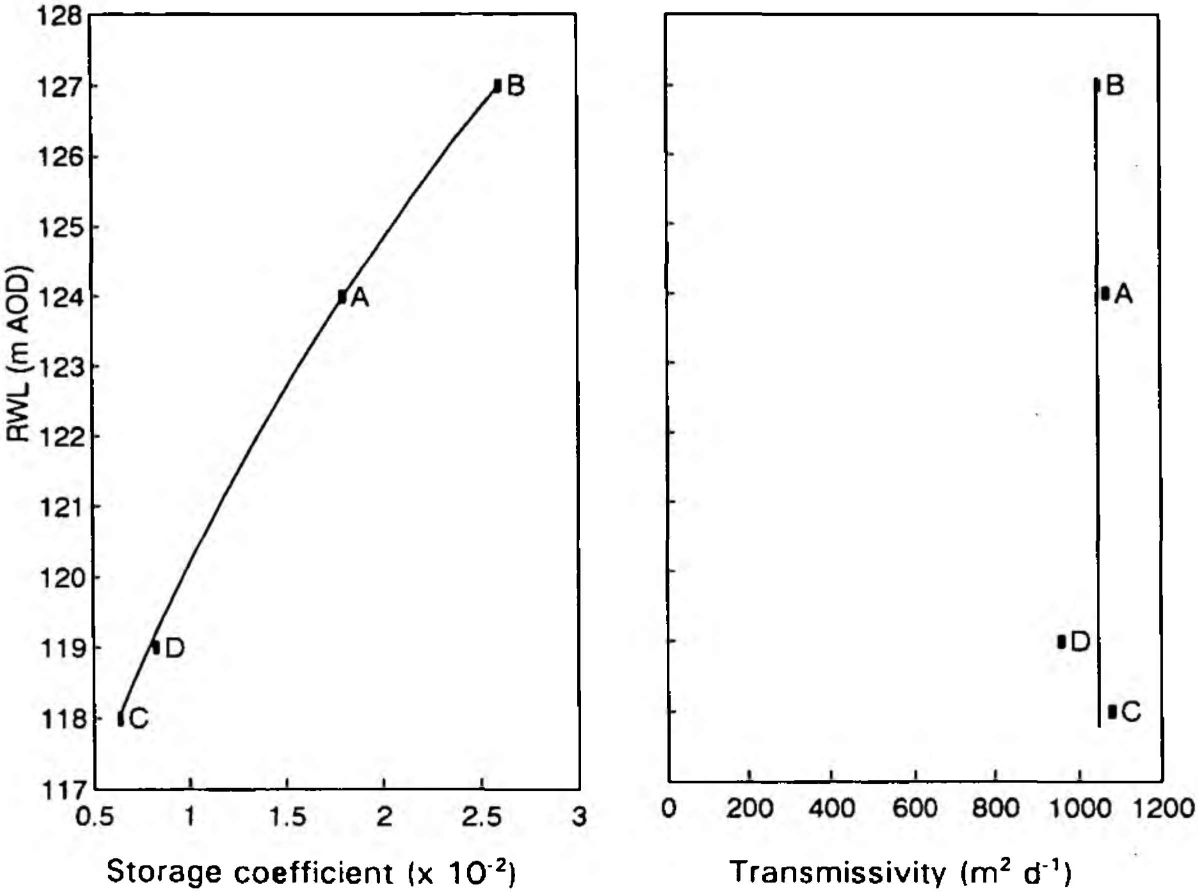


Figure 3.7 Transmissivity and storage coefficient variation for differing rest water levels, Mile End (after Owen et al., 1976)

Table 3.3a Storage coefficient and transmissivity variation for differing rest water levels, Thames Groundwater Scheme

Site	Test	RWL (m AOD)	T (m^3/day)	S	Source
Avebury Lower Chalk SU 0890 7008		145 140	598 661	$1.2x10^{-3}$ $4.9x10^{-4}$	Thames NRA Pumping Test records
Mile End Middle and Lower Chalk SU 331 810	Group drawdown (B) 14 day (A) Short (D) Group recovery (C)	127 124 119 118	1050 1070 960 1080	$2.6x10^{-2}$ $1.8x10^{-2}$ $8.3x10^{-3}$ $6.4x10^{-3}$	Owen et al 1976 (Thames Groundwater Scheme)
Farm Combe Middle and Lower Chalk SU 3108 7806	Group drawdown (B) 14 day (A) Group recovery (C) Short (D)	125 122 119 119	1010 880 900 450	$9.0x10^{-3}$ $6.5x10^{-3}$ $3.5x10^{-3}$ $7.0x10^{-3}$	Owen et al 1976 (Thames Groundwater Scheme)
Longacre Middle and Lower Chalk SU 3275 8232	14 day Phase II (A1) 14 day Phase I (A) Group drawdown (B) Short (D) Group recovery (C)	143 135 130 123 118	1780 780 620 360 340	$3.1x10^{-2}$ $1.4x10^{-2}$ $9.7x10^{-3}$ $6.4x10^{-3}$ $4.7x10^{-3}$	Owen et al 1976 (Thames Groundwater Scheme)
Upper Lambourn Middle and Lower Chalk SU 3171 8051	14 day (A) Group drawdown (B) Group recovery (C) Short (D)	131 127 119 119	2650 1420 1520 1400	$4.6x10^{-2}$ $2.3x10^{-2}$ $9.2x10^{-3}$ $1.1x10^{-2}$	Owen et al 1976 (Thames Groundwater Scheme)

Table 3.3b Storage coefficient and transmissivity variation for differing rest water levels, Candover Groundwater Scheme

Site	Abstraction BH	Observation BH	Test	Date	T (m^2/day)	S	Source
Axford Upper and Middle Chalk SU 611 430	1A	1B	37 days 10 days Early time	1975 (I) 1975 (II) 1976	1500 1400 900	$1.2x10^{-2}$ $1.2x10^{-2}$ $0.8x10^{-2}$	Southern Water Authority, 1979
	1A	Strat BH	37 days 10 days Early time	1975 (I)) 1975 (II)) 1976	2200 1900 2000	$2.3x10^{-2}$ $1.8x10^{-2}$ $1.2x10^{-2}$	Southern Water Authority, 1979
	1A	OB1	37 days 10 days Early time	1975 (I)) 1975 (II) 1976)	3300 3100 3400	$2.6x10^{-2}$ $2.6x10^{-2}$ $2.4x10^{-2}$	Southern Water Authority, 1979
Wield Upper and Middle Chalk SU 625 405	3B 3A	3A 3B	37 days 10 days Early time	1975 (I) 1975 (II) 1976	8400 8500 6200	5.0^{-2} $0.4x10^{-2}$ $0.3x10^{-2}$	Southern Water Authority, 1979

Final testing of the scheme was carried out in 1976, to achieve the design yield of 27.2 Ml d^{-1}. Four of the holes maintained their yields, but the yield declined in the two Axford boreholes; this was attributed to the fact that these boreholes were located near the northern boundary of the groundwater catchment, where the hydraulic conductivity was believed to be low. The area of drawdown was extensive, although relatively small in magnitude, being less than 4 m in the centre of the pumping area. Net gain of the scheme started at 80%, decreasing to 54% by the end of pumping.

The success of the Candover Pilot Scheme prompted the development of the Alre Scheme (previously known as the Further Itchen River Augmentation Scheme) during the early 1980s. Four production boreholes were brought into operation in the dry summer of 1989; unfortunately these alone were not sufficient to maintain the minimum residual flow for the Itchen, and the Candover boreholes were also used. As a result, analysis of the Alre pumping test data was complicated.

The onset of winter recharge in December 1989 caused a recovery in groundwater levels which triggered the shutdown of the Alre and Candover Schemes. This in turn led to additional groundwater recovery, and groundwater levels recovered almost to an all-time high by February 1990. This was followed by an unusually steep recession in 1990, with very low groundwater levels. The effects were attributed to a 'residual' cone of depression, presumably masked in February by perched water tables as air was trapped in the aquifer during rapid recharge. This rapid accession and recession has also been noted in other areas (Monkhouse, Personal Communication; Connorton, Personal Communication).

The hydrogeology of the area is dominated by the Upper Chalk to a depth of between 80 and 120 m, and many boreholes derive their water solely from this part of the aquifer. Drift deposits are very limited in extent.

Limited pump tests were carried out at different water levels for both the Candover (1975 and 1976) and the Alre (1984 and 1989) schemes. Storage coefficient and transmissivity values obtained for the Candover catchment from the 1975 and 1976 pumping tests were plotted against rest water level (Figure 3.8 and Table 3.3b). Although values of storage coefficient tended to decline with depth, similar variations were not observed for transmissivity. Headworth et al. (1982) suggested this could be due in part to a change in pumping regime between 1975 and 1976. Results from the Alre pumping tests also indicated a slight decrease in storage coefficient with depth.

In order to investigate the extent to which transmissivity and storage coefficient had been reduced by the low groundwater levels in 1976, short (three day) aquifer tests were carried out, and aquifer properties derived at various observation boreholes. The results are plotted in Figure 3.9, and indicate the tendency of storage coefficient and transmissivity to decrease non-linearly with drawdown. In particular, there appears to be a very rapid decrease in transmissivity when drawdowns exceed 2 m.

Aquifer properties were plotted on maps of the area to show their lateral distribution. Initial examination of the results suggested that transmissivity increased with distance away from the main Candover valley, while there was no systematic variation in storage coefficient. This was thought to be related to the vertical variation of transmissivity through the aquifer, with values decreasing as the distance from the pumping boreholes decreased, and as a consequence, drawdown increased (as indicated by Figure 3.9). Thus, the results could be interpreted as

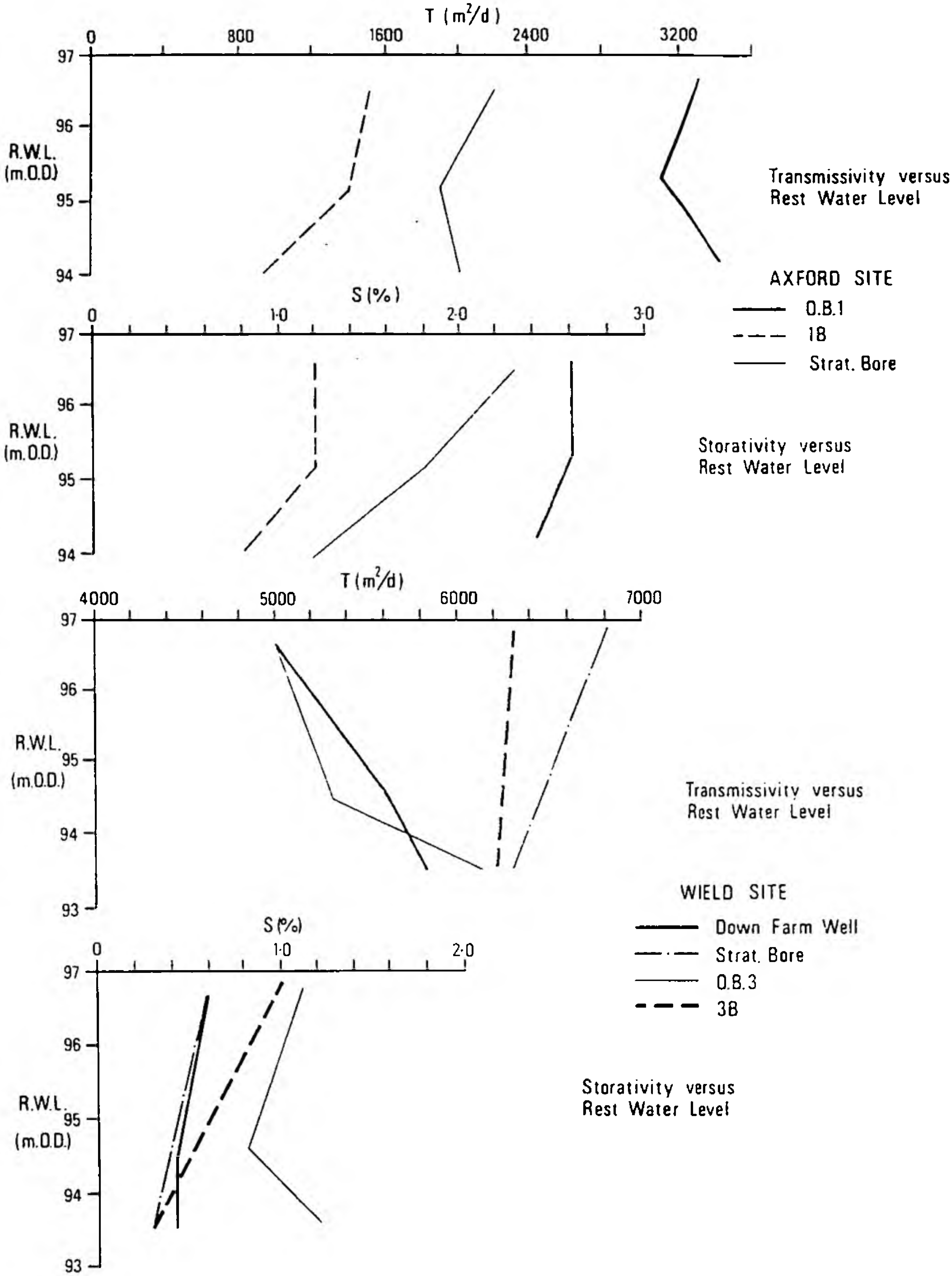


Figure 3.8 Variation in transmissivity and storage coefficient with rest water level for 1975 and 1976 aquifer tests, Candover Pilot Scheme (after Southern Water Authority, 1979)

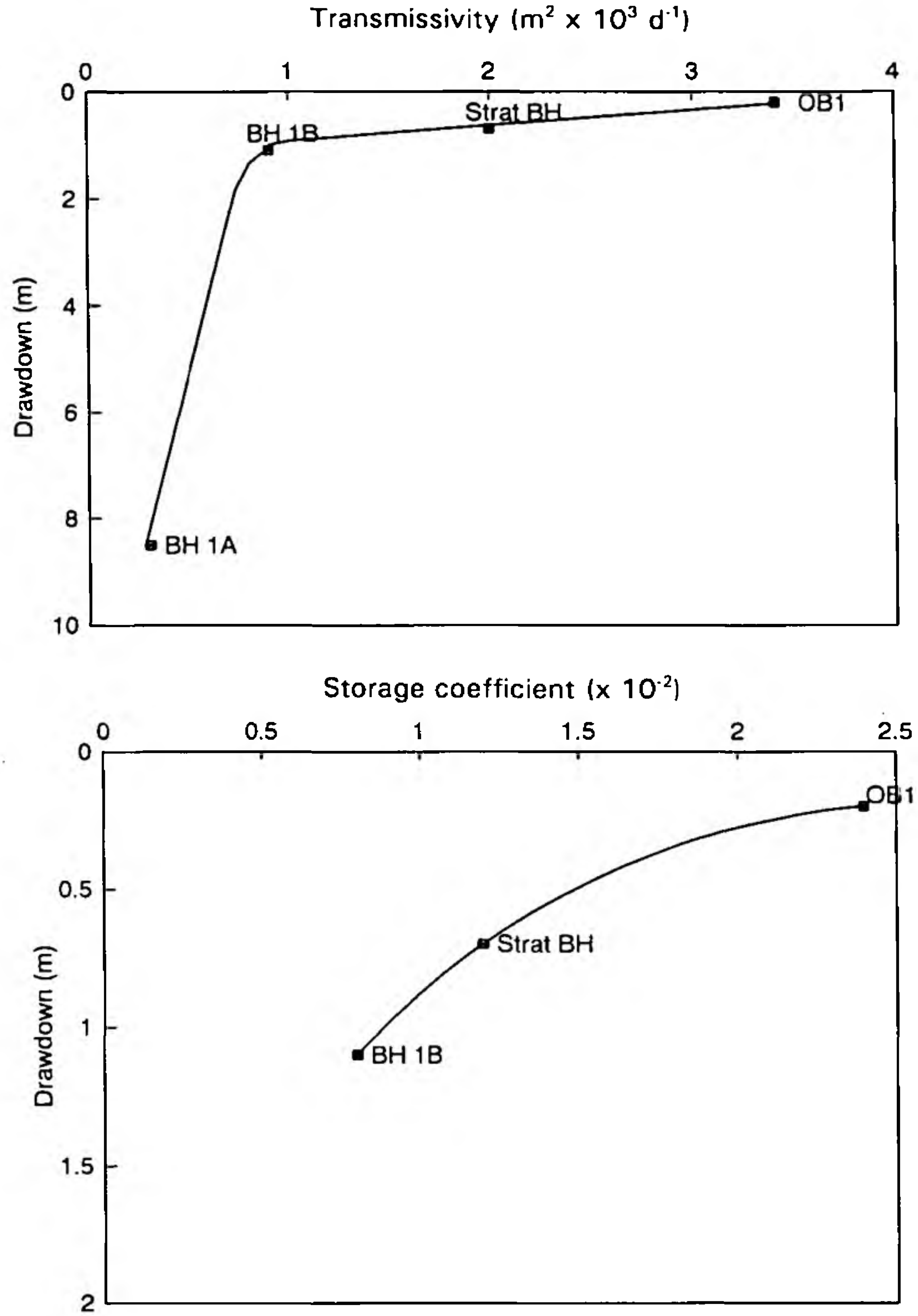


Figure 3.9 Variation in transmissivity and storage coefficient with drawdown in pumped and observation boreholes during early-time 1976 pumping tests (after Southern Water Authority, 1979)

indicating increased hydraulic conductivity within the zone of natural water table fluctuation.

The confusion as to how aquifer properties vary laterally and vertically through the Candover catchment is due partly to the small range of groundwater fluctuations in the area (Southern Water Authority, 1979), and largely to the lack of appropriate data. In particular, the analysis of transmissivity and storage variation with depth was based on three different water levels for each observation well; it is difficult to extrapolate such limited data. In addition, the observation wells being used were situated at distances up to 11 km from the pumping centre. Storage and transmissivity values obtained over this distance should be treated with caution, particularly in consideration of the anisotropic and heterogeneous nature of the Chalk.

The test pumping and analysis of groundwater fluctuations indicated several unusual features of the Candover catchment; groundwater fluctuations were very small (of the order of 3 to 5 m), and the hydraulic gradient in the central part of the catchment was very flat. Calculations of regional storage indicated storage coefficients between 5 and 7 x 10^{-2}, compared with 1 to 3 x 10^{-2} elsewhere in Hampshire. Pump test analysis for the Candover catchment also indicated a storage coefficient of 1 to 3 x 10^{-2}.

It was suggested that these anomalous results were caused by an unusual combination of storage and transmissivity. Modelling of spring flows and groundwater levels required the existence of a narrow zone of high transmissivity and storage coefficient in the region of water table fluctuation. This narrow zone provided the winterbourne component of stream flow, its high storage being confirmed by Headworth's (1972a) analysis of groundwater fluctuations. The bulk of the aquifer had much lower transmissivity and storage coefficients, identified by pumping test analyses.

The origin of the exceptionally high permeability/storage zone is uncertain; it is possibly related to the maintenance of groundwater levels within a certain horizon, and the subsequent development of fissures at this level.

3.7.4 Great Ouse River Regulation Scheme

The Great Ouse pilot scheme was initiated to investigate the use of groundwater to augment flow in the Ely Ouse and Nar rivers (Great Ouse River Authority, 1972). The pilot area was the catchment of the River Thet, with the Wissey catchment being used as a control area. Pumping tests were carried out at 18 abstraction wells over a period of four years, the results being used to assess how far groundwater levels could be lowered, and the effects of doing so. Stable conditions were achieved after 200 days; this was thought to be due to induced flow across the eastern boundary.

The total thickness of the Chalk in the area is approximately 225 m. However, geophysical logging demonstrated significant fissuring to a depth of only 30 m in most boreholes. The depth of fissuring did not appear to be related to distance from the river system, although more extensive fissuring was reported in riverside boreholes (Great Ouse River Authority, 1971).

The long-term pumping tests carried out indicated that storage coefficients could vary abruptly in the Great Ouse basin (Great Ouse River Authority, 1970); it was suggested this was due to a change in storage at some distance from the abstracting well. The storage coefficients obtained were frequently not true chalk values, but were affected by contributions from the overlying drift deposits.

Conclusions of the pilot scheme were that, it would be practical to use groundwater from the Chalk for river regulation, during times of extreme drought. As spring flow would be affected by pumping (Backshall et al., 1972) abstraction would have to be capable of maintaining the flow of the river as well as the yield for which it was designed.

Several models have since been developed for catchments in the area of the Great Ouse scheme (see Table 3.4). Although regional variation in storage coefficient were included in the models, only the Lodes-Granta investigations (University of Birmingham, 1988) attempted to model the variation of these factors with depth. (Many of the models are in the process of being updated at present (National Rivers Authority, 1991)). This work identified two notable features influencing groundwater flow mechanisms in the area:

- The high permeability of the Melbourn Rock and Totternhoe Stone. Although this affected the flow into boreholes, the effect on regional groundwater flow was uncertain.
- Enhanced hydraulic conductivity in the zone of water table fluctuation.

The model incorporated the following features: flow from the adjacent catchment; variation of transmissivity and storage coefficient with changing water tables; regional distribution of transmissivity and storage coefficient; reduction in yield as a result of pumped drawdown; recharge mechanisms; spring flows; and river/aquifer interaction.

It was found to be difficult to obtain detailed information about the changes in storage coefficient and transmissivity with depth to the saturated zone, however field evidence suggested that both decreased with falling water levels.

As one of the purposes of the investigation was to evaluate resources at depressed water levels, it was considered to be essential to account for the variation. Hydraulic conductivity was assumed to be uniform at depth, increasing linearly in the zone of fluctuation. The storage coefficient was varied as follows:

(i) If the water table fell to between 5 and 10 m below the initial level, storage coefficient was 75% of the initial value.

(ii) At depths greater than 10 m below the initial water level, the storage coefficient was set at 40% of the initial value.

The model was used to generate groundwater heads and springflows, the results being compared with historical data. It could then be used to explore the probable response of a variety of alternative pumping strategies.

3.7.5 Summary

Three river augmentation schemes have been outlined. The success of any scheme relies on a proper understanding of the groundwater system, in particular, the ways in which aquifer properties vary with depth and across the region. It has been suggested that the properties of the Chalk aquifer below the zone of groundwater fluctuation are critical to the success or failure of a large-scale augmentation scheme. Without such understanding, proposed augmentation schemes may fail to achieve their objectives.

The situation is complicated further by the lack of understanding of the contribution of drift deposits to chalk recharge and to the values of storage derived from pumping tests.

Table 3.4 Summary of regional groundwater models developed for the area covered by the Great Ouse River Regulation Scheme (adopted from NRA, 1991).

Model	Description	Application
Lodes-Granta	Regional groundwater flow model of the Chalk north-east of Cambridge	Model used to design groundwater development scheme, including new sources for public water supply and river support
Gipping	Regional groundwater flow model of the Gipping Valley Chalk	Model developed to help quantify resources in the Gipping Valley, and assess saline intrusion in the Ipswich area.
Pant Valley	Distributed regional groundwater flow model for the Pant Valley, Essex	Model to help estimate catchment resources and assess reasons for the development of the Braintree depression.
Rhee/Cam	Distributed regional groundwater flow model of the Rhee and Cam catchments to the south-west of Cambridge	Model was developed to assist with defining the resources of the Rhee/Cam catchment and with operational planning.

4. CALCULATION OF THE LIMITS OF THE CHALK

4.1 Method

To obtain the bounding surfaces of the Chalk, structural contour maps were prepared for the following horizons of the Chalk:

- top of Chalk
- base of Middle Chalk
- base of Lower Chalk

These are enclosed as Maps 1 - 3 in the Annex.

The contours were constructed from a combination of contours shown on previously published maps and on- and off-shore borehole data (including some which are currently commercial-in-confidence and hence actual sites and depths cannot be given here). The modified contours were digitised, each contour being held as a series of data points, these were then merged with the individual borehole data to create scattered data files for the various surfaces. The Interactive Surface Modeling (ISM), Version 7.0 package from Dynamic Graphics Inc., run on a VAX mainframe computer, was used to grid the data. ISM is a versatile package for the modelling, analysis and contouring of surfaces. It allows for the inclusion of faults (necessary in the Chalk surface interpolation); mathematical operations on grids; volumetric calculations and the production of two or three dimensional contour maps. A 1 km x 1 km grid spacing was used and this provided the gridded files from which the structural contour maps could be produced.

The contours were initially compiled separately for the north and the south of the country, using National Grid Line 200 km northing (which runs west-east through Buckinghamshire, Hertfordshire and Essex) as the dividing line. This was done for several reasons:

- to make the size of the data and gridded files more manageable.
- to separate the structurally less complex north from the more complex south.
- to separate the predominantly glacial drift-covered Chalk of the north from the virtually drift-free southern Chalk.

Due to edge effects across this artificial boundary, the joining of the separate files created some problems; these were time-consuming to solve.

The outcrop or updip limit of each horizon was digitised from existing geological and hydrogeological maps. The larger inliers of Lower Cretaceous and Jurassic were included, but the numerous smaller outliers (particularly the Tertiary ones between Marlborough and Maidenhead and between Dartford and Gravesend) were omitted. It was considered that their omission would not significantly affect the estimation of the rock and groundwater volumes for the Chalk.

4.2 Structural contours

4.2.1 Base of Lower Chalk and base of Middle Chalk

The contours indicate that the base of the Chalk in Yorkshire and Lincolnshire dips more steeply seaward and is up to 100 metres deeper at the coast than previously thought (Whittaker, 1985).

Minor flexures on the basal surface in this area are also apparent. Some, such as the Caistor monocline, appear to be significant structures and will affect any estimates of the thickness of the Chalk (Evans et al., 1989). These minor flexures are also apparent on the base of the Middle Chalk surface.

An isopach map was produced for the thickness of the Lower Chalk in the northern half of the country. The map was obtained by contouring the actual borehole values of the thickness of the Lower Chalk, rather than subtracting the base of the Lower Chalk grid from the base of the Middle Chalk grid. This ensured that the isopachytes were not influenced by the extrapolation and gridding operations in ISM, particularly in areas with little or no data. The isopachs indicate that the Lower Chalk thins along the northern part of East Anglia and in parts of East Yorkshire and immediately off-shore. It is thicker in Lincolnshire and to the south and south-east of the grid line 200 km northing.

Jeans (1980) suggested that the deposition of the Red and Lower Chalks throughout eastern England were controlled by the East Midlands Shelf, which extended from the northern limit of the Market Weighton Structure southwards to the Wash Line (Figure 4.1). In Yorkshire it has long been recognised that sedimentation throughout the Jurassic and Cretaceous was controlled by the Market Weighton Structure, which is probably underlain by a buried granite body (Bott et al 1978; Bott 1988). Donato and Megson (1990) interpreted another buried granite batholith east of that at Market Weighton, the buoyancy of which may have affected deposition of the Lower Chalk in the same way as if affected the distribution and thickness of the Rotliegend Sands offshore.

The thinning of the Lower Chalk in north Norfolk is not so easily attributable to the buried batholith postulated by Chroston et al (1987) and Allsop (1987), as the two are not coincident. However the isopachytes indicate that significant thicknesses in excess of 25 to 30 m only occur south of the axis of the postulated batholith. This probably represents a better position than the Wash Line for the southern limit of the East Midlands shelf that attenuated Lower Chalk deposition (Evans et al., 1990).

In the southern half of the country the contours for the base of the Lower Chalk and the base of the Middle Chalk were not constructed in isolation. In several areas the zero contour for the base of the Middle Chalk was constructed by isopaching from the zero contour for the base of the Chalk in Whittaker (1985) using proven thicknesses of the Lower Chalk from boreholes (Evans and Penn, 1990). Along the south coast, there is a complex development of *en echelon* anticlines and synclines. In this area the base of the Chalk contours published in Whittaker (1985) were amended using the base of Middle Chalk contours from the South Downs hydrogeological map (Institute of Geological Sciences, 1978a) and borehole information.

4.2.2 Top of the Chalk

In the northern half of the country (north of National Grid Line 200 km northing), the upper surface of the Chalk is equivalent to ground level where it outcrops in the west, and the base of drift or Tertiary to the east. Therefore, where the Chalk is at outcrop, topographic contours were used to define the top of the Chalk. These were merged with the contours on the top of the Chalk beneath drift or solid formations obtained from published hydrogeological maps for Yorkshire, Lincolnshire, and East Anglia (Institute of Geological Sciences, 1980; 1967; 1976; 1981). In the southern half of the country, as the drift deposits are relatively thin and sparsely distributed, their presence was unlikely to affect the position of the Chalk surface. The top of

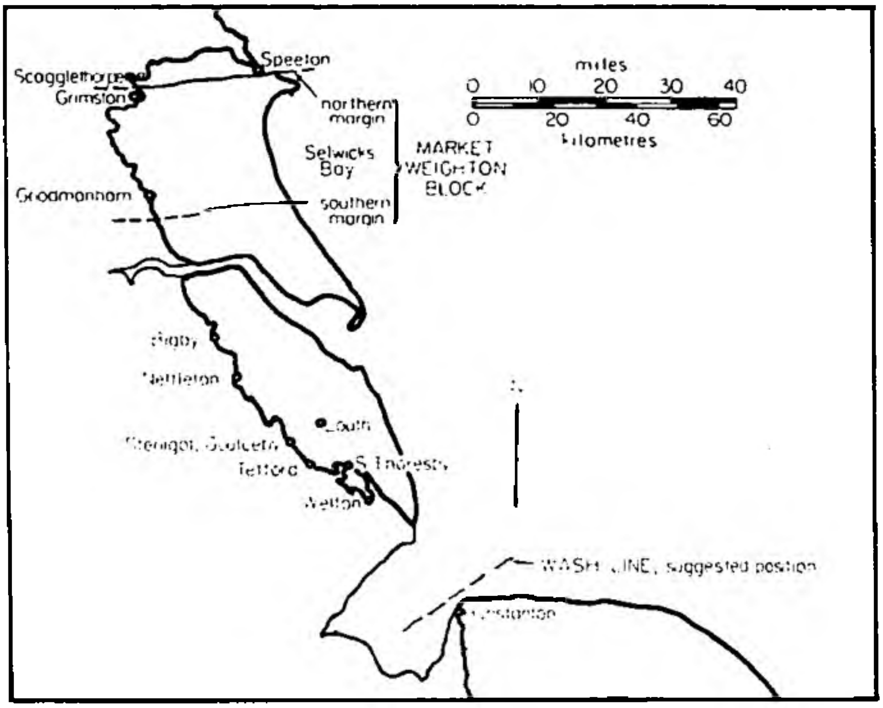


Figure 4.1 Location of the Market Weighton Structure and the Wash Line (from Jeans, 1980)

the Chalk contours south of 200 km northing are therefore a combination of the topographic contours (where the Chalk is at the surface or overlain by drift deposits) and contours on the base of the Tertiary. The latter were mainly obtained from the hydrogeological map series, namely: Kent (Institute of Geological Sciences 1970), south-west Chilterns and Berkshire and Marlborough Downs (Institute of Geological Sciences 1978b), Wessex (Institute of Geological Sciences 1979a) Hampshire and Isle of Wight (Institute of Geological Sciences 1979b) and Cambridge and Maidenhead (British Geological Survey, 1984). Other sources of information used were borehole data, contours published in the report on the Hydrogeology of the London Basin (Downing et al, 1972), the Southend and Foulness geological memoir (Lake et al, 1986) and the metric well inventory for South London (Hearsum et al, 1979).

4.3 Rock Volumes

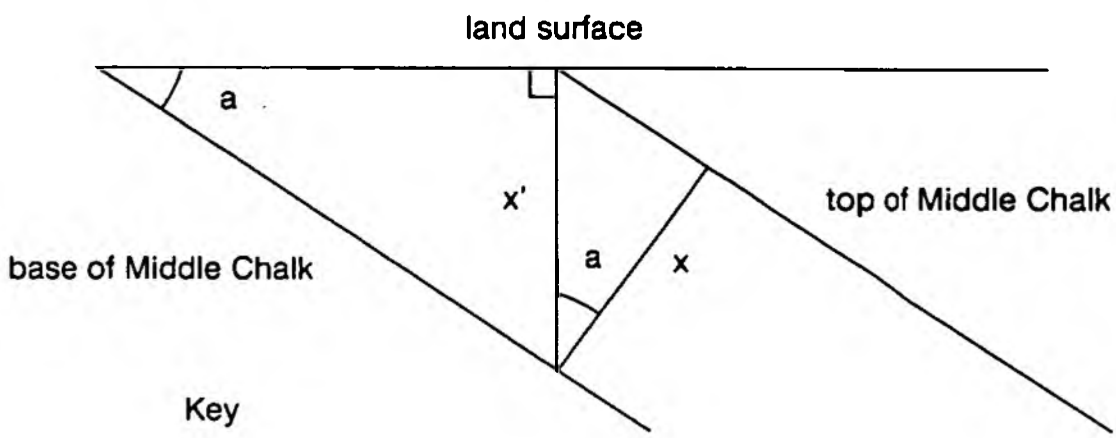
The total volume of Chalk beneath onshore England was obtained by calculating the volume of rock between the surfaces representing the top of the Chalk and the base of the Lower Chalk. This volume of 6.88×10^{12} m^3 was then subdivided into volumes of Lower, Middle and Upper Chalk. All of the calculations were carried out using the volumetrics option in ISM. Because contours had not been produced for the base of the Upper Chalk, an average thickness of the Middle Chalk had to be used which complicated the calculations.

A gridded surface was obtained for the top of the Lower Chalk using a combination of the base of the Middle Chalk, and the topographic contours where the Lower Chalk was at outcrop. The Middle Chalk was taken to be 50 m thick in the northern province, and 60 m thick over the rest of England. A top of Middle Chalk gridded surface was obtained within ISM by adding the appropriate constant to the base of Middle Chalk gridded surface. Where this produced a surface above ground level, the topographic contours were used. The base of the Upper Chalk was defined by the top of Middle Chalk, where the latter surface was not at outcrop. The top of Upper Chalk gridded surface was taken as the top of Chalk surface where this was coincident with a non-null base of Upper Chalk node.

The true thickness of the Middle Chalk was used in these calculations rather than the apparent thickness (Figure 4.2). When dips are less than 10°, the difference is small; as the average dip of the Chalk is probably nearer 3°, it was felt that this difference was not significant compared with the other errors inherent in the method. As the assumed mean thickness of the Middle Chalk was different for the northern and southern Chalk provinces, the calculations were carried out independently for each of these areas. The results are given in Table 4.1.

Table 4.1 Volumes of Chalk ($\times 10^{12}$ m^3).

	Northern province	Southern province	Whole of England
Upper Chalk	0.38	3.19	3.57
Middle Chalk	0.13	1.54	1.67
Lower Chalk	0.07	1.57	1.64
Chalk	0.57	6.31	6.88



Key

a = dip
x = true thickness of Middle Chalk
x'= apparent thickness of Middle Chalk

$x/x' = \cos a$, if $a < 10°$, $x \approx x'$

Figure 4.2 Relationship between true and apparent thickness

5. DATABASING AND INTERPOLATION OF GROUNDWATER LEVELS

Groundwater level contour maps were constructed for two pairs of maximum and minimum levels. The maximum and minimum levels for each pair could then be compared to calculate the volume of groundwater lost from storage due to natural water level fluctuations. The volumes were derived from two pairs of dates for the purpose of comparison. Recent dates when maximum water levels were known to have occurred are spring 1975 and spring 1988 and minimum levels in the autumns of 1976 and 1990. The water levels in the indicator wells held by BGS in the National Groundwater Level Archive were then studied to select the average month when wells reached their maximum and minimum levels respectively within these seasons. In some areas the turning points (i.e. peak or low water levels) were one or more months before or after this mean, due to local variations in rainfall, soil moisture deficit and thickness of the unsaturated zone. However, it was considered preferable to construct contours that referred to one specific date, rather than an all time maximum or minimum level. The months selected were April 1975 and March 1988 for high water levels and September 1976 and December 1990 for low water levels. The actual dates when the indicator wells reached their maximum and minimum levels are shown in Table 5.1.

The production of the groundwater level contour maps was carried out in the following stages:

- Collection of groundwater level data from NRA regions.
- Databasing of groundwater levels.
- Verification of input data.
- Interpolation of groundwater levels onto a regularly spaced grid.
- Contouring from the grid and production of hard copy plots.

5.1 Data Collection and Databasing

Groundwater level data for April 1975, September 1976, March 1988 and December 1990 were obtained for the five NRA regions which enclose Chalk i.e. Yorkshire, Anglian, Thames, Southern and Wessex. In some areas, if records were not available for these dates, data for adjacent months were accepted.

Where there was more than one groundwater level for the month required the highest or lowest value was used depending on whether it was a maximum or minimum level year respectively. In areas (e.g. Kent) where limited data were available for the months required, readings before and after that date were searched for. If such levels existed they were used to calculate a value for the date required. Where groundwater levels are only recorded bi-yearly, substantial numbers of boreholes could not be included.

A groundwater level database was created using the computer software package Lotus 1-2-3. The database has a simple structure, each row is a record and each column a field. The fields vary for each region. They always include the northings and eastings of the grid reference, and groundwater levels for the four months. In some cases the local well identification code and the wellhead datum level are also included.

Table 5.1. Dates when indicator wells reached maximum and minimum levels.

Grid Reference	Site	Measuring Authority	Highest level Spring 1975	Lowest level Autumn 1976	Highest level Spring 1988	Lowest level Winter 1990/91
SE 9212 3634	Dale Plantation	NRA-Y	22/5	28/7	15/2	31/12
SE 9651 4530	Dalton Holme	NRA-Y	31/5	2/10	15/4	6/12
SE 9345 7079	Green Lane	NRA-Y	30/5	2/10	15/4	23/11
SP 9470 0875	Champneys	NRA-T	30/4	-	26/2	24/3
SP 9380 1570	Pitstone Green Farm	NRA-A	1/4	1/9	23/3	9/10
ST 3763 0667	Lime Kiln Way	NRA-SW	8/4	1/10	7/4	4/1
SU 0160 1946	West Woodyates Manor	NRA-W	1/1	1/10	5/2	1/11
SU 0310 4883	Tilshead	NRA-W	13/1	4/9	11/2	-
SU 1655 7174	Rockley	NRA-T	16/2	1/10	21/2	13/1
SU 3817 2724	Bailey's Down Farm	NRA-S	5/2	24/9	29/2	22/12
SU 3315 5645	Woodside	NRA-S	12/3	24/9	19/2	13/12
SU 5875 1655	Hill Place Farm	NRA-S	29/1	29/9	24/2	21/12
SU 5586 3498	Abbotstone	NRA-S	-	31/8	1/2	3/12
SU 5628 7530	Calversleys Farm	NRA-T	27/4	28/11	29/3	6/1
SU 6578 1775	Chidden Farm	NRA-S	29/1	22/10	24/2	21/12
SU 6890 1532	Hinton Manor	NRS-S	26/2	29/9	24/2	29/1
SU 6360 4049	Lower Wield Farm	NRA-S	20/2	8/10	17/3	2/10
SU 6442 8525	Well Place Farm	NRA-T	-	12/12	20/3	13/1
SU 7755 1490	Compton House	NRA-S	6/2	14/10	11/2	8/1
SU 7048 3491	Faringdon Station	NRA-T	19/2	20/10	6/3	24/11
SU 7367 6251	Riseley Mill	NRA-T	20/4	21/11	1/3	7/12
SU 7419 8924	Stonor Park	NRA-T	11/5	5/12	15/3	30/1
SU 8356 1440	Chilgrove House	NRA-S	8/2	11/9	11/2	18/12
SU 8336 7885	Farm Cottage, Coldharbour	NRA-T	14/1	15/8	19/2	1/11
SU 8103 9417	Piddington	NRA-T	5/5	22/10	30/3	8/1
SY 662 881	Ashton Farm	NRA-W	5/2	24/9	8/2	1/11
TA 0490 6120	Nafferton	NRA-Y	29/5	15/8	13/4	8/12
TA 0940 7740	Hunmanby Hall	NRA-Y	-	6/10	12/5	8/12
TA 1375 0885	Little Brocklesby	NRA-A	15/5	24.9	30/3	5/12
TA 2670 1890	Church Farm	NRA-Y	3/3	18/8	22/3	19/8
TF 7710 2330	Off Farm	NRA-A	1/6	1/10	9/3	7/12
TF 7690 3290	Moor Farm	NRA-A	-	-	4/5	-
TF 8738 0526	Houghton Common	NRA-A	1/4	1.10	9/2	1/12
TF 8138 1960	Washpit Farm	NRA-A	1/6	1/10	4/5	2/1
TF 9160 4135	Cuckoo Lodge	NRA-A	19/5	23/9	4/5	-
TF 9869 2183	Tower Hills Pumping Station	NRA-A	24/4	-	5/2	8/11
TG 0440 0020	High Elm Farm	NRA-A	1/3	1/8	18/3	17/10
TG 0382 3583	The Hall, Brinton	NRA-A	25/7	24/9	13/4	10/10
TG 1691 1101	The Spinnesy, Costessey	NRA-A	24/4	24/8	6/4	16/10
TG 1126 2722	Heydon Pumping Station	NRA-A	24/4	28/7	10/2	9/11
TG 2400 1657	Frettenham Depot	NRA-A	24/4	26/8	11/2	11/10
TG 2699 1140	Grange Farm	NTA-A	24/4	28/10	1/2	20/3
TG 2932 3101	Melbourne House	NRA-A	24/4	26/8	15/4	8/8
TG 3365 1606	Woodbastwick	NRA-A	-	26/8	1/2	8/8
TG 3700 2682	Brumstead Hall	NRA-A	-	-	15/4	10/9
TL 1560 1555	Mackerye End House	NRA-T	3/6	2/9	1/3	3/12
TL 1692 1965	The Holt	NRA-T	15/6	24/11	5/4	16/2
TL 1200 3026	West Hitchin	NRA-A	28/4	9/9	14/2	28/12
TL 2978 2433	Box Hall	NRA-T	13/4	26/10	22/2	7/1
TL 3330 3720	Therfield Rectory	NRA-T	22/6	23/11	23/3	(2/5)
TL 4536 2676	Hixham Hall	NRA-T	3/6	22/11	2/3	11/2
TL 4669 2955	Berden Hall	NRA-T	1/6	25/10	2/3	3/1
TL 4522 4182	Redlands Hall	NRA-A	1/6	1/11	-	23/1
TL 5925 5606	Lower Farm	NRA-A	-	-	19/2	10/2

Grid Reference	Site	Measuring Authority	Highest level Spring 1975	Lowest level Autumn 1976	Highest level Spring 1988	Lowest level Winter 1990/91
TL 7982 2516	Rectory Road	NRA-A	26/1	12/12	24/1	-
TL 8465 4106	Smeetham Cottages, Bulmer	NRA-A	27/4	12/9	14/2	-
TF 8578 3606	South Creake	NRA-A	23/5	23/9	2/3	6/12
TL 8850 6470	Cattishall Farm	NRA-A	1/5	1/11	9/3	27/12
TL 8131 9001	Grimes Graves	NRA-A	9/5	11/10	15/4	7/12
TL 9657 2562	Lexden Pumping Station	NRA-A	-	-	28/2	21/10
TM 1201 5618	Dial Farm	NRA-A	23/5	23/11	4/5	11/12
TM 1671 7903	Old Parsonage House	NRA-A	21/4	24/9	-	4/8
TM 2461 6109	Fairfields	NRA-A	22/4	24/9	11/4	8/11
TM 2786 6397	Strawberry Hill	NRA-A	-	27/7	4/2	13/12
TQ 0850 1170	Chantry Post, Sullington	NRA-S	-	-	27/1	9/1
TQ 2850 1289	Old Rectory, Pyecombe	NRA-S	20/2	17/10	5/2	12/10
TQ 2996 8051	Trafalgar Square	NRA-T	2/3	-	24/1	9/9
TQ 3220 1180	North Bottom	NRA-S	-	-	10/2	9/11
TQ 3363 5924	Rose & Crown	NRA-T	-	30/9	5/2	7/12
TQ 3509 8536	Hackney Public Baths	NRA-T	13/2	-	6/6	2/11
TQ 5592 9380	Old Rectory, Folkington	NRA-S	-	-	4/2	8/10
TQ 5648 6124	West Kingsdown	NRA-T	16/4	14/11	5/2	1/11
TQ 5880 7943	Thurrock A13	NRA-A	-	-	4/2	30/12
TQ 5622 8408	Bush Pit Farm	NRA-T	-	13/8	-	-
TQ 6649 6873	Owletts	NRA-S	6/5	3/9	19/3	-
TQ 8595 6092	Little Pett Farm	NRA-S	-	-	1/6	3/7
TQ 947 971	Burnham	NRA-A	-	-	7/2	-
TR0142 5874	Portway House, Faversham	NRA-S	6/5	6/7	21/6	-
TR 1225 4690	Little Bucket Farm	NRA-S	8/5	1/11	10/2	26/11
TR 1265 4167	Glebe Cottage	NRA-S	6/2	4/10	24/2	12/11
TR 3173 4725	Church Farm	NRA-S	5/5	1/9	26/4	-
TR 3330 5090	Cross Manor Cottages	NRA-S	5/5	1/10	26/4	26/8
TR 3208 6634	Alland Grange	NRA-S	28/4	16/7	15/3	3/9
TN 5290 9920	Westdean 3	NRA-S	14/2	24/8	8/2	21/12
Mean date			8/4	30/9	9/3	25/11

5.2 Verification of Input Data

Tens of thousands of values were input into the computer database, with inevitable typing mistakes occurring. These, coupled with errors in the original data obtained from the NRA regions, meant verification of the input data was important.

The input data was first checked by comparing printouts of the database against the original data sheets. This identified most of the typing mistakes but not data errors, such as incorrect grid references and groundwater levels. For the second stage of verification the software package SURFER (Golden Software, Inc) was used. SURFER is primarily a contouring package. It allows the production of two or three dimensional representations of spatial variables from internally interpolated regular grids (see Section 5.3). SURFER is a PC package and has the advantage over mainframe packages that it is more efficient for small data sets. It can also produce basemaps, allowing for the plotting of well positions and relevant boundaries.

A basemap was plotted for each NRA region, which included the digitised outline of the Chalk (using the coastline as a boundary to the east). If a well was located either outside the region's boundaries or the Chalk, it was checked manually. This method identified most of the mistakes caused by grid references and unsuitable wells. Wells with incorrect grid references that still lay within the boundaries were highlighted by the next stage of verification.

Most contouring packages require the initial interpolation of scattered data onto a regular grid. This grid is then used to position the contour lines. The subject of interpolation methods is addressed in more detail in Section 5.3. The methods can be divided into two groups, local and global interpolation. Local interpolation tends to highlight more local variations in the spatial variable, as groundwater levels generally vary smoothly incorrect levels are highlighted by large local mounds or troughs.

Inverse squared distance weighting, a local interpolation method, was carried out using SURFER on the groundwater level data for each NRA region. Possible errors in groundwater levels were identified and then checked. In some cases the levels were correct, the anomaly being due to local topographical features. Where errors were evident comparison with the original data identified a few typing mistakes. There were also a number of errors caused by the depth to groundwater in boreholes being input in place of height above Ordnance Datum (OD). Occasionally, errors in the datum level were discovered. These were corrected either by consulting the NRA regions or by reading off wellhead elevation from the topographic maps.

With a verified data set the next stage, the groundwater surface interpolation for the whole of the Chalk, could be carried out.

5.3 Interpolation of groundwater levels

Interpolation of groundwater levels onto a regularly spaced rectangular grid was carried out for the whole of the Chalk. The concatenation of data for the five regions produced a large data set of over 3,000 records. To be able to interpolate such a mass of data in reasonable CPU time it was decided that a mainframe package was needed and ISM was again used. This also enabled a higher standard of hard copy to be obtained.

ISM has two interpolation options: trend gridding and minimum tension gridding. The former calculates a surface that shows the general shape or trend of input scattered data but ignores local variations which are important in this study. The latter technique honours the input scattered data and was the method used.

There are two stages in minimum tension gridding, an initial estimate and biharmonic iterations with scattered data feedback. The initial grid estimate calculates a Z-value for every grid node using an inverse distance weighted average of nearest data points to each node. A biharmonic cubic spline function is then fitted locally to the grid nodes. The useful characteristic of this function is the distribution of tension (second derivative or curvative) among the nodes so the sum of the squares of the second derivative is minimised. The value on a node is re-evaluated using a fit to the surrounding nodes and the function at the position of the original data points is monitored so the error reduces with each iteration.

The grid spacing used both in the x and y coordinate directions was again 1 km. This spacing allowed the local variations in the groundwater level data to be identified while keeping computer processing time down to a reasonable level. The size of the grid used was 341 x 411 nodes.

5.4 Contouring and production of hard copy plots

Once a gridded file was obtained the final contour plot could be produced. The contouring package interpolates between grid nodes to find the position of previously defined contour levels and then joins these points to produce contour lines. The groundwater levels for the four dates were contoured at an interval of 25 metres. The base of the Lower Chalk and the coastline formed boundaries for the contours. The final contour plots are included as Maps 4-7.

5.5 Problems associated with computer-generated plots

Examination of the initial groundwater level contour plots highlighted a number of problem areas.

5.5.1 Unpaired data

When comparing contours for 1975/1976 and 1988/1990, it was evident that where levels only existed for one of the two years in any pair, the resultant interpolated surfaces could be noticeably different. The lack of paired data was due to a number of reasons

- wells drilled between measuring dates.
- wells went dry under low groundwater level conditions.
- measurements of groundwater levels not coincident with required dates in all years.

To obtain reasonable comparisons of the surfaces the spread of data has to be similar for each pair as the interpolation routine honours the input data closely. Where the missing years were for wells in areas of high well density there was little problem; however, where well density was low the loss of one control point caused more of a problem. In addition even if well density was high, data missing from a well positioned at the apex of a groundwater mound or trough could cause large differences in the shape of the groundwater surface. This problem was particularly evident for wells in high topographical positions where the unsaturated zone is thick, and there was greater possibility of boreholes becoming dry during periods of low groundwater levels.

Unfortunately computer contouring packages cannot take "less-than" conditions into account, the situation when a well is dry.

To overcome this problem some groundwater levels had to be estimated for the wells in question. This was done with the help of staff in the NRA regions and by comparing levels with wells in similar hydrogeological and topographical conditions. In a few extreme conditions it was necessary to delete data points when estimates for the missing year could not be made.

5.5.2 Wessex Region

The Wessex Region had a particularly low number of sampled groundwater levels. It was not possible to improve the coverage by estimating borehole levels. To overcome this problem the groundwater levels were contoured by hand. These hand-drawn contours were then digitised and added to the data set for the whole of the Chalk, replacing the original Wessex data.

5.5.3 Covered Chalk

In areas where the Chalk is covered with Tertiary sediments or a substantial thickness of drift, fewer boreholes to the Chalk aquifer exist. These areas include the London Basin, Hampshire Basin, East Anglia, and parts of the Sussex coast. The lack of data points reduces the confidence in the resultant interpolated groundwater surface. This is especially true for the last three areas where, in one case, extrapolation resulted in levels in excess of 50 metres below Ordnance Datum along the coast. To overcome this problem it was again found necessary to add data points to bring the contours up to more realistic levels. It is important to bear in mind the scarcity of data in the areas of covered chalk when viewing the contours.

5.5.4 London Basin

Problems in the London Basin were three-fold. Firstly, as mentioned in the previous section, the number of wells on the Chalk with thick Tertiary cover is generally low. However, as the London Basin is almost surrounded by areas of outcrop Chalk, the effects of unrealistic extrapolation are not as evident. Therefore it was not felt necessary to add control points.

Secondly, due to overdevelopment of the Chalk aquifer in the past, water levels were lowered significantly. By the 1960s many of these sources had stopped pumping and levels started to rise. This rise, coupled with seasonal fluctuations, made it difficult to estimate values for dates when groundwater levels were not available. Thirdly, pumping of many public supply boreholes locally lowered the water table. This complicated the situation, as the contouring package was then using levels which were artificially low as representative of the area.

In summary, the contours in the London Basin, which are locally based on the estimation of rates of groundwater rise or levels near pumped sources, have a low level of confidence.

5.5.5 Yorkshire Escarpment

The topographic positions of springs were added to well data along the escarpment of the Yorkshire Chalk. It was realised that at low groundwater level some of these springs would dry up or be supplied by a perched water table. However, as unpaired data caused contouring problems, data could not be used for one year of the maximum/minimum pair and not the other. The detail these points added to the interpolated surface outweighed possible inaccuracies, and they were utilised.

5.5.6 Preferential Groundwater Level Sampling

The distribution of wells and boreholes across a region is rarely, if ever, uniform. Remote areas without mains water supply, areas with more highly permeable Chalk, and areas within river augmentation schemes, will generally have a greater number of sites. Conversely, areas with mains water supplies, and those where the depth to groundwater is large, will have a lower density of wells. As a result the density of groundwater level measurements and the resulting interpolated contours are biased.

Without a coverage of data points that fully describe the features of the groundwater table the interpolated surface cannot be completely representative. This problem may be partially overcome by hand contouring, using topographic contours in conjunction with available borehole data to produce groundwater levels that describe a subdued topography. Although it was considered at the beginning of the project that computer-drawn contours would be adequate, in retrospect, problems encountered with this approach suggest that it may have been better to have used hand-drawn contours.

5.6 Analysis of groundwater level contour plots

Examination of the plots showed that the detail in the contours for the maximum groundwater levels is slightly greater than that of the respective minimum groundwater levels. It is also noticeable that the later pair of levels, March 1988 and December 1990, have more detail than the earlier pair, April 1975 and September 1976. In each case the enhanced detail is due to a greater number of input data points. The number of real and estimated water level values in the data sets (excluding digitised contour lines) are given below:

April 1975	1434 values
September 1976	1292 values
March 1988	2456 values
December 1990	2020 values

There is a correlation between the groundwater levels in the four months and topography, though there are the exceptions in areas such as the London Basin and around Braintree due to the effects of abstraction in the past. The correlation with topography is also apparent from the difference between maximum and minimum groundwater levels.

It is difficult to see a consistent difference trend when comparing the two maximum groundwater levels and the two minimum levels. This would suggest the choice of these dates as approximate overall long-term maximum and minimum levels was suitable.

6. VOLUME CALCULATIONS

6.1 Porosity and Storage Coefficient

6.1.1 Porosity

A decrease in porosity with depth has been noted by several workers (see Section 3.3.1); whether the variation is due to the depth of burial or to actual sedimentological or diagenetic differences has not been proven. However previous work suggests that stratigraphic level is a significant factor; this is supported by Chalk porosity data from the British Geological Survey's porosity database.

a) Variation with depth

Figures 6.1 and 6.2 show the porosity of cored samples obtained from boreholes plotted against depth below ground surface, for the southern and northern Chalk provinces respectively. Each point represents the average porosity of all the samples over a 10 metres depth interval for individual boreholes, for each stratigraphic horizon.

Although there is obviously some overlap between the stratigraphic levels, porosity, in general, decreases with age. Due to the scarcity of Upper and Middle Chalk samples from depths greater than 100 metres, it is difficult to place any statistical significance on these conclusions. The low porosity 'tail' for the Upper Chalk of the southern province in Figure 6.1 is derived from a single borehole; this being the only location where porosity values were measured throughout a thick sequence.

It was appreciated that hard grounds within the Chalk sequence have a low porosity. However, their contribution to overall storage will be small because of their limited vertical extent, and no adjustment was made for them in the porosity calculations.

The Lower Chalk in general, and the marl layers in particular, have lower porosity than the Upper and Middle Chalk. In terms of decreasing the pollution potential of organic compounds, the clay minerals within these marls may play an important role by adsorbing compounds onto their surfaces.

b) Regional variations

Average porosity was calculated for each 100 km grid square from data held in the BGS porosity database. Because of the paucity of data points, and their uneven distribution throughout the country, a systematic regional variation was not observed within the southern province. As a result, porosity values were assigned according to stratigraphic horizon in this area as follows, without reference to geographic location.

Upper Chalk	35-45%
Middle Chalk	30-35%
Lower Chalk	20-30%

Some of the lowest Upper Chalk values (average 31%) were recorded from the Poole area (SY 88). It was believed that these low values were due to tectonic deformation of this chalk (Alexander 1981). As the area affected is relatively small, no adjustment was made

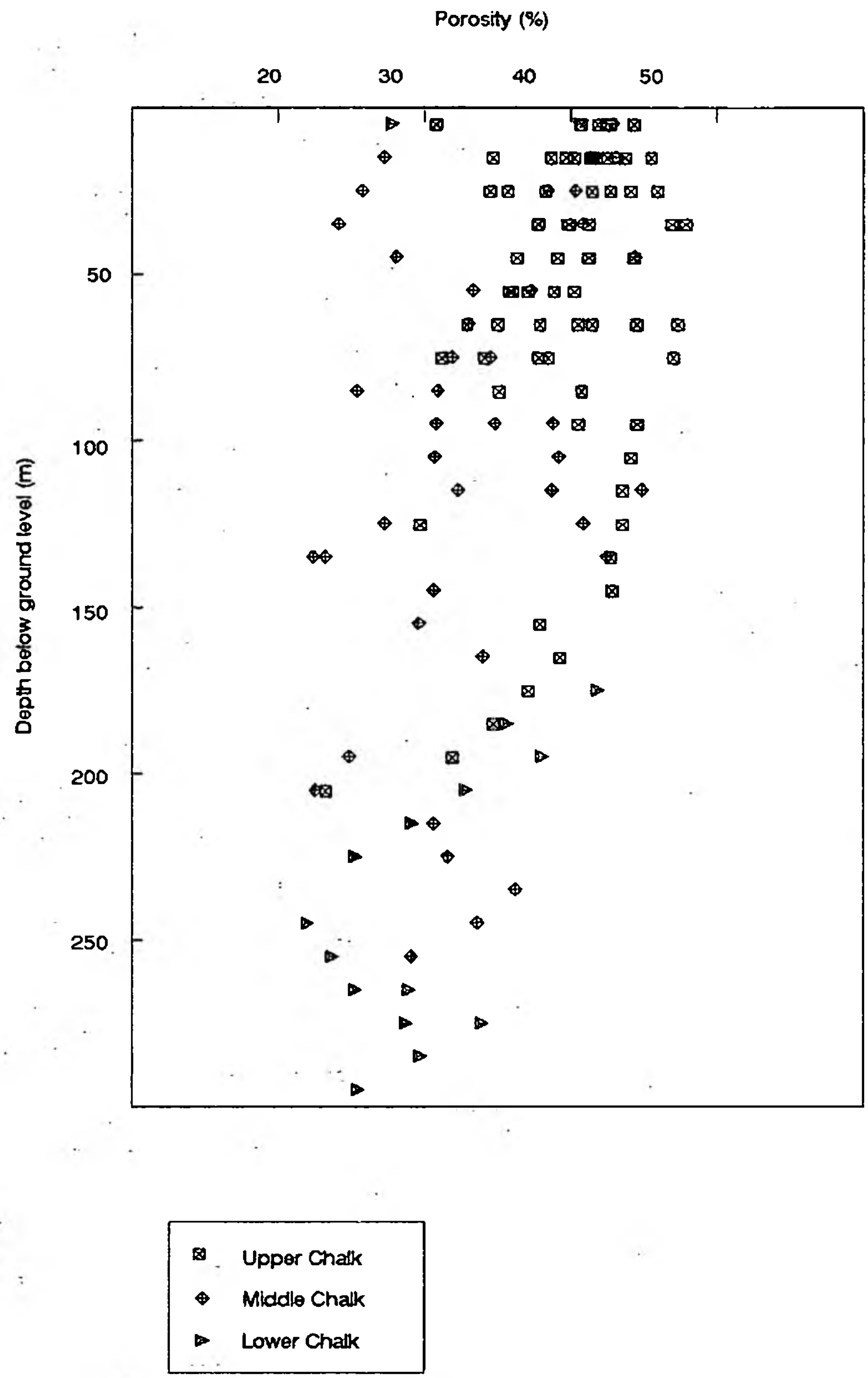


Figure 6.1 Variation in porosity with stratigraphic level and depth from ground surface - southern province

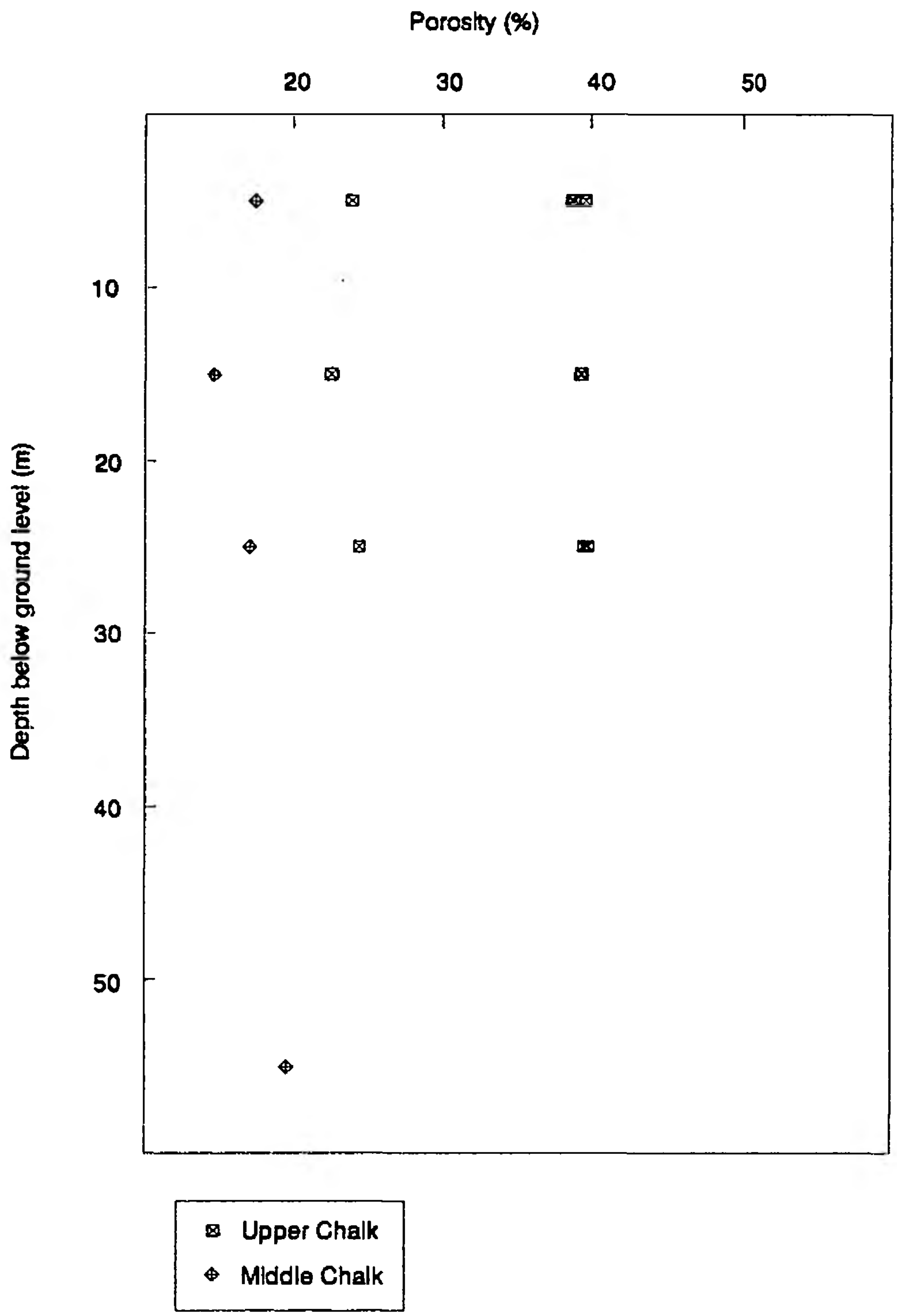


Figure 6.2 Variation in porosity with stratigraphic level and depth from ground surface - northern province

for this in the volume calculations.

Porosity values for Yorkshire were in general lower than those for the southern province, the lower values being confirmed by figures given in the Yorkshire Groundwater Study (Yorkshire Water Authority, 1985). Although no data was available for the Lincolnshire Chalk, this was considered to be similar in character to the Yorkshire Chalk, and the same porosity values were assigned.

The values chosen were:

Upper Chalk	25-35%
Middle Chalk	15-25%
Lower Chalk	15-25%

6.1.2 Storage Coefficient

Perhaps the biggest uncertainty in the data used to calculate the usable storage was the values of storage coefficient used, and the way they varied regionally and with depth. Values of storage coefficient were obtained from pumping test results, modelling studies, and regional studies, utilising numerous sources, including NRA and BGS pump test reports, river regulation scheme reports and research theses. Borehole records and hydrogeological maps were examined to obtain additional information about aquifer and borehole characteristics.

The reliability of the storage coefficients was particularly difficult to evaluate in many cases because of the lack of information about the length of the tests used in their derivation. Some of the sources of error when estimating storage coefficients from pumping tests in the Chalk have already been outlined (Section 3.6.4); many of the problems arise from the fact that the Chalk fails to conform to many of the assumptions of pump test analyses. In particular:

- the assumption of instantaneous release of water from storage may lead to incorrect curve matching, if the length of the test is insufficient for the effects of delayed yield to be seen.
- leakage or recharge boundaries not recognised.
- interdependence of transmissivity and storage coefficient; the solutions for storage coefficient and transmissivity may be non-unique.
- many tests, particularly in East Anglia, were carried out on multi-aquifer systems (for example, Chalk and Crag or Chalk and glacial drift), where the overlying deposit has a higher storage and lower transmissivity than the Chalk. The resulting values obtained from these pumping tests are therefore for the combined aquifer system, and do not represent true Chalk values.

A conceptual model was proposed for the Kennet valley (Robinson, personal communication) that related regional variation in transmissivity and storage coefficient to three parameters:

- thickness of the unsaturated zone at minimum water levels
- stratigraphic height above the base of the Lower Chalk
- distance from a winter-flowing stream.

Variation in each of these values was known to affect transmissivity and it was decided to halve it each time a parameter reached the present limits shown in Table 6.1a. Maps of the three parameters were then combined to produce a transmissivity map. This fitted well with pump test-derived values of transmissivity, and the concept was extended to the Chilterns. The distribution of storage coefficients was then related to the lateral and vertical variation in transmissivity (Table 6.1b).

The distribution of storage coefficients observed for the above areas was considered to be applicable for most of the southern province. Analysis of the available data indicated the highest values are observed close to rivers where the water table is close to the surface, and a significant thickness of saturated Upper and Middle Chalk is present. Therefore the Chalk was subdivided into volumes of rock with differing storage coefficients, based on the position of the water table in relation to:

- depth from the top of the Chalk
- position in the stratigraphic sequence.

The role of secondary fissures in controlling storage coefficient and transmissivity has been described in Section 3.2. The Thames model, and other work (see Section 3.4), indicated that storage coefficient probably declines exponentially with depth, due to the decreasing number and spacing of fissures as depth increased. The difficulty of defining this function meant a step function was used instead (Figure 6.3). The values allocated are shown in Tables 6.2a and b. In each case the storage coefficient comprises contributions from specific storage and specific yield. An explanation of the mathematics behind the calculations is given in Appendix A.

By definition, where it is confined there is no specific yield from the Chalk, and all the water released from the Chalk is derived from specific storage. However water from the overlying formation contributes to yield from the Chalk, and an attempt was made to quantify the volume of water stored above the Chalk. There is very little information available on the storage coefficients of the various formations that overlie the Chalk, particularly those that are fined-grained. A further problem was that the relative volumes of the various drift lithologies could not be quantified. Therefore the resulting volumes of water should be treated with caution. The storage coefficients used for these estimates are shown in Tables 6.3a and b. Specific storage is related to porosity and the compressibility of the rock (Section 3.1.2), therefore different values were used for the Upper, Middle and Lower Chalk. In the unconfined aquifer the major contribution to the storage coefficient is generally considered to be from the specific yield. However the specific storage had becomes a significant component of the storage coefficient when the aquifer thickness is great.

Where the Chalk is overlain by drift or Tertiary deposits, lower values of specific yield were used, representing the fact that the development of secondary fissures, and hence specific yield, is limited beneath relatively impermeable cover. It was originally planned to exclude the Lower Chalk from all the calculations, as it is generally a poor aquifer when compared with the Middle and Upper Chalk. However, it contributes a significant proportion of the specific storage, and locally specific yield. It was therefore included in the volume calculations.

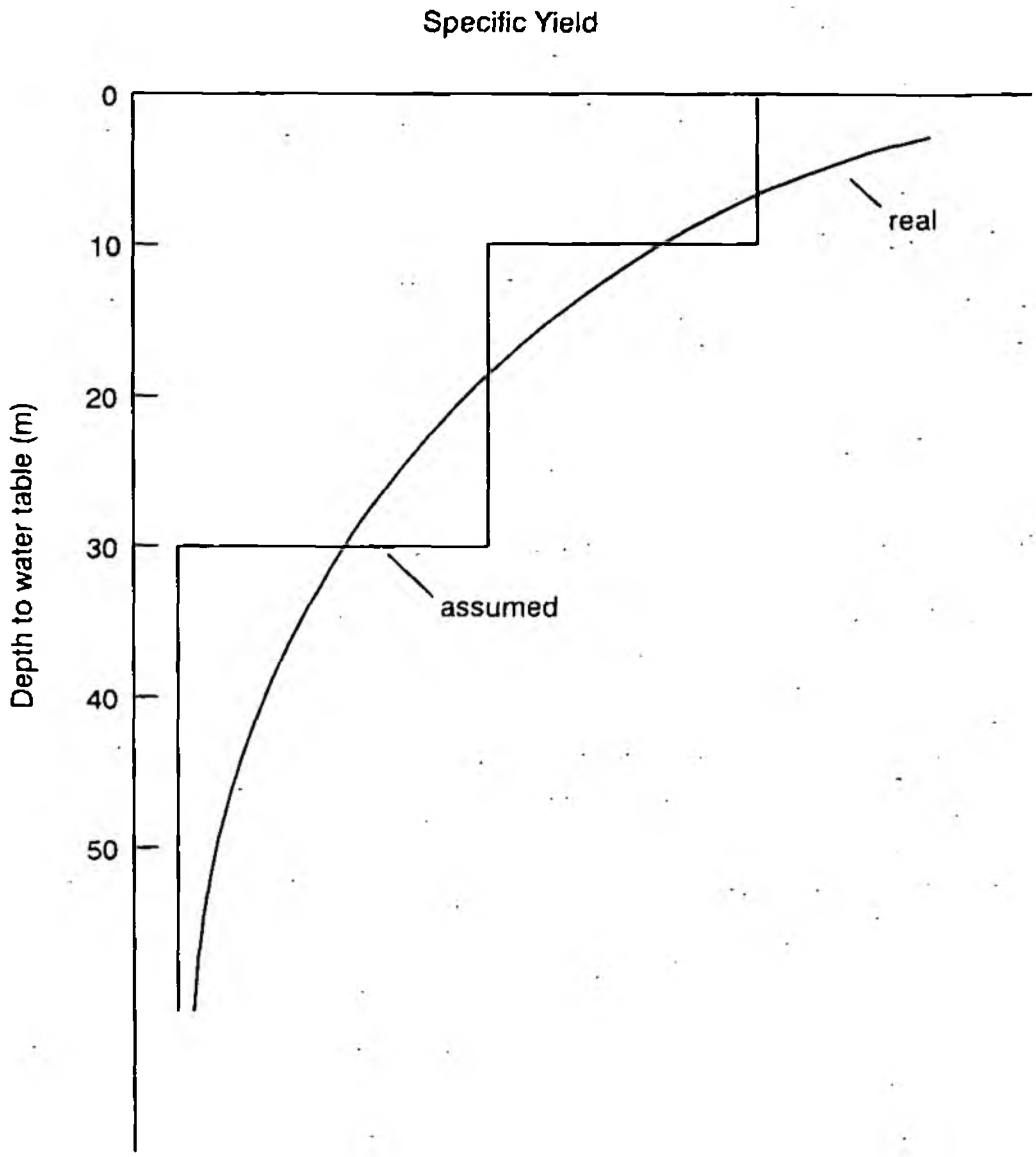


Figure 6.3 Variation in specific yield with to depth to the water table

Table 6.1a Factors affecting transmissivity in the Kennet valley (after Robinson).

	T	T/2	T/4	T/8	T/16
Depth to minimum groundwater contours (m)	<30	30-40	40-50	50-60	>60
Saturated thickness above base of Lower Chalk (m)	>90	60-90	30-60	<30	
Distance away from winter flowing stream pattern (km)	<1	1-2	2-3	>3	

T = transmissivity in Upper Chalk valley bottom situation

Table 6.1b Relationship between transmissivity and storage coefficient in the Kennet valley (after Robinson).

Transmissivity	Storage coefficient
2T	>1%
T to T/8	1%-0.1%
≤T/16	<0.1%

Table 6.2a Storage coefficients for the Chalk of the northern province

	RWL > top Chalk		< 10m below top Chalk		10-30 m below top Chalk		> 30 m below top Chalk	
	Sy	Ss	Sy	Ss	Sy	Ss	Sy	Ss
Above top of Chalk	*	*	$0.5\text{-}2 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$2\text{-}7 \times 10^{-3}$	$1.5\text{-}1.6 \times 10^{-5}$	1×10^{-3}	$1.5\text{-}1.6 \times 10^{-5}$
Top Chalk to (Base Middle + 40 m)			$0.5\text{-}2 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$0.5\text{-}2 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$1\text{-}2 \times 10^{-3}$	$1.5\text{-}1.6 \times 10^{-5}$
(Base Middle + 40 m) to base Middle			$0.5\text{-}2 \times 10^{-2}$	$6.6\text{-}7.1 \times 10^{-6}$	$2\text{-}7 \times 10^{-3}$	$6.6\text{-}7.1 \times 10^{-6}$	1×10^{-3}	$6.6\text{-}7.1 \times 10^{-6}$
Lower Chalk			$0.5\text{-}1 \times 10^{-2}$	$6.6\text{-}7.1 \times 10^{-6}$	2×10^{-3}	$6.6\text{-}7.1 \times 10^{-6}$	1×10^{-3}	$6.6\text{-}7.1 \times 10^{-6}$

Table 6.2b Storage coefficients for the Chalk of the southern province

	RWL > top Chalk		< 10m below top Chalk		10-30 m below top Chalk		> 30 m below top Chalk	
	Sy	Ss	Sy	Ss	Sy	Ss	Sy	Ss
Above top of Chalk	*	*	$1\text{-}3 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$2\text{-}7 \times 10^{-3}$	$1.5\text{-}1.6 \times 10^{-5}$	1×10^{-3}	$1.5\text{-}1.6 \times 10^{-5}$
Top Chalk to (Base Middle + 40 m)			$3\text{-}5 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$0.5\text{-}2 \times 10^{-2}$	$1.5\text{-}1.6 \times 10^{-5}$	$1\text{-}2 \times 10^{-3}$	$1.5\text{-}1.6 \times 10^{-5}$
(Base Middle + 40 m) to base Middle			$1\text{-}3 \times 10^{-2}$	$7.3\text{-}7.6 \times 10^{-6}$	$2\text{-}7 \times 10^{-3}$	$7.3\text{-}7.6 \times 10^{-6}$	1×10^{-3}	$7.3\text{-}7.6 \times 10^{-6}$
Lower Chalk			1×10^{-2}	$6.8\text{-}7.3 \times 10^{-6}$	2×10^{-3}	$6.8\text{-}7.3 \times 10^{-6}$	1×10^{-3}	$6.8\text{-}7.3 \times 10^{-6}$

*dependent on saturated formation overlying the Chalk (see Table 6.3)
Sy = specific yield RWL = rest water level
Ss = specific storage

Table 6.3a Storage values used for formations above the Chalk

	Specific Yield	Specific Storage (m^{-1})
Sand and Gravel	$1\text{-}2 \times 10^{-1}$	$10^{-6} - 10^{-3}$
Boulder Clay	$0.5\text{-}2 \times 10^{-2}$	$10^{-4} - 10^{-2}$
Crag	$1\text{-}5 \times 10^{-2}$	$10^{-4} - 10^{-2}$
London Clay	10^{-4}	10^{-3}
Woolwich & Reading Beds	$10^{-3} - 10^{-2}$	$10^{-4} - 10^{-3}$
Thanet Sands	$1\text{-}2 \times 10^{-1}$	$10^{-4} - 10^{-2}$

Table 6.3b Combined storage coefficients for saturated formations above the Chalk for individual hydrometric areas.

Hydrometric Area (m^{-1})	Overlying Deposits	Specific Yield	Specific Storage
26	Boulder clay, sands & gravels	$1 - 5 \times 10^{-2}$	$10^{-4} - 10^{-3}$
27	-	-	-
29	Boulder clay, sands & gravels	$1 - 5 \times 10^{-2}$	$10^{-4} - 10^{-3}$
30	Boulder clay	$0.5 - 2 \times 10^{-2}$	$10^{-4} - 10^{-2}$
33	Boulder clay	$0.5 - 2 \times 10^{-2}$	$10^{-4} - 10^{-2}$
34) 35) 36)	Boulder clay, sands & gravels, crag	$1 - 5 \times 10^{-2}$	$10^{-5} - 10^{-3}$
37	Boulder clay, Woolwich & Reading Beds, London Clay	$1 - 5 \times 10^{-3}$	$10^{-4} - 10^{-3}$
38	Thanet Beds	$1 - 2 \times 10^{-1}$	$10^{-4} - 10^{-2}$
39	Woolwich & Reading Beds, London Clay	$0.5 - 5 \times 10^{-3}$	$10^{-4} - 10^{-3}$
40	Thanet Beds, Woolwich & Reading Beds, London Clay	$0.5 - 2 \times 10^{-2}$	$10^{-4} - 10^{-3}$
41) 42) 43) 44)	Woolwich & Reading Beds, London Clay	$0.5 - 5 \times 10^{-3}$	$10^{-4} - 10^{-3}$
53	-	-	-

In the northern province, the different diagenetic and glacial history of the Chalk means that storage coefficients are not so obviously related to present day drainage systems or stratigraphic level. The limited data from this area suggested that specific yield was generally less than for the southern province, but probably declined similarly with depth below the water table. Therefore specific yields of 0.5-2.0 x 10^{-2} were used throughout the unconfined Chalk. Where these values were higher than those for an equivalent position in the southern province, they were reduced to the southern value. Specific storage was allocated according to formation, in the same way as in the south. The values used are shown in Table 6.2b.

6.2 250 mg/l isochlor

Saline intrusion limits the useful storage of the Chalk along much of the eastern coast of England. The 250 mg/l chloride ion concentration was chosen to represent the limit of potable water, this being the WHO limit for chlorides in drinking water (World Health Organization 1984).

The information used to define the isochlor was derived from numerous sources, (Table 6.4). In the absence of more recent data, reference was made to historical records held by BGS. Recent changes in pumping regimes may well have affected the extent of saline intrusion, and more recent data, if available, would assist in clarifying its position.

In certain areas high chlorides have been recorded as a result of mine drainage (e.g Kent) or waste disposal practice. For the purpose of this report, these have not been included.

6.3 Volumes of Water in Storage

The values of porosity and storage coefficient allocated in Section 6.1 were used in conjunction with the volumes of Chalk obtained in Section 4.3, the structural contours (Section 4), the potentiometric contours (Section 5) and the position of the 250 mg/l isochlor (Section 6.2) to calculate the following volumes of water stored in the Chalk:

- Total storage
- Dynamic storage
- 'Dead' storage

The calculations were carried out on the basis of hydrometric areas, as these divide the country up into manageable sized areas, and are generally coincident with NRA regional and Water Company boundaries. They are also static, unlike groundwater catchments which shift with seasonal water level fluctuations and are difficult to delineate.

The calculations were carried out using a FORTRAN code with the gridded ISM and SURFER files as input. The value on each node of the grid was taken to be the average of the surface over a 1 km^2 area centred on the node. Thicknesses of saturated Chalk were calculated at each node, converted to volumes, and the values for individual nodes summed for the appropriate hydrometric area. Conditions and constraints inherent in the code are listed in Appendix B; problems concerned with the calculation of volumes (plus general problems with the computing) are described in Appendix C.

Table 6.4 Sources of chloride data used in preparation of the 250 mg/l isochlor.

NRA Area	Data Source
Yorkshire	1. Recent chloride analyses from NRA, Yorkshire region, 1992. 2. Data collected from Anglian Water Authority, 1976. 3. Hydrogeological map: East Yorkshire (Institute Geological Sciences 1980)
Anglian	1. Recent chloride analyses from NRA Anglian region, Northern Area Office, 1992. 2. Data collected from Anglian Water Authority in 1976. 3. Hydrogeological maps: North and East Lincolnshire, (Institute Geological Sciences 1967). Northern East Anglia, (Institute Geological Sciences 1976). Southern East Anglia, (Institute Geological Sciences 1981). 4. Section 14 Report, (East Suffolk and Norfolk River Authority 1971). 5. Section 14 Report, (Essex River Authority 1971). 6. National Well Record collection various dates.
Thames	1. Hydrogeological map: Dartford (Kent) (Institute Geological Sciences, 1968). 2. Water Resources Board 1972. Data from Thames Water Authority, 1976. 3. Geology of south-east Essex. BGS Technical Report in press. 4. National Well Record Collection, post-1963.
Southern	1. Hydrogeological maps: South Downs (Institute Geological Sciences 1978a and b). Dartford (Kent) (Institute Geological Sciences 1968) Kent (Institute Geological Sciences 1970). 2. Data from Southern Water Authority, 1976.

6.3.1 Total Storage

The total storage is the total volume of water stored in the saturated and unsaturated zones. This was calculated by multiplying the rock volumes (Section 4.3) with the porosity values for the northern and southern Chalk provinces. The results are shown in Table 6.5. The ranges represent the values obtained using both the minimum and maximum porosities for each unit. Chalk in the unsaturated zone is generally 90% saturated and for the purpose of this calculation it was assumed that all the Chalk was fully saturated. The difference this makes to the volume calculations will be relatively insignificant when compared with the volume differences caused by the range in porosity values.

Table 6.5 Volumes of water stored in the Chalk ($x10^{12}$ m^3).

	Northern province	Southern province	Whole of England
Upper Chalk	0.01-0.13	1.12-1.44	1.22-1.57
Middle Chalk	0.02-0.03	0.46-0.54	0.48-0.57
Lower Chalk	0.01-0.02	0.31-0.47	0.32-0.49
Chalk	0.13-0.18	1.89-2.45	2.02-2.63

6.3.2 Dynamic Storage

The dynamic storage is taken as the water in the zone of fluctuation which drains out of the Chalk between maximum and minimum water levels. Using the storage coefficients detailed in Section 6.2, this volume was calculated for two periods, namely April 1975 to September 1976 and March 1988 to December 1990. As discussed in Section 5, these represent the two most recent months for which data were available when water levels were higher (April 1975 and March 1988) and lower (September 1976 and December 1990) than average.

The storage coefficients were allocated on the basis of thickness of the unsaturated zone and position in the sequence at the maximum water level of April 1975. The storage coefficient was allocated at a particular grid node according to its stratigraphic position. The storage coefficient was then decreased by moving across this row as the thickness of the unsaturated zone increased. However, the row was then set, and could not be changed even if the water level dropped into the next stratigraphic horizon. This ensured that a specific body of rock always had the same storage coefficient allocated to it, irrespective of the water level. If the increase in the thickness of the unsaturated zone between maximum and minimum water levels was sufficiently large to result in a change of column, the change in water level was divided up between the columns. For example where the water level was 8 m below the surface and in the Upper Chalk at maximum levels, and fell by 8 m to 16 m below the surface at minimum levels; the storage coefficient used was 2 m of $3\text{-}5 \times 10^{-2}$ and 6 m of $0.5\text{-}2 \times 10^{-2}$ to calculate the volume of water stored between the two levels. Similarly if the maximum water level was 15 m beneath the surface either within the basal 40 m of the Middle Chalk or in the Upper Chalk beneath drift, and it dropped 10 m to minimum level, the storage coefficient used was 10 m of $2\text{-}7 \times 10^{-3}$.

The volumes of water for both the northern and southern provinces both in total and subdivided up by hydrometric area and NRA regions, are given in Appendix D and summarised in Table 8.2.

6.3.3 'Dead' Storage

The term 'dead' storage is used to describe the volume of water stored (that could actually be drained) within the aquifer, between low water level and OD. This was calculated as two separate volumes:

- that within 10 m of the minimum water levels encountered in September 1976 or December 1990
- the water between 10 m below these minimum levels and above Ordnance Datum.

In the first case, levels were also restricted to OD. For much of the Chalk the Lower Chalk lies below sea level and has therefore been excluded. Values of storage coefficient were allocated in the same way as for the dynamic storage volumes (Section 6.3.2), for the whole country, NRA regions, and individual hydrometric areas.

7. INDIVIDUAL CATCHMENT STUDIES

7.1 Introduction

The values of storage coefficient obtained from pumping tests represent mean values for the small volume of aquifer 'sampled' by the test. Regional values that apply to whole catchments have also been obtained from the analysis of water level fluctuations (Section 3.6.2). The volume of groundwater lost from storage can be calculated from both changes in groundwater levels and from the volume of baseflow in a period of no recharge to the aquifer and the results compared. The difference between the results can then be used to indicate whether the model proposed in Section 6.1.2 for the lateral and vertical variation in storage coefficient is likely to be correct.

It was originally planned to select various catchments on the basis of geographical location and hydrogeological setting, so that the study covered a range of conditions. Thus, catchments would be selected from both the north and the south of the country, from different types and stratigraphic levels of the Chalk, of various sizes, in high and low rainfall areas and those with and without overlying superficial deposits. However the only catchments with good temporal and spatial coverage of hydrological and hydrogeological data were those that had already been studied in detail.

7.2 Selection of catchments

Initially fifteen catchments in Lincolnshire and East Anglia (Table 7.1) covering the range of geographical and hydrogeological conditions, outlined in Section 7.1, were selected for further investigation. They were chosen using the following criteria:

- Catchment wholly underlain by Chalk
- Catchment either drift-free or entirely drift-covered (with exception of stream channels)
- Artificial influences on low flows minimal

Five of the fifteen catchments had to be discarded due to artificial influences on riverflow (34010, 36008, 36011, 36012) and in one case no data being available for the relevant period (33067). Preliminary streamflow analysis was carried out on the remaining catchments. However more detailed study of the catchments meant that five more were considered unsuitable because 'drift-free' catchments were overlain in part by boulder clay (29002, 29003), groundwater abstractions were significant in relation to streamflow (33029, 38003) or there were artificial influences on riverflow (33049). The remaining five 'drift-covered' catchments were all suitable for streamflow analysis, however none had sufficient water level information such that accurate groundwater contours could be constructed. No further work was therefore carried out on these catchments.

The two series of catchments finally selected for detailed analysis (the Itchen and the Kennet) are both in the southern half of the country and virtually drift-free. They have both been investigated over a period of nearly 20 years, for schemes to abstract groundwater for river augmentation (Section 3.7), and therefore contain a large number of observation boreholes with water level information. These river augmentation schemes were tested or operated in most years. The periods studied were therefore generally shortened by this pumping, and stopped mid-summer at its commencement. This minimised artificial influences on the streamflows.

Table 7.1 List of Lincolnshire and East Anglian catchments with reasons for rejection.

29002	Great Eau at Claythorpe Mill 20% catchment underlain by Gault, 40% overlain by boulder clay	TF 416 793
29003	Lid at Louth 40% Chalk overlain by boulder clay	TF 337 879
33029	Stringside at White Bridge groundwater abstraction large compared with streamflow	TF 716 006
33045	Wittle at Quidenham limited water level data	TM 027 878
33046	Thet at Red Bridge limited water level data	TL 996 923
33049	Stanford water at Buckenham Tofts artificial influences on river flows	TL 834 953
* 33067	New River at Burwell no data for 1975-76	TL 608 696
* 34010	Waveney at Billingford Bridge artificial influences on river flows	TM 168 782
34011	Wensham at Fakenham limited water level data	TF 919 294
34012	Burn at Burnham Overy limited water level data	TF 842 428
36002	Glem at Glemsfort limited water level data	TL 846 472
* 36008	Stour at Langham artificial influences on river flows	TM 020 344
* 36011	Stour Brook at Sturmer artificial influences on river flows	TL 696 441
* 36012	Stour at Keningdon artificial influences on river flows	TL 708 450
38003	Mimram at Panshanger Park groundwater abstraction large compared with streamflow	TL 282 133

* streamflows not analysed.

7.3 Selection of Dates

The years 1975, 1976, 1988 and 1989 were selected to cover a range of high and low flows. Both the Itchen and the Kennet comprise several sub-catchments (Figures 7.1 and 7.2). The normalised streamflows at the various gauges were plotted to indicate when daily flow data was available and artificial influences minimal. From a combination of these plots, the best overall start and end dates for all the sub-catchment recessions were chosen (to the nearest half month). The dates differed slightly for the Itchen and the Kennet catchments, reflecting the differing hydrogeology and dates when the river augmentation boreholes started pumping.

The dates when water level information was available from observation boreholes were scanned. Where a large proportion of readings had been taken on the same date, close to that selected from the recessions, the chosen date was altered to this. The dates selected for both catchments are shown in Table 7.2.

The water levels recorded in three other years were later studied for selected boreholes in the catchments. This was to check whether the four chosen years covered the full range of water level fluctuations that have occurred in the recent past, and hence that the maximum amount of information on the variation of storage coefficient with depth to the water table was obtained. The extra years were 1977 and 1987 for high water level conditions, and 1990 for low levels. The data for the selected sites for all seven years are shown in Table 7.3, from which it can be seen that the three additional years do not cover a significantly different range of water levels to those already chosen.

7.4 Storage Calculations from Hydrograph Separation

In this section the methods and results of the hydrological approach to calculating volume of groundwater in storage are described. The volume of baseflow is calculated from the daily discharge data and two statistical analyses: the Baseflow Index Separation Method (Institute of Hydrology, 1980) and the recession ratio (Gustard et al, 1989).

First the selection of catchments suitable for analysis is discussed, then the data selection summarised and results of the calculations of the volume of water in store presented.

7.4.1 Initial criteria

The river Itchen, in NRA Southern region, and the river Kennet, in NRA Thames region, both comprise several sub-catchments. The flow in these rivers is gauged at 5 and 11 sites respectively, including the gauging stations on the subcatchments (Figure 7.3).

Gauging stations were selected for analysis if they met the following criteria:

- daily flow data available
- minimal artificial influences on low flows

Information on the second criterion has been obtained from the 1992 Low Flow Study station assessment record (Gustard et al., 1992) where the quality of the flow record has been indicated with two codes, one for the flow measurement errors and one for the amount of artificial influences in the gauged catchment. The information necessary to make these assessments was

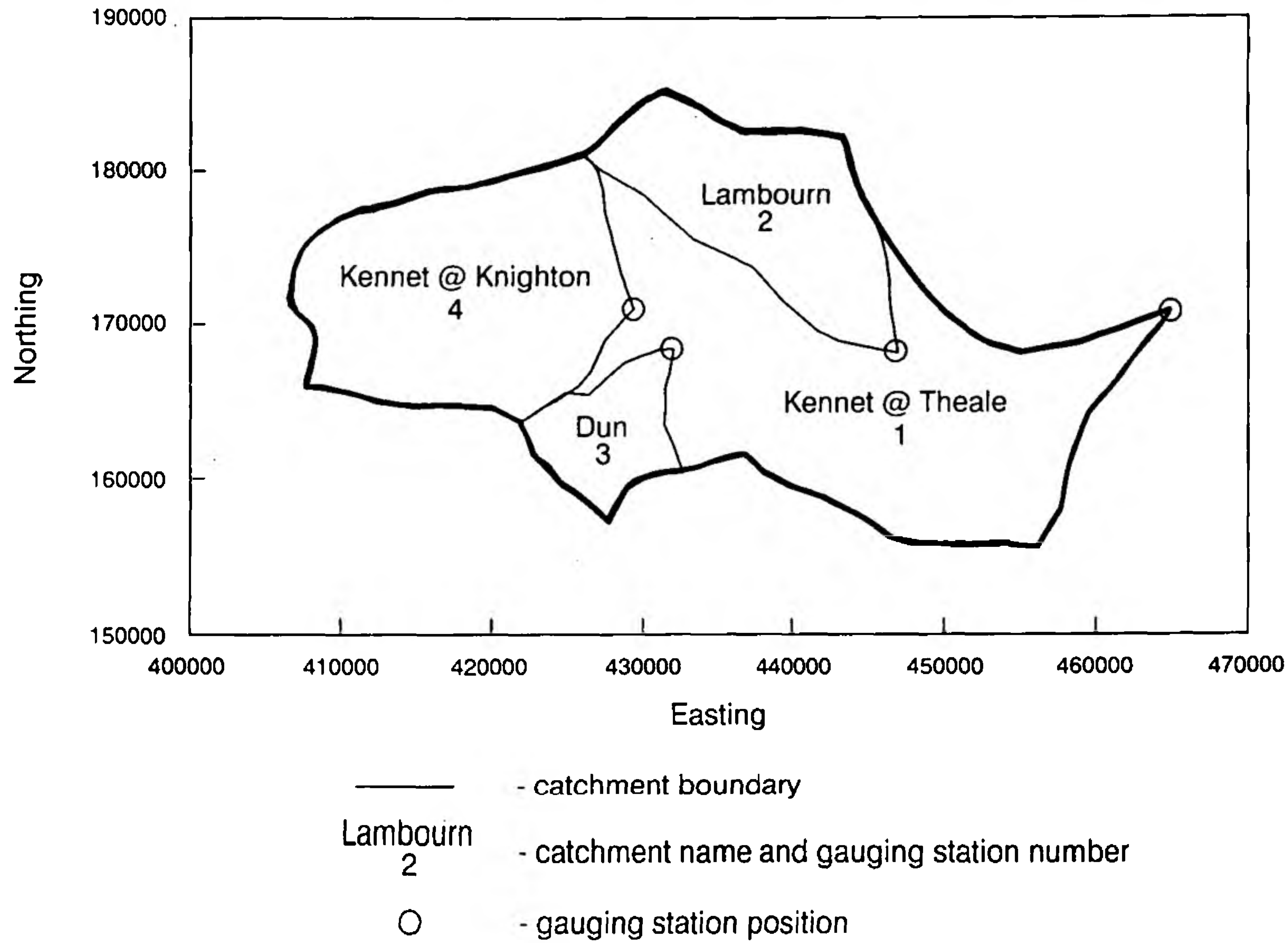


Figure 7.1 Groundwater catchments and sub-catchments for the River Kennet

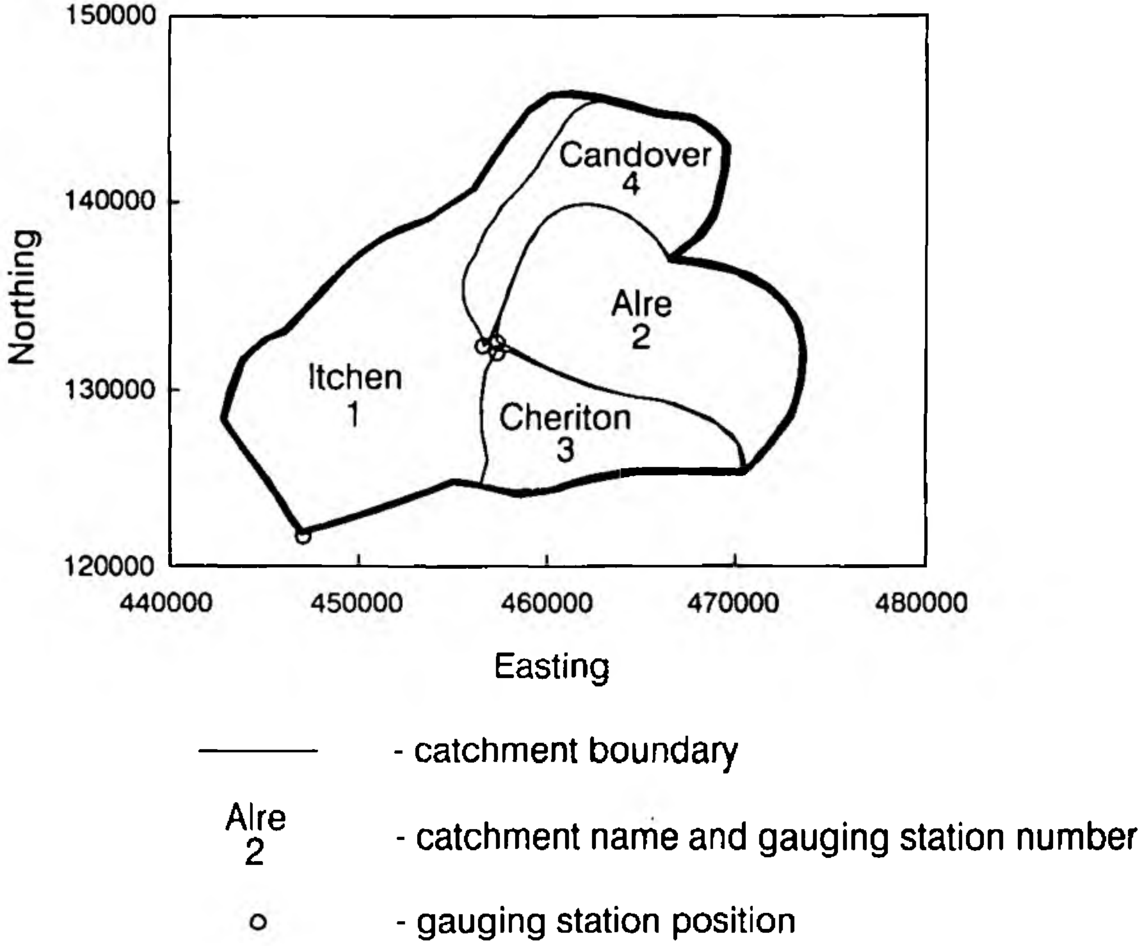


Figure 7.2 Groundwater catchments and sub-catchments for the River Itchen

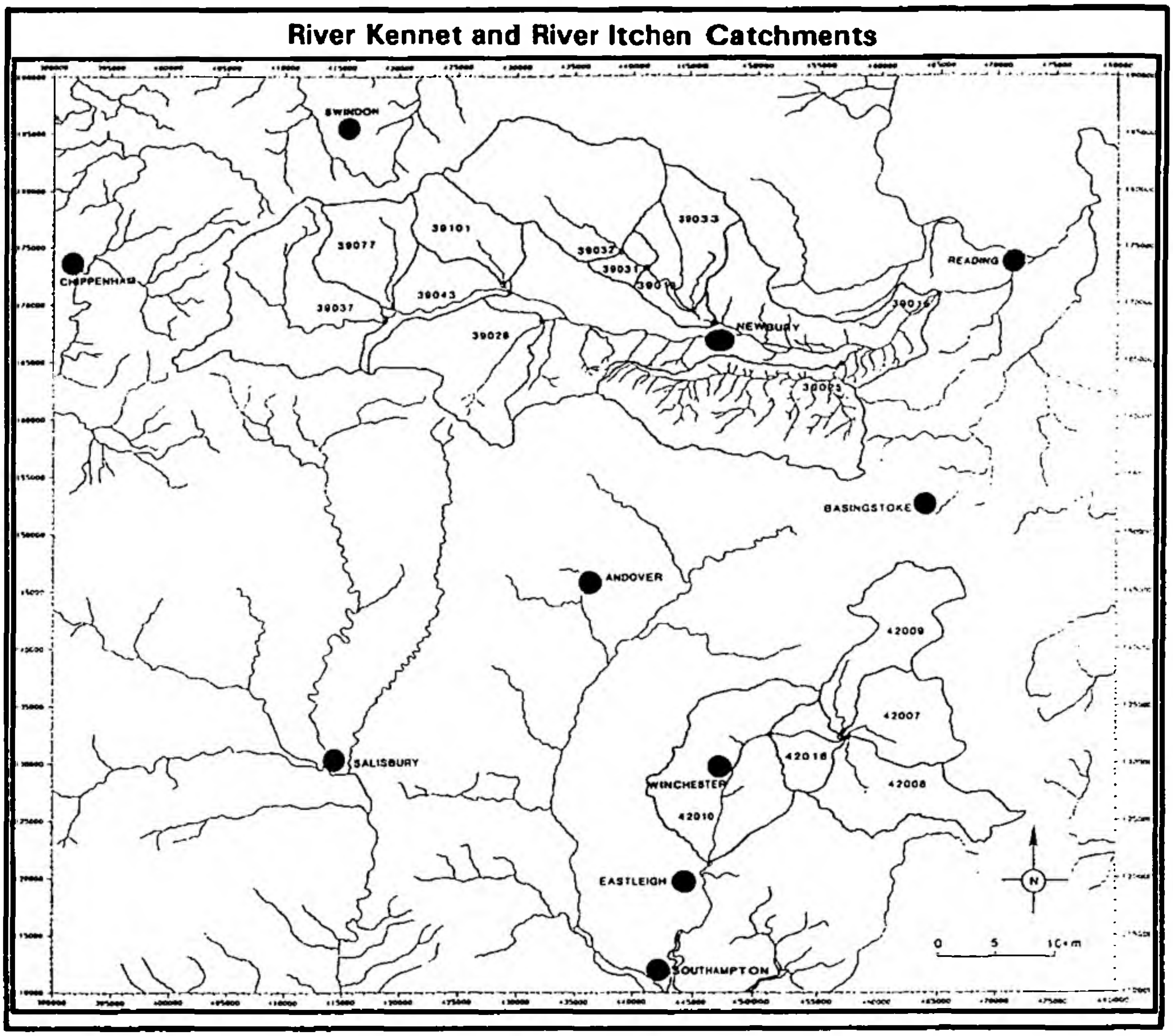


Figure 7.3 Gauged surface catchments in the River Kennet and River Itchen catchments

Table 7.2 Water levels for selected sites in the Kennet and Itchen catchments.

	1975		1976		1977		1987		1988		1989		1990	
KENNET	1/4	31/8	15/3	15/8	1/4	3/7	1/5	30/9	15/4	31/8	1/3	15/9	1/4	30/9
Rockley SU 1655 7174	140.04	131.38	129.12	<128.7	142.84	134.00	139.17	130.37	138.04	130.62	132.62	130.21	140.27	129.23
Woodside SU 3315 5645	115.57	102.87	97.52	97.00	114.89	103.75	115.58	100.08	112.00	100.53	99.31	97.52	115.66	97.24
Calversley Farm SU 5628 7530	77.28	70.97	67.30	65.53	72.64	70.70	73.27	69.08	75.87	69.64	67.91	67.23	73.28	67.85
Well Place Farm SU 6442 8525	-	-	-	-	71.07	69.39	70.41	68.21	72.16	69.01	63.44	64.66	70.76	65.62
ITCHEN	12/3	31/8	2/4	31/7	1/4	31/7	1/6	31/8	17/3	31/8	24/4	31/7	1/3	31/7
Abbotstone SU 5586 3498	-	-	65.7	65.56	66.47	65.90	65.79	65.53	65.99	65.63	65.89	65.30	66.30	65.52
Lower Wield Farm SU 6369 4048	99.96	95.06	94.98	90.91	97.42	96.28	96.62	95.39	98.12	95.81	95.77	94.42	97.00	95.09
Faringdon Station SU 7048 3491	114.13	99.56	95.51	<92.0	114.12	103.02	108.58	95.77	112.62	98.12	104.83	97.45	114.58	98.27

obtained from the relevant NRA region, and the final code was verified with them. For the present study, initially only those catchments were retained for which both grades were either A or B (see Table 7.3 for a definition of these grades). The region of study is underlain by the Chalk aquifer, and so no catchment is entirely free from groundwater abstraction. However, the choice of grade A or B stations implies a limited influence of groundwater pumping on the flows.

7.4.2 Analysis of annual hydrographs

In addition to the initial selection described above, the station selection was verified by examination of hydrographs for the selected years (see Appendix E), which resulted in accepting one station (42008) where artificial influences are classified as C but some years were acceptable for analysis. It is important to note that the artificial influences grade only reports the degree of influence on the low flow statistic Q95 (the flow which is exceeded 95 percent of the time), whereas in the present analysis a wider flow range is of interest.

Table 7.4 lists all gauging stations in the Itchen and Kennet catchments and the reason for rejection, if applicable. Some more detailed comments on the hydrographs are presented in Appendix A. Information on the nature and extent of artificial influences was obtained from the 1981-1985 Hydrometric Register (Institute of Hydrology, 1988) and station files kept at the Institute of Hydrology, as well as from the relevant NRA regions.

Because of data processing limitations for the hydrogeological part of this study, it was necessary to select one period of analysis for a catchment and for a year, for example for all Kennet catchments the same period of analysis had to be used for 1989. This of course limited the possibility of analysis of very long recessions.

Table 7.5a lists hydrological properties of the catchments that were retained for analysis. They were calculated for all catchments for the period 1970-1990 to make direct comparison of the figures possible. The flow statistics BFI (Base Flow Index) and Q95 are in a narrow band for all catchments, indicating that the catchment characteristics are very similar. The following figures of mean flow expressed as a depth over the catchment are presented for comparison only and are calculated using the surface water catchment. In practice some of these topographic catchment areas are very different from the groundwater catchment areas. In the Kennet catchment the mean flow expressed in mm/year is very similar at 230-290 mm/year. The higher mean flow from the whole Kennet catchment compared to the subcatchments may be attributed to groundwater flow from the upstream catchment, which is (partly) discharged into the stream below the upstream catchment and above the downstream gauging station.

In the Itchen catchment the runoff in mm/year gives a wide range of figures, although the rainfall is similar with all catchment average figures between 820 and 883 mm/year: the Alre catchment (42007) 869 mm/year, the downstream Itchen catchment (42010) 451 mm/year and the Candover (42009) and Cheriton Stream (42008) approximately 250 mm/year. Using the average groundwater catchment areas (Table 7.5b) the mean flow figures are more similar in the Itchen, ranging from 384 mm yr^{1} in the Alre to 252 mm yr^{1} in the Candover. In the Kennet the results of the mean flow calculations using groundwater catchment areas are spaced further than when surface water catchment areas were used, particularly the Dun.

The flows in the Alre and the Candover (42007 resp. 42009) are occasionally influenced by

Table 7.3 Classification scheme for low flow suitability

GRADE A

Accurate low flow measurement over a sensitive control (S.I. less than 20%) with the scatter of spot gaugings about the rating curve at the Q95 discharge having a factorial standard error of estimate of less than 1.1, and no obvious deterioration of the gauging station due to siltation, weed growth or vandalism.

GRADE B

Less accurate low flow measurement with either a less sensitive control (S.I. between 20% and 50%) or a factorial standard error of estimate of between 1.1 and 1.2, and/or observed periodic deterioration of the gauging station due to siltation, weed growth or vandalism.

GRADE C

Station with low accuracy of low flow measurement due to either an insensitive control (S.I. in excess of 50%), and/or with the scatter of gaugings about the rating curve at the Q95 discharge having a factorial standard error of estimate in excess of 1.2, and/or observation of sustained deterioration of the gauging station due to siltation, weed growth or vandalism.

CLASSIFICATION OF DEGREE OF ARTIFICIAL INFLUENCE

GRADE A

The gauged Q95/mean flow ratio differs by less than 20% from the estimated natural Q95/mean flow ratio.

GRADE B

The gauged Q95/mean flow ratio differs by more than 20% but less than 50% from the estimated Q95/mean flow ratio.

GRADE C

The gauged Q95/mean flow ratio differs by more than 50% from the estimated Q95/mean flow ratio.

Table 7.4 Gauging stations in the study area

Station	Selected/reason for rejection
RIVER KENNET	
39016 Kennet at Theale	selected
39019 Lambourn at Shaw	selected
39025 Enbourne at Brimpton	rejected: clay catchment
39028 Dun at Hungerford	selected
39031 Lambourn at Welford	rejected: incomplete record (1962-1983)
39032 Lambourn at East Shefford	rejected: incomplete record (1966-1983)
39033 Winterbourne at Bagnor	rejected: catchment area too small
39037 Kennet at Marlborough	rejected: grading BC
39043 Kennet at Knighton	selected
39077 Og at Marlborough	rejected: incomplete record (1980-)
39101 Aldbourne at Ramsbury	rejected: incomplete record (1982-)
RIVER ITCHEN	
42007 Alre at Drove Lane, Alresford	selected
42008 Cheriton St at Sewards Bridge	selected
42009 Candover St at Borough Bridge	selected
42010 Itchen at Highbridge+Allbrook	selected
42016 Itchen at Easton	rejected: incomplete record (1975-1983)

Table 7.5a Statistics of the selected catchments, calculated for the period 1970-1990 using surface water catchment areas

Station Location	Catchment area (km^2)	Grade	Record length	MF ($m^3 s^{-1}$)	MF ($mm y^{-1}$)	Rainfall ($mm y^{-1}$)	BFI (-)	Q95 (% MF)
RIVER KENNET								
39016 Kennet at Theale	1033.4	AA	1961-	9.516	291	761	0.875	39.7
39019 Lambourn at Shaw	234.1	AB	1962-	1.696	227	724	0.967	47.7
39028 Dun at Hungerford	101.3	AA	1968-	0.735	229	770	0.950	37.3
39043 Kennet at Knighton	295.0	BA	1962-	2.462	263	782	0.950	20.4
RIVER ITCHEN								
42007 Alre at Drove Lane, Alresford	57.0	AA	1970-	1.570	869	851	0.980	65.1
42008 Cheriton Stream at Sewards Bridge	75.1	AC	1970-	0.622	261	883	0.969	43.5
42009 Candover Stream at Borough Bridge	71.2	AB	1970-	0.540	239	821	0.964	55.7
42010 Itchen at Highbridge +Allbrook	360.0	AA	1958-	5.148	451	833	0.962	55.9

Notes: grade = result of station quality assessment during 1991 Low Flow Study.
AA = high quality flow measurements, few artificial influences
AB = high quality flow measurements, some artificial influences
BA = moderate quality flow measurements, few artificial influences
AC = high quality flow measurements, considerable artificial influences
(see Table 1 for full definitions)

MF = mean flow for 1970-1990
BFI = Base Flow Index for whole period of record, in fraction of mean flow
(see section 3 for a further description)
Q95 = 1-day mean flow that was exceeded or equalled for 95% of the time during the whole period of record, in % of mean flow

Table 7.5b Statistics of the selected catchments, calculated for the period 1970-1990 using average groundwater catchment areas

Station Location	Catchment area (km^2)	MF ($m^3 s^{-1}$)	MF ($mm\ y^{-1}$)	Rainfall ($mm\ y^{-1}$)
RIVER KENNET				
39016 Kennet at Theale	957	9.516	314	761
39019 Lambourn at Shaw	172	1.696	311	724
39028 Dun at Hungerford	51.9	0.735	447	770
39043 Kennet at Knighton	276	2.462	281	782
RIVER ITCHEN				
42007 Alre at Drove Lane, Alresford	129	1.570	384	851
42008 Cheriton Stream at Sewards Bridge	71.9	0.622	273	883
42009 Candover Stream at Borough Bridge	88.0	0.540	252	821
42010 Itchen at Highbridge +Allbrook	472	5.148	344	833

Notes:
MF = mean flow for 1970-1990
BFI = Base Flow Index for whole period of record, in fraction of mean flow
Q95 = 1-day mean flow that was exceeded or equalled for 95% of the time during the whole period of record, in % of mean flow

groundwater augmentation. In both the Kennet and the Itchen catchments, the effects of the artificial influences in the upstream catchments (groundwater augmentation, water management in
cress beds) are relatively small at the gauging stations further downstream. Details of the effect of the operation of the groundwater augmentation schemes are described in Appendix A.

7.4.3 Calculations of baseflow volume

Runoff from a catchment is often considered as being composed of a rapid response component and a slow flow or baseflow component which is derived from groundwater sources. Separating the baseflow from the total hydrograph therefore enables an approximation of the groundwater hydrograph to be derived. Many different methods of separation exist (e.g. Ineson & Downing, 1964) ranging from purely statistical to those based on water-chemistry. In this analysis a numerical baseflow separation algorithm has been used (Gustard et al., 1989). The advantages of this method are:

- automated and quick derivation from observed daily flows
- the result is objective and not influenced by the user, resulting in a unique solution for a given hydrograph

In a period of no recharge to groundwater, the volume of baseflow over the period (V_B in Figure 7.4) gives the volume of change in storage of the groundwater reservoir. If at the end of the period the storage, and therefore the baseflow, is negligible, the calculated volume represents the total baseflow volume present at the beginning of the period.

In practice, zero storage does not occur, and the available baseflow volume at the end of the period has to be estimated (V_R in Figure 7.4). This has been done by integration until infinity of the estimated baseflow recession curve, starting at the end of the period over which the baseflow separation was performed.

In order to reduce the errors in estimation of the baseflow it is desirable to perform these calculations over as long a period as possible, and to use periods when the discharge at the end of the period is low. The periods that were chosen were the summers of 1975, 1976, 1988 and 1989. It was not possible to select periods including a winter season, because the separated baseflows indicated that recharge occurred in most catchments.

a) Calculation of baseflow volume by hydrograph separation

The start and end dates of the periods of analysis (Tables 7.7a to 7.7d) have been chosen by inspection of the hydrograph and the separated baseflow line for the selected catchments and are defined as periods without apparent significant recharge. For every year one common period has been chosen for each river basin. However, in some catchments a year had to be rejected due to artificial influences on the hydrograph.

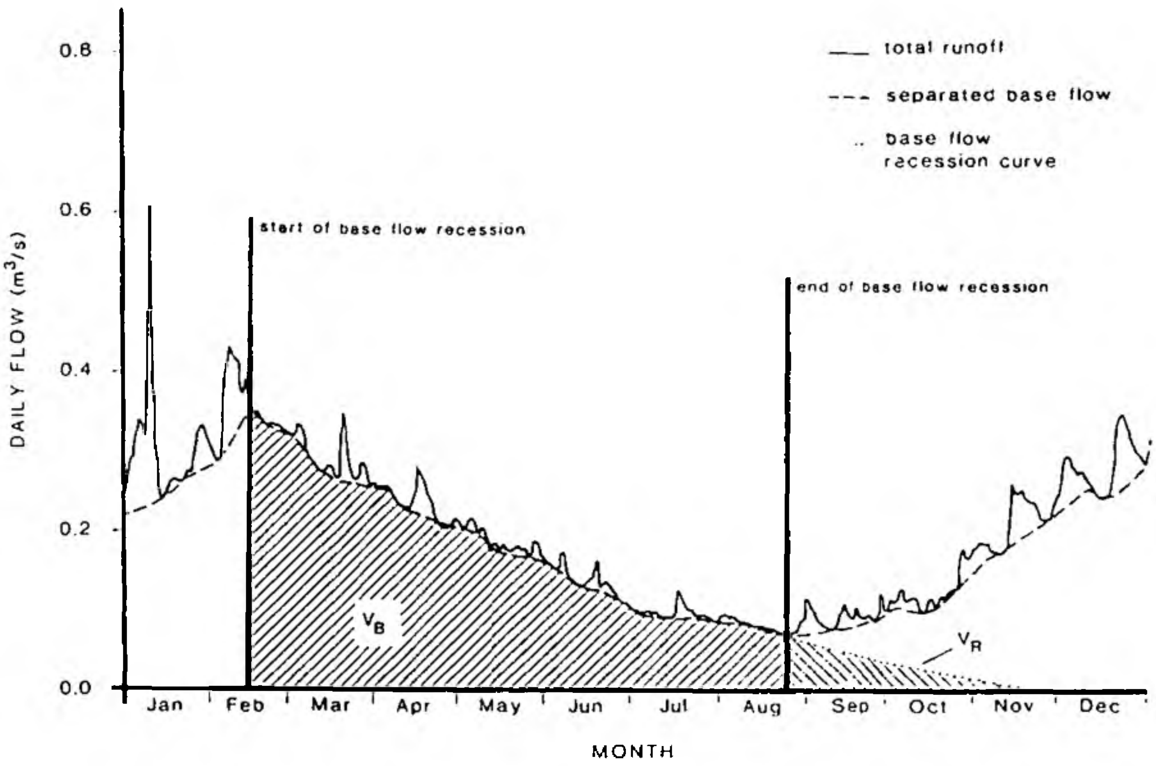


Figure 7.4 Hydrograph with separated baseflow and calculated baseflow recession curve

Table 7.6 Mean groundwater catchment areas for the period of analysis

Station Location	Catchment area (km^2)				
	1975	1976	1988	1989	average
RIVER KENNET					
39016 Kennet at Theale	950	927	1000	974	957
39019 Lambourn at Shaw	179	177	168	167	172
39028 Dun at Hungerford	69.3	40.7	63.7	62.4	51.9
39043 Kennet at Knighton	287	272	273	274	276
RIVER ITCHEN					
42007 Alre at Drove Lane, Alresford	133	129	127	125	129
42008 Cheriton Stream at Sewards Bridge	69.7	66.8	79.2	72.2	71.9
42009 Candover Stream at Borough Bridge	82.7	90.0	89.2	90.0	88.0
42010 Itchen at Highbridge +Allbrook	465	468	471	479	472

Table 7.7a Calculated baseflow volumes in Spring 1975

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 1 4 1975 to 31 8 1975 (153 days)									
39016 Kennet	0.953	8.94	112.6	118	0.9884	4.57	33.8	36	146.4	154
39019 Lambourn	0.988	2.19	28.6	160	0.9918	1.15	12.0	67	40.6	227
39028 Dun	0.959	0.76	9.60	139	0.9909	0.417	3.94	57	13.5	196
39043 Kennet	0.870	2.96	34.1	119	0.9904	1.14	10.2	36	44.3	155
RIVER ITCHEN catchment	period of analysis: 12 3 1975 to 31 8 1975 (173 days)									
42007 Alre	0.982	1.96	28.8	217	0.9960	1.43	30.8	232	59.6	449
42008 Cheriton Str	0.992	0.70	10.5	151	0.9940	0.820	5.59	80	16.1	231
42009 Candover	0.975	0.64	9.34	113	0.9937	1.42	6.21	75	15.6	188
42010 Itchen	0.982	5.52	81.0	174	0.9921	3.37	36.7	79	117.7	253

Notes
(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve baseflow, i.e. $-Q_T * 86400/\ln K$, in $10^6 m^6$
(8) Volume of recession curve baseflow as in (7), in mm, calculated using groundwater catchment area
(9) Total baseflow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total baseflow volume water in mm, i.e. (4) + (8)

Table 7.7b Calculated baseflow volumes in Spring 1976

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 3 1976 to 15 8 1976 (154 days)									
39016 Kennet	0.904	2.53	30.4	33	0.9884	1.31	9.70	10	40.1	43
39019 Lambourn	0.984	0.607	7.95	45	0.9918	0.426	4.47	25	12.4	70
39028 Dun	0.967	0 279	3.59	88	0.9909	0.201	1.90	47	5.49	135
39043 Kennet	0.886	0.345	4.07	15	0.9904	0.132	1.18	4	5.25	19
RIVER ITCHEN catchment	period of analysis: 2 4 1976 to 31 7 1976 (121 days)									
42007 Alre	0.982	0.978	10.0	78	0.9960	0.820	17.7	137	27.7	215
42008 Cheriton Str	0.970	0.247	2.50	37	0.9940	0.174	2.50	37	5.00	74
42009 Candover	not suitable (groundwater augmentation)									
42010 Itchen	0.969	2.83	28.7	61	0.9921	2.46	5.81	12	34.5	73

Notes
(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve baseflow, i.e. $-Q_T$ * 86400/ln K, in $10^6 m^6$
(8) Volume of recession curve baseflow as in (7), in mm, calculated using groundwater catchment area
(9) Total baseflow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total baseflow volume water in mm, i.e. (4) + (8)

Table 7.7c Calculated baseflow volumes in Spring 1988

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 4 1988 to 31 8 1988 (138 days)									
39016 Kennet	0.964	7.45	86.3	86	0.9884	6.65	49.2	49	135.5	135
39019 Lambourn	0.965	1.69	19.6	117	0.9918	1.21	12.7	76	32.5	193
39028 Dun	0.971	0.582	6.78	106	0.9909	0.381	3.60	57	10.4	163
39043 Kennet	0.985	1.94	22.9	84	0.9904	1.08	9.67	35	32.6	119
RIVER ITCHEN catchment	period of analysis: 17 3 1988 to 31 8 1988 (168 days)									
42007 Alre	0.987	1.79	25.6	202	0.9960	1.42	30.6	241	56.2	443
42008 Cheriton Str	0.984	0.638	9.11	115	0.9940	0.432	6.20	78	15.3	193
42009 Candover	0.981	0.568	8.09	91	0.9937	0.425	5.81	65	13.9	156
42010 Itchen	0.978	5.15	73.1	155	0.9921	2.62	41.5	88	114.6	243

Notes
(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve baseflow, i.e. $-Q_T$ * 86400/ln K, in $10^6 m^6$
(8) Volume of recession curve baseflow as in (7), in mm, calculated using groundwater catchment area
(9) Total baseflow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total baseflow volume water in mm, i.e. (4) + (8)

Table 7.7d Calculated baseflow volumes in Spring 1989

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 4 1989 to 15 9 1989 (154 days)									
39016 Kennet	0.959	6.21	79.2	81	0.9884	4.45	33.0	34	112.2	115
39019 Lambourn	0.982	1.35	17.6	105	0.9918	0.896*	12.1	72	29.7	177
39028 Dun	0.970	0.470	6.07	97	0.9909	0.275	3.94	63	10.0	160
39043 Kennet	0.997	1.82	24.2	88	0.9904	0.792	10.2	37	34.4	125
RIVER ITCHEN catchment	period of analysis: 24 4 1989 to 31 7 1989 (99 days)									
42007 Alre	not suitable (groundwater augmentation)									
42008 Cheriton Str	0.994	0.486	4.13	57	0.9940	0.284	4.08	57	8.21	114
42009 Candover	0.982	0.416	3.49	39	0.9937	0.282	3.85	43	7.34	82
42010 Itchen	0.955	3.96	32.3	67	0.9921	2.62	28.5	59	60.8	126

Notes

* Because the gauge was drowned from 10.9.89, the flow on 9.9.89 has been taken to represent the correct value

(1) Base Flow Index over specified period, in fraction of mean flow (column 2)

(2) Mean Flow over specified period, in $m^3 s^{-1}$

(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$

(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area

(5) Recession constant

(6) Flow at the end of the 'no recharge' period

(7) Volume of recession curve baseflow, i.e. $-Q_T * 86400/\ln K$, in $10^6 m^6$

(8) Volume of recession curve baseflow as in (7), in mm, calculated using groundwater catchment area

(9) Total baseflow volume in $10^6 m^3/s$, i.e. (3) + (7)

(10) Total baseflow volume water in mm, i.e. (4) + (8)

Baseflow was separated from direct runoff by a standard Institute of Hydrology algorithm (see Section 7.3.1) (Gustard et al 1989). The algorithm follows a stepwise approach:

- divide the daily flow data into five day non-overlapping blocks and calculate the minimum for each of these blocks
- determine turning points of the five-day minimum values
- connect the turning points to give the separated baseflow line

Tables 7.7a to 7.7d give the results of the calculations of baseflow runoff volume for all catchments (columns 3 and 4). The value which is most easily comparable is the baseflow volume expressed as a depth over the catchment area (in mm), calculated using the average value of the estimated groundwater catchment area for the appropriate year (see Table 7.6).

b) Calculation of baseflow volume by recession analysis

The baseflow recession curve is given by (Ineson & Downing, 1964):

$$Q(t) = Q_T K^t \qquad (1)$$

where Q_T is the flow at the start of the recession and K the recession constant. Alternatively this can be expressed as:

$$K^t = Q(t)/Q_T \qquad (2)$$

The recession constant, K, in Equation (1) has been calculated using a standard Institute of Hydrology algorithm (Gustard et al., 1989). According to this algorithm, all 2-day recession pairs with a starting point less than the mean flow are extracted from the flow record, and their individual 2-day K value (or ratio of the flows) is calculated with Equation (2). The 1-day K is the square root of the 2-day K. The algorithm then proceeds to calculate the distribution of the K values. The 90-percentile K was selected as the catchment recession 'constant' to calculate the baseflow volume under the recession curve with the following formula:

$$\int_0^{\infty} Q^T K_t dt = -86400 Q_T / \ln K \qquad (3)$$

where the constant converts from seconds to days. The solution of the integral assumes that the groundwater reservoir decays exponentially. Tables 7.7a to 7.7d present the results of these calculations (columns 5 to 8). The baseflow volume under the recession curve in mm was calculated using the estimated groundwater catchment area for the appropriate year (see Table 7.6).

c) **Calculation of total baseflow volume**

The estimated total baseflow volume at the start of the analysis period is the sum of the results of the calculations presented in Sections 7.4.3a) and b). The results are presented in Tables 7.7a to 7.7d (columns 9 and 10).

A second approach to comparing the results from hydrogeological and hydrological calculations has been to calculate the depletion of the groundwater reservoir over a specified period, not taking into account the baseflow volume of water that may have remained at the end of the 'no recharge' period. In this case, the baseflow volume under the recession curve has not been considered, and the calculations are confined to those described in Section 7.4.3a.

7.4.4 Volume Calculations

a) **Baseflow Volume**

Comparison of values of the volumes of water that were calculated for the 8 catchments is only possible if the volumes are converted to a depth of water, for example expressed in mm. A summary of all figures is given in Table 7.8. Apart from the differences in catchment area, the length of the period analysed has to be taken into account when comparing the volume of baseflow. The following observations can be made:

- In all years except 1989 the average volume of separated baseflow in the Itchen (49010) was higher than in the Kennet (39016). This may be explained by higher annual rainfall in the Itchen (Table 7.5a). The exception in 1989 is a result of a much shorter period of analysis in the Itchen; a similar length of period would have given more baseflow in the Itchen than in the Kennet.

- In the Itchen and the Kennet the average volume of separated baseflow was lowest in 1976. This was a result of the low rainfall, and therefore low recharge and low runoff, in the winter of 1975-1976.

- In general the pattern of variation in the separated baseflow in the subcatchments within the main catchments is consistent from year to year. This suggests that no great errors result from the hydrological calculations. However, there is a wide spread of figures amongst the subcatchments within the main Itchen catchment (42007, 42008 and 42009). Three reasons may be identified: a) variation in recharge, b) variations in the hydraulic relation between the aquifer and the stream, c) the groundwater catchments do not represent the actual contributing catchment.

It may be assumed that the results for the main catchments are more accurate than for the small subcatchments because of the smaller relative errors in flow and area calculations.

In the Kennet the calculated volume of separated baseflow (in mm) is consistently higher in the subcatchments Lambourn (39019) and Dun (39028), compared with the Kennet as a whole (39016). The differences in catchment average rainfall do not explain this. It is possible that the groundwater catchments in the two subcatchments have been underestimated. Alternatively, there may be more water draining into the stream in the upstream catchments because of a steeper hydraulic gradient of the water table. The calculated volume in the upstream Kennet (39043) is very close to the volume calculated for the whole Kennet (39016), apart from 1976. A possible explanation for the different behaviour in this very dry year is that a severe lowering of the water table caused the effective contributing catchment to be reduced significantly.

In the Itchen the calculated volume in the Alre (42007) is much higher than from the total catchment (42010), and that in the Candover (42008) is much lower. A possible explanation for this would be a groundwater divide which makes the Candover catchment too big at the expense of the Alre. The calculated volume in the Cheriton Stream (42009) agrees with the figure for the whole Itchen.

b) Recession curve baseflow volume

The baseflow volumes under the recession curve were converted to a depth of water, expressed in mm. A summary of all calculations is given in Table 7.8. The following observations can be made:

- In all years the average volume of recession curve baseflow was higher in the Itchen (42010) than in the Kennet (39016). This may be explained by higher annual rainfall in the Itchen (Table 7.5a). The volume of recession curve baseflow in 1976 was similar in both catchments, and very low.
- In general the pattern of variation in the volume of recession curve baseflow in the subcatchments within the main catchments is consistent from year to year. This suggests that no great errors result from the hydrological calculations. However, there is a wide spread of figures amongst the subcatchments within both main catchments. In addition to the three reasons for this variation identified above (Section 7.4.3a), the choice of the catchments' recession constant K is uncertain and has a big effect on the result of the calculations. For example, an addition of 0.001 to the K value of the Kennet at Knighton (0.9904) would change the calculated volume in 1975 from 10.2 to 11.4 x $10^6 m^3$.

The latter problem is illustrated by the consistently high figures in the Alre catchment. In all seasons the volume of water still in store is estimated to be equal to the volume of recession baseflow, and higher than or equal to the total baseflow volume in the other catchments. In the other catchments the volume of recession curve baseflow is generally estimated to be a third to half of the separated baseflow volume. The high K value for the Alre, the highest of all K values, is supported by the highest Q95 and the highest Baseflow Index. It is possible that the recession is slower from the Alre catchment than from the other catchments because the groundwater catchment is much larger than the surface water catchment. This would mean that the water from the top end of the catchment would take longer to reach the stream than when the groundwater divide is closer to the stream.

c) Total baseflow volume

The total baseflow volume over the analysed periods is the sum of the volumes discussed above (Sections 7.4.4) and b)). The same pattern of variation between the years and between the catchments can be observed in the total baseflow volumes, and the same comments therefore apply to these figures.

The proportion of this total baseflow volume which is taken by the volume of recession curve baseflow (Table 7.8) depends, amongst other things, on the catchment's recession constant K: the proportion of water that is estimated to remain in store is consistently higher in the Itchen catchments. Excluding the extremely dry year 1976, which shows different behaviour to the other years, in the Itchen the fraction of the total volume which is taken by the recession curve baseflow varies from 0.54 to 0.31 with an average of 0.44, while in the Kennet it varies from 0.41 to 0.21 with

The total volumes will have to be compared with the volumes of drainable water calculated using hydrogeological data and methods.an average of 0.32. In general, the relative contribution of the recession curve baseflow volume is smaller in the main catchments (39016 and 42010) compared to the upstream subcatchments.

7.5 Storage Calculations from Groundwater Levels

Groundwater level data were obtained for the Itchen and Kennet catchments and surrounding areas from the Southern and Thames regions of the National Rivers Authority. If data were not available for the exact date required, or within a few days of it, a level was obtained by interpolation from the two dates either side of it, (assuming that the water level varied linearly between them). This is not strictly the case, but the method provided many additional data points that are likely to be within half a metre of the true level. Interpolations were only carried out between points if they were on the same portion (slope) of the groundwater hydrograph. In a few cases the start date of the streamflow recession occurred before the peak of the groundwater hydrograph, and therefore water levels continued to rise for a short period after this date. This means that the volume of groundwater calculated as lost from storage will be an under-estimate (see Figure 7.5a). At the end of the recession, although the date chosen was prior to commencement of pumping, a later date used to interpolate data may have been affected by pumping and hence the volume of groundwater calculated as lost from storage in this case will be an over-estimate (Figure 7.5b).

Because of the problems experienced with the computer generated water level contours for the whole of the Chalk (Section 5.5) the water level contours were produced by hand. This enabled both the surface topography (particularly in areas with limited data points) and the topography of the rivers (which are generally in hydraulic continuity with the underlying aquifer) to be taken into account. It also ensured that the positions of the contours could be controlled to ensure that the groundwater divides which define the groundwater catchments flowing to each of the river gauges, looked realistic and cut the contours perpendicularly. The groundwater level contour plots for the catchments appear in Appendix F.

The volumes of rock within each of the categories detailed in Section 6.3.2 were calculated. The volume of water draining from the Chalk, during the summer recessions of 1975, 1976, 1988 and 1989 was then calculated for each sub-catchment, using the same storage coefficients as in Section 6.3.2. The total volume of water that could be drained from each catchment between the water level at the second (end) date of the recession and the height of the gauge, in infinite time, was also calculated. The results were then compared with the values obtained from the stream flow recession analysis (see Section 8).

The FORTRAN code referred to in Section 6.3 was again used to calculate the volumes. A refined grid of 250 x 250 m was used in the catchment work, and the value at each node was taken as the average over a 0.625 km^2 area.

Table 7.8 Summary of the baseflow volume calculations

	1975			1976			1988			1989		
	BF vol (mm)	REC vol (mm)	TOTAL (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)
RIVER KENNET catchment												
39016 Kennet	118	36	154	33	10	43	86	49	135	81	34	115
39019 Lambourn	160	67	227	45	25	70	117	76	193	105	72	177
39028 Dun	139	57	196	88	47	135	106	57	163	97	63	160
39043 Kennet	119	36	155	15	4	19	84	35	119	88	37	125
RIVER ITCHEN catchment												
42007 Alre	217	232	449	78	137	215	202	241	443	-	-	-
42008 Cheriton Str	151	80	231	37	37	74	115	78	193	57	57	114
42009 Candover	113	75	188	-	-	-	91	65	156	39	43	82
42010 Itchen	174	79	253	61	12	73	155	88	243	67	59	126

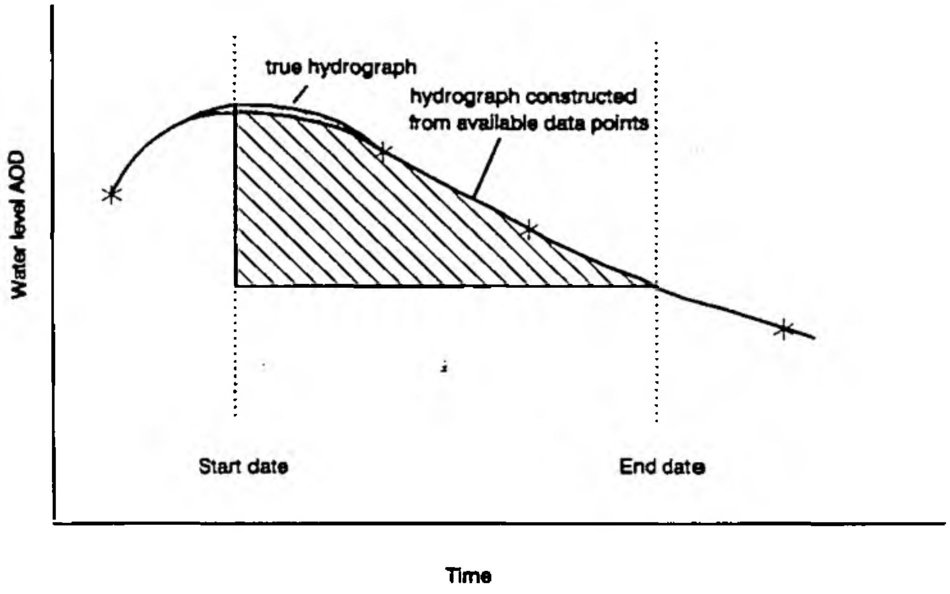


Figure 7.5a Volume of water calculated from groundwater fluctuations - errors at the start of the recession period

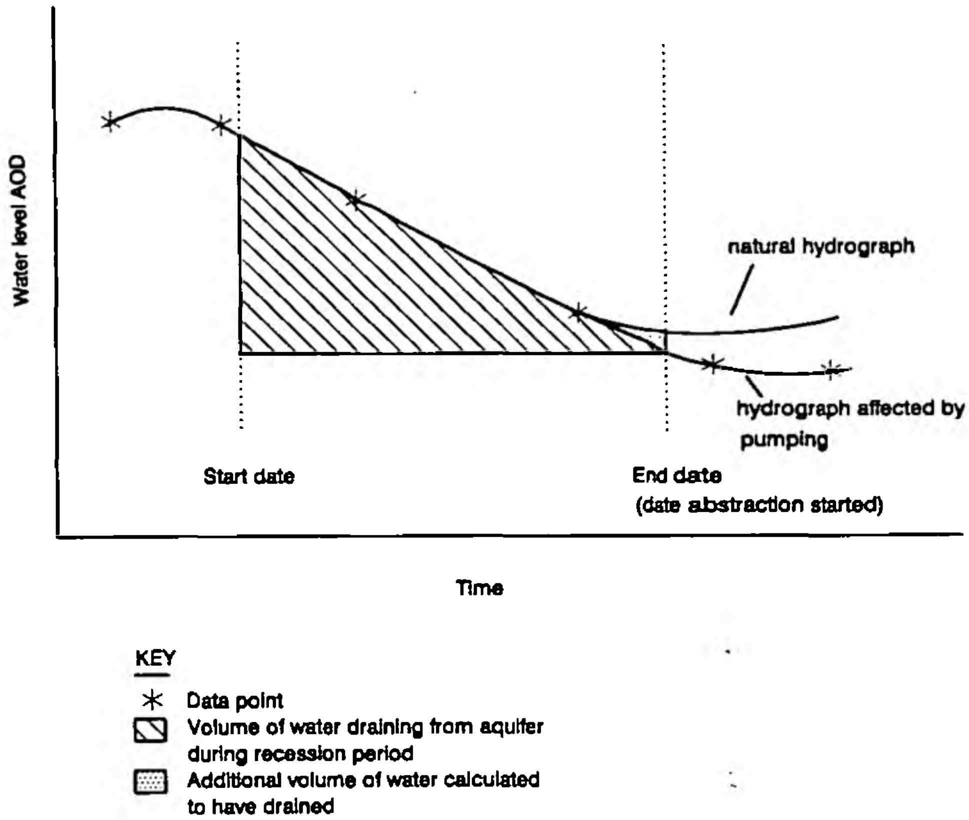


Figure 7.5b Volume of water calculated from groundwater fluctuations - errors at the end of the recession period

8. RESULTS

The development of the Chalk structure and water level contour maps, and the calculation of the water volumes have already been described in Sections 4 to 6. This section describes the results of the calculations. Full tables of the results for the catchments, NRA regions, and the whole of the Chalk of England, are given in Appendix D. These tables give: total volumes (between various levels), contributions to that total from the Chalk and the cover, and the proportion of the maximum to minimum volume that is contributed by the specific storage.

8.1 Total Volume of Water

The total volume of water contained within the Chalk, and sub-divided into Lower, Middle, and Upper Chalk is given in Table 6.5; this was calculated to represent the volume of Chalk water susceptible to pollution.

8.2 Volume of 'Usable' Water

8.2.1 Catchment Studies (Kennet and Itchen)

The baseflow separation method calculated the volume of water lost from the aquifer between the start and end of chosen recession periods (baseflow volume), and estimated the volume of water remaining between the final level and the point at which the stream would theoretically cease to flow (recession volume). The hydrogeological approach yielded values for the volume of water between the start and end dates of the recession period, and between the final water level and gauge level. Whilst the latter is similar in concept to the 'recession' volume, there are differences. These will be discussed in Section 9.

The results are summarised in Table 8.1. The volumes calculated by the two approaches are significantly different, the hydrogeological approach apparently underestimating volumes in storage. The table also summarises the results of the two approaches to measuring the volume of water remaining in storage below the low water level. Although the results for the two approaches are very similar for the sub-catchments, the volumes calculated for the overall catchments are an order of magnitude greater for the hydrogeological approach than for the streamflow method.

Due to an error in the 1989 data, no volume calculations have as yet been carried out for the Kennet catchment for that year.

8.2.2 The whole of the Chalk

Table 8.2 summarises the volume calculations for each hydrometric area, NRA regions (defined as groups of hydrometric areas, as given in Appendix D), and for the UK as a whole; the results are given in full in Appendix D. The table also shows the estimated yearly infiltration to, and abstraction from, the Chalk aquifer in each case (from Monkhouse and Richards, 1982). The volumes calculated between minimum and minimum minus 10 m, and between minimum minus 10 m and OD were virtually identical for both time periods, and only the 1988/1990 figures are given in Table 8.2. The table also shows the amount of water stored in the overlying deposits.

Table 8.1 Results of streamflow recession and groundwater fluctuation methods for the Kennet and Itchen catchments

1975

	Baseflow vol ($m^3 \times 10^6$)	Max - min ($m^3 \times 10^6$)	Recession vol ($m^3 \times 10^6$)	Min - gauge ($m^3 \times 10^6$)
Kennet				
0 Overall	113	13 - 22	34	120 - 200
2 Lambourn	29	2.5 - 5.0	12	15 - 23
3 Dun	10	0.4 - 0.8	4	2.1 - 4.4
4 Kennet	34	3.9 - 5.2	10	11 - 14
Itchen				
0 Overall	81	5.9 - 11	37	75 - 120
2 Candover	9	1.1 - 1.8	6	11 - 16
3 Alre	29	2.0 - 3.0	31	11 - 16
4 Cheriton	11	1.0 - 2.0	6	4.1 - 7.6

1976

	Baseflow vol ($m^3 \times 10^6$)	Max - min ($m^3 \times 10^6$)	Recession vol ($m^3 \times 10^6$)	Min - gauge ($m^3 \times 10^6$)
Kennet				
0 Overall	30	5.2 - 10	10	110 - 180
2 Lambourn	8	1.3 - 2.1	4	12 - 17
3 Dun	4	0.2 - 0.5	2	1.4 - 3.3
4 Kennet	4	0.01 - 0.27	1	9.1 - 12
Itchen				
0 Overall	29	2.3 - 4.6	6	72 - 110
2 Candover	-	0.7 - 1.5	-	11 - 16
3 Alre	10	0.6 - 1.1	18	8.9 - 13
4 Cheriton	2.5	0.2 - 0.5	3	3.7 - 6.8

Note: The two groundwater volumes result from the minimum and maximum storage values given Table 6.2
Baseflow vol and Recession vol calculated from the streamflow recession
Max - min and Min - gauge calculated by the groundwater fluctuation approach

1988

	Baseflow vol ($m^3 \times 10^6$)	Max - min ($m^3 \times 10^6$)	Recession vol ($m^3 \times 10^6$)	Min - gauge ($m^3 \times 10^6$)
Kennet				
0 Overall	86	12 - 21	49	120 - 200
2 Lambourn	20	2.5 - 5	13	9.1 - 13
3 Dun	7	-0.3 - -0.9	4	2.6 - 5.7
4 Kennet	23	2.1 - 2.6	10	12 - 15
Itchen				
0 Overall	73	4.9 - 9.4	42	76 - 120
2 Candover	8	0.5 - 1.0	6	12 - 18
3 Alre	26	1.8 - 2.9	31	9.9 - 15
4 Cheriton	9	1.4 - 2.8	6	4.3 - 7.6

1989

	Baseflow vol ($m^3 \times 10^6$)	Max - min ($m^3 \times 10^6$)	Recession vol ($m^3 \times 10^6$)	Min - gauge ($m^3 \times 10^6$)
Kennet				
0 Overall	79	*	33	*
2 Lambourn	18	*	12	*
3 Dun	6	*	4	*
4 Kennet	24	*	10	*
Itchen				
0 Overall	32	4.7 - 8.6	29	77 - 120
2 Candover	3	0.8 - 1.3	4	11 - 17
3 Alre	-	1.8 - 3.1	-	8.7 - 13
4 Cheriton	4	0.8 - 1.5	4	3.9 - 7.0

Note: The two groundwater volumes result from the minimum and maximum storage values given Table 6.2
Baseflow vol and Recession vol calculated from the streamflow recession
Max - min and Min - gauge calculated by the groundwater fluctuation approach
* not yet computed

Table 8.2 Volumes of water stored in the Chalk and overlying deposits for individual hydrometric areas, NRA regions, and in total

Hydrometric Area	1975/76 ($m^3 \times 10^6$) Max-Min Chalk	Cover	1988/90 ($m^3 \times 10^6$) Max-Min Chalk	Cover	Min - 10 Chalk	Cover	(Min-10) - OD Chalk	Cover	Av. Yearly infiltration ($m^3 \times 10^6$)	Av. Yearly abstraction ($m^3 \times 10^6$)
26	20-38	9.6-53	29-56	9-50	38-66	24-130	25-38	0.2-1	) 321	) 15
27*	0.7-0.9	-	0.9-1	-	2-3	-	7-8	-	)	)
29	9-19	17-99	11-23	23-130	5-9	19-110	0.8-1	0.8-5	) 115	) 58
30*	0.4-0.6	0.1-1	0.2-0.3	0.1-0.9	-	0.03-0.7	-	-	)	)
33	83-170	12-61	110-230	12-63	180-380	28-150	240-490	21-100	428	80
34	47-75	44-310	50-83	43-290	190-300	240-1600	390-780	220-1400	298	31
35	14-23	8-52	15-26	12-78	66-100	76-500	93-200	42-260	92	26
36	16-24	17-110	17-26	16-98	59-110	61-380	150-320	38-220	39	23
37*	14-16	37-350	14-20	27-250	51-74	76-700	120-200	68-610	not avail	31
38	46-94	11-190	30-61	11-170	86-180	37-650	200-360	39-540	89	97
39•	180-310	97-970	120-230	-25--250	260-450	170-1700	730-1100	390-3900	822	408
40	27-45	6-38	29-52	5-39	55-93	10-55	81-120	4-22	330	153
41	35-53	2-17	40-60	1-14	29-42	2-20	40-50	0.02-0.2	303	89
42•	100-190	10-100	75-130	13-130	120-210	65-650	300-430	25-250	733	110
43*	23-47	-8- -0.8	10-24	0.1-1	120-200	46-460	270-410	33-330	635	96
44*	-0.05-0.2	1-9	8-15	1-14	30-54	8-81	51-75	0.8-8	256	44
53*	0.4	0	0.4	-	0.8	-	1.2	-	39	3

* denotes poor borehole coverage over a large part of the hydrometric area

• denotes poor coverage over the Thames Basin or Hampshire Basin

Table 8.2 ctd   Volumes of water stored in the Chalk and overlying deposits for individual hydrometric areas, NRA regions, and in total

	1975/76 ($m^3 \times 10^6$)				1988/90 ($m^3 x10^6$)			
Hydrometric	Max-Min		Max-Min		Min - 10		(Min-10) - OD	
Area	Chalk	Cover	Chalk	Cover	Chalk	Cover	Chalk	Cover
NRA :-								
Yorks	21-39	10-53	30-57	9-50	41-70	24-130	32-46	0.1-1
Anglian	180-330	130-980	220-410	130-920	560-980	500-3400	1000-2000	390-2600
Thames	220-400	110-1200	150-290	-14--80	350-630	210-2300	930-1500	430-4500
Southern	170-280	18-160	140-240	20-190	210-340	76-220	420-600	29-270
Wessex	24-48	0.1-1	18-39	2-6	54-540	54-540	320-480	34-340
UK	620-1100	270-2400	560-1000	150-1100	1300-2300	860-7200	2700-4600	890-7700

Note: The two groundwater volumes result from the minimum and maximum storage values given Table 6.2
The two cover volumes result from the minimum and maximum storage values given Table 6.3

9 DISCUSSION

9.1 Discussion of Results

The results summarised in Table 8.1 show significant differences between the volumes calculated by the baseflow and hydrogeological approaches. The following sections highlight some of the differences and discuss some of the possible explanations.

9.1.1 Baseflow Volume Estimates

When expressed in mm of water (i.e. the volume of water calculated divided by the catchment area - see Section 7), it was found that, for the Kennet catchment, the volume of water between maximum and minimum was invariably higher in the Lambourn subcatchment, than for the rest of the Kennet subcatchments or the whole Kennet catchment. This was also revealed by the baseflow calculations; it could be caused by the under-estimation of the catchment area, or by real hydrogeological differences between the Lambourn and the remainder of the catchment.

The baseflow approach also noted showed for the Itchen, although there was a wide range between the subcatchments, the variation tended to be consistent from year to year. The hydrogeological approach also showed a wide range between subcatchments; however there did not appear to be very much consistency between the years. The reasons for these variations are not apparent.

Comparing the two approaches, the hydrogeological volume estimates were significantly less than the baseflow estimates. Using the Lambourn catchment as an example, the baseflow calculations estimated that the volume of water draining during the 1975 recession period would be 20 x 10^6 m^3. For the catchment area of 160 square kilometres, this is equivalent to approximately half of the year's annual infiltration (250 mm); it is, however, nearly an order of magnitude higher than the estimates of 3 to 5 x 10^6 m^3 derived from the analysis of groundwater fluctuations. This implies that the latter approach is failing to account for a large volume of water.

Possible sources of error in the baseflow estimation of storage include the separation of baseflow from run-off, regional groundwater flow, and the effects of pumping; these were not considered to be major problems in these catchments.

9.1.2 Recession Volume Estimates

Explanation of the differences between the baseflow and hydrogeological estimates is difficult because of the lack of a conceptual model of the physical processes controlling the recession volume. The streamflow recession approach is empirical: it measures the volume of water passing the gauging point and equates this to the volume of water lost from the aquifer. The hydrogeological approach instead estimates the volume of rock dewatered between the low water level and a horizontal plane i.e. the gauge level.

Comparison of both sets of the figures for both approaches from year to year, indicate that the recession volumes appear to be related to antecedent hydrogeological conditions. For 1976 and 1989, years when groundwater levels were low following reduced winter recharge, the recession volumes are correspondingly low. The hydrogeological approach estimates the residual volume between the final water level and gauge level; as the gauge level is fixed, differences between years will rely only on the magnitude of the differences in groundwater levels. The change in volume represents a relatively small proportion of the residual volume, and the changes between years, as would be expected, are small.

The similarity of the results for the sub-catchments is reassuring for both approaches, however the following should be noted:

- There is a low degree of confidence in the volumes calculated from the recession analysis due to the sensitivity of the method to the recession constant.

- The extrapolation used in the recession approach assumes that storage coefficient and transmissivity do not vary through the aquifer; that is, the aquifer properties that control the streamflow recession do not vary spatially or temporally. The way in which the actual variation would affect streamflow is complex, and has not been evaluated in this study.

The catchment studies illustrate some of the problems in the water level difference method, that could also affect the results of the calculations for the whole of the Chalk.

9.1.3 Results for the Chalk of England

The UK results are summarised in Table 8.2. In some areas the cover appears to be contributing significantly to the overall storage in the Chalk, as is probably the case in hydrometric areas 34, 35, and 36, which are overlain by the Crag, and 38 which is covered by the Thanet Beds. The loss of the cover storage if water levels were lowered into the Chalk could reduce available water resources in many areas. In some areas, the high values for areas 37, 39, and 40 may be strongly influenced by the high specific storage of London Clay or boulder clay deposits, and should be treated with caution. Although there is a significant amount of water available from such fine-grained deposits, it would take a vary long period of time for it to drain.

The situation in East Anglia is particularly complex because of the variation in cover materials. Areas overlain by the Crag would have a significant proportion of their water contributed from this source, whereas in areas overlain by boulder clay, the contribution from the clay would be negligible, and the total water available of the Chalk would be reduced. Much more work is required to accurately map the overlying deposits, and identify their contribution to measured specific yield.

Negative volumes indicate a rise in groundwater levels between the two dates of the analysis. This can be due to a real rise in the water table, or may result from sparse water level data coverage (see Section 5.5). The negative values of storage in the cover of hydrometric area 39 for the 1988/1990 analysis are caused by the rising groundwater levels in the Thames Basin. This does not cause negative values between 1975/1976, probably because at that time the problem was not as extensive. The apparent decrease in the volume of water in the Chalk between the two sets of dates is also caused by the increasing effect of rising groundwater levels. It is also important to note that borehole coverage in the Thames Basin is very sparse, and the results should therefore be treated with caution. Water moving into the Thames Basin to feed the rising water levels is a wasted resource, at least in the short term.

In the Wessex region (hydrometric areas 43 and 44), there was a paucity of observation-well data; a problem that was exacerbated by a narrow range of groundwater level fluctuations. For these reasons, there is low confidence in the maximum to minimum volumes calculated for these areas. Other areas with very poor borehole coverage are hydrometric areas 27, 30, and 37 (in the south east). Areas 27 and 30 are both very limited in area.

The volume of water drained between maximum and minimum water levels could be expected to represent the amount draining to streams or abstracted by pumping. With the exception of areas where long term water level changes are occurring, this would be expected to be of the same order as estimated infiltration. Thus, comparison of the 1988/90 volumes and the estimated recharge volume provides an indication of how the volumes relate to estimated recharge.

Examination of Table 8.2 indicates that for the majority of the hydrometric areas, the volume of water calculated is approximately only one fifth of the average annual infiltration. Two hydrometric areas (33 and 36) have a much closer correspondence between the two sets of figures, whereas catchments 43, 44, and 53 differ by at least an order of magnitude, although it should be noted that these areas all have very poor borehole coverage. The fact that the volume calculated between maximum and minimum water levels is approximately one fifth of the infiltration reinforces the conclusions drawn from the catchment studies, that the water level difference approach underestimates the volume of water moving through the system.

Comparison of the volumes derived from the zone of water table fluctuation with the minimum to minimum minus 10 m volumes (Table 8.2) generally indicates a much greater quantity of water in the latter zone, the exceptions being hydrometric areas 29, 30, and 41. Such results indicate that the range of groundwater fluctuations is, on average, quite small. For the whole of the UK, average groundwater fluctuation in the Chalk was calculated to be approximately 6 m between maximum and minimum groundwater levels.

Comparison of the maximum minus minimum water level volumes for the two periods show the volumes estimated for 1988/90 were usually fractionally greater than for 1975/76. This could be due to two effects:

- water fluctuations were greater between 1988/1990, and hence a larger volume of rock was dewatered
- initial water levels were higher in 1988, and hence higher values of storage coefficient were applied.

Certain areas i.e. hydrometric areas 38, 39, 42, and 43 are the opposite, with greater water volumes calculated for 1975/1976. If this is due to greater fluctuation in water levels, it implies that the present drought is not presently affecting these areas as badly as the drought of 1976. However, this should not give rise to complacency, as the two droughts are very different in character; the present one being a symptom of long-term rainfall deficiency and heavy demands on groundwater.

The calculation of water stored between minimum and minimum water level minus 10 m was carried out to estimate the amount of water available for abstraction below drought water level. The results of the catchment studies indicated greater confidence in these estimates than the calculations of the volume between maximum and minimum water levels. Although the values cannot be regarded as definitive, they do provide an indication of areas where groundwater abstraction is possibly close to the yield from below the minimum water level. Thus, comparison of the average abstraction (as estimated in Monkhouse and Richards, 1982) and the minimum to minimum minus 10 m volume highlights areas that might expect to suffer most severe problems in the absence of infiltration. Examination of Table 8.2 suggests that hydrometric areas 29 and 30, 38, 40 and 41 could be particularly susceptible. Hydrometric area 39 also appears susceptible; however, as noted above, this area is influenced by the rising groundwater levels in the Thames Basin, and the volumes are therefore likely to be under-estimated.

9.1.4 General Discussion of Results

The catchment studies highlighted some of the problems inherent in the hydrogeological approach that could also affect the volume calculations for the whole of the Chalk. The following discussion therefore centres around the discrepancies observed in the catchment studies, and the way these affect the interpretation of the UK results.

The difficulties of estimating storage coefficient have already been discussed (Section 6.3); the storage coefficients, although based on available field data may not be correct. In particular, the way in which storage coefficients were assigned (spatially) may be inappropriate, although the model was felt to approximate reality.

Although it would be possible to adjust the storage coefficients to arrive at similar values to the baseflow results, on the basis of available data it has not proved possible to decide on a sensible method of adjustment - an infinite number of non-unique solutions could be obtained. Simple scaling of the coefficients, or setting a single value, is not appropriate: the adjustment required to obtain agreement between the baseflow and high to low volume estimates, would then result in unrealistically high minimum to gauge level volumes.

Apart from the inadequacies in the storage coefficient model, two time-dependant factors will tend to cause the hydrogeological method to under-estimate the total volume in storage.

- Firstly, there may be significant long-term drainage through the unsaturated zone - here termed 'delayed infiltration' - providing recharge during the groundwater recession. The equivalence of the volume lost between high and low water levels with the baseflow volume relies on the assumption that no recharge was occurring between the two dates. From lysimeter data, it is known that downward percolation of water continues through the unsaturated zone at depth months after the onset of a soil moisture deficit. Under such conditions, the groundwater hydrograph would not only be delayed, but also smoothed, with the high water levels being reduced due to the delay of the recharge, and the low water levels being partially prevented by the continuing drainage through the summer period. The magnitude and timing would be affected not only by the thickness of the unsaturated zone, but also by the interaction between the matrix, primary fissures, and secondary fissures. One consequence is that in areas with a thick unsaturated zone, the groundwater recession would be offset from the surface water recession.

  The magnitude of delayed infiltration needed to resolve the volume discrepancy may be estimated. Using the Kennet catchment as an example, drainage area is approximately 1030 km^2, with an average unsaturated zone thickness of 20 m. This gives an unsaturated zone volume of 2×10^{10} m^3. The discrepancy between the calculations is approximately 8×10^7 m^3. Thus storage in the unsaturated zone amounting to only 0.4% of the total rock volume could account for the volume of 'missing' water.

- It is important to emphasise that the storage coefficients derived from pumping tests are not appropriate for this approach; such tests are normally carried out over relatively short time periods which do not allow sufficient time for delayed drainage - often termed delayed yield - to occur. The initial specific yield would reflect mainly the contribution from larger fissures. Contributions from smaller fissures and the matrix would be affected by the duration of the pumping test: the greater the duration of the test, the greater the delayed yield.

The long term implications of these mechanisms on the yield obtained from the Chalk depends on the relative proportions of delayed infiltration and delayed drainage. Delayed infiltration is probably volumetrically more important; however this is effectively a limited resource, which will decrease with time. Similarly, the lowering of the water table with time, and the decrease of secondary fissures with increasing depth, would result in declining specific yield and specific storage.

If water levels have been maintained by the slow percolation of water through the unsaturated zone over the period of the recent drought, this could explain the apparently small number of public abstraction boreholes with significantly reduced yield. The important implication is that water levels in the Chalk could decline increasingly rapidly as the unsaturated 'reservoir' becomes depleted. This effect would be in addition to that expected due to the decline of storage coefficient with declining groundwater levels.

The effects would be expected to be particularly severe in areas where average groundwater abstraction is comparable with, or greater than, the volume of water between minimum and minimum minus 10 m. In these areas, average abstraction would result in a drawdown of 10 m or greater. Such areas have been identified as 29 and 30, 40, and 41, although several others could also be subjected to abstraction problems.

There are other effects that will influence the results:

- definition of the groundwater catchment. As the groundwater divide is, by definition, the location at which the hydraulic gradient is flat, there is a large margin for error in its identification. The errors introduced could be negative or positive.

- movement of groundwater beneath the gauge. This would result in an additional discrepancy.

9.2 Discussion of Methodology

The results and their interpretation present a partial answer to the question of what are the reserves of the Chalk aquifer. The project has raised a large number of interesting questions and highlighted many areas where future research is required.

The hydrogeological basis for the project was that the 'dynamic storage' could be equated with the volume of water released from the zone of water table fluctuation. The catchment studies were carried out to validate this simple hydrogeological approach; however, the significant discrepancies indicate that additional processes should be taken into account. In particular, the studies indicated that delayed yield and delayed infiltration through the unsaturated zone could significantly influence the volumes of water calculated.

One of the main objectives of the project was to "quantify the dynamic volume by mapping the range of groundwater levels". Although this has been done, the calculated volumes do not represent the total 'dynamic storage' of the Chalk; the important implication being that storage is provided both within the zone of water table fluctuation, and above it.

The contribution from elastic storage, from the whole thickness of the chalk may also represent a large percentage of the total. Although it is often considered to be relatively insignificant in a water table aquifer when compared with the volume draining by gravity, these calculations indicate it could frequently represent 50% or more of the water derived from storage. The relative importance of specific storage is due to the great saturated depth of the aquifer, compared with the modest water table fluctuations. The large contribution from elastic storage implies that the 'dead' zone cannot be discounted from volume calculations; even when below OD, water will be released by a reduction in head. (See also Appendix A for mathematical discussion of this point).

9.3 Discussion of Problems

Many problems were encountered throughout the history of the project; these include those associated with computing and actual manipulation of the data (Appendix C), collection of appropriate values of storage coefficient (Section 6.3), and collection of valid water level data (Section 5). These have already been discussed in detail; however, it is worth listing some of the factors expected to cause inaccuracies in the water level data:

- gaps in data where the Chalk is overlain by thick cover
- problems along scarp edges
- gaps from one date to another
- problems with contouring caused by missing data points
- contouring intervals were 5 m; so water level differences are likely to inaccurate, particularly in areas where there was little fluctuation in water levels.

9.4 Resources Implications

The results provide an estimate of the volume of water stored in the Chalk aquifer. Although comparisons with the streamflow recession results (the Kennet and Itchen catchment studies) indicate that the volume calculated between maximum and minimum water levels is an under-estimate of the total dynamic storage, there is greater confidence in the volumes below minimum water level. However, the storage volume calculated cannot all be considered to all be 'usable' storage; this volume could not be abstracted without an extensive distribution of boreholes, or without causing excessive drawdown. Locally, pumping to 10 m below the 'minimum' water level could dewater shallow wells, and drain rivers and wetlands. In the absence of significant recharge, the volume available down to this level would represent a little as one year's average abstraction for some hydrometric areas.

The volumes have been calculated for individual hydrometric areas, as well as for NRA regions. As present abstraction is unlikely to be evenly distributed across the hydrometric areas, this implies that certain localities must already be encountering reduced yield. Even in areas where the results indicate there are reasonable resources, caution must be exercised. Local studies, and possibly modelling on a local scale, would enable the assessment of:

- the cost-effectiveness of developing new boreholes, as opposed to continuing pumping existing ones. As discussed previously, excessive drawdown would result in dewatering of the effective part of the aquifer, and consequent increases in pumping costs.
- possible impacts of increased abstraction on local ecology (especially wetlands and river life), shallow private well supplies, and the effects of possible subsidence.

9.5 Future Work

The project has highlighted many areas where future work is required. These may be divided into those that could improve the volume estimates, and those that are essential to further our understanding of the processes discussed in this report.

9.5.1 Improvements in the Volume Estimates

The volume estimates could be improved with some additional work. Areas of particular concern are:

- The water level data was not evenly distributed, and improved coverage would improve the volume estimates. Geostatistical techniques could be used to identify areas where sample density was inadequate
- Hand contouring the water level maps would have produced more accurate results than computer contouring
- The aquifer properties of the Middle and Upper Chalk were originally thought to be similar, and the volume calculations were carried out assuming a mean thickness of the Middle Chalk. This is not particularly accurate and the figures could be refined by constructing contours on the base of the Upper Chalk and using these in conjunction with its outcrop to calculate accurate volumes for both the Middle and Upper Chalk.

However, the relevance of carrying out relatively minor adjustments must be questioned when the hydrogeological processes are not fully understood.

9.5.2 Scope for Future Research

<u>Investigation of delayed infiltration</u>

There is a very strong need to understand the role of infiltration and delayed drainage with respect to recharge to the Chalk, and the estimation of its resources. There has already been significant research input to the Kennet and Itchen catchments, additional work there could yield valuable results. In particular, the development of models that are able to account for the transient nature of these processes would be required.

Further understanding could also be gained from the use of lysimeters to investigate delayed infiltration on a local scale.

<u>Determination of specific yield and storage coefficient</u>

A major uncertainty in the calculation of the volume of usable water stored in the Chalk, was the accuracy and reliability of the storage coefficients used in the calculations. In many cases, storage values were simply not available; where they were, values from different boreholes exhibited large ranges, with no apparent explanation.

Further to this problem was the lack of knowledge of the spatial distribution of specific yield. Limited work has been carried out to investigate the variation of specific yield as the water level drops. The Thames and Candover groundwater schemes both illustrated the non-linear decline in specific yield with falling water levels. However, in both cases the restricted data available prevented quantification or statistical analysis of the changes.

The current exceptionally low water levels provide a unique opportunity to investigate the decline in storage and transmissivity with depth. Such knowledge could prove to be invaluable in the event of the drought continuing, or similar droughts in the future. This would be of particular concern if the current drought is related to global climatic change rather than being one of the cyclical dry periods that are known to occur periodically.

Particular attention needs to be paid to delayed yield, on time scales spanning days to several years.

Determination of specific storage

Since the specific storage was found in this study to contribute a high percentage of the overall water available from the Chalk, it requires further investigation. The compressibility of the rock strongly controls the values of specific storage. The values used were derived from limited rock compressibility data; these values may not be representative of the field situation and limits the confidence in the specific storage values used. A critical assessment of the values of compressibility is required, perhaps with the assistance of engineering geological expertise.

Determination of specific yield from tracer tests

Theoretically tracer tests could be used to obtain a value for the storage coefficient. Small vertical sections of the aquifer could be isolated by installing packers in two adjacent boreholes. A tracer could be injected into one borehole, and the timing of its arrival in water pumped from a second borehole monitored. The tracer concentrations could then be related to the hydraulic gradient, the hydraulic conductivity (obtained from packer testing) and the kinematic porosity. As the kinematic porosity is related to the specific yield, an estimate of the latter parameter can be obtained. The main advantage of this approach is that it determines the storage coefficient of the aquifer at levels that are currently below the water table, and also over discrete horizons. It could therefore provide a better understanding of the vertical variation of the Chalk aquifer.

There are several assumptions inherent in the method. Firstly it is assumed that the vertical component of flow will be small compared with the lateral component, and that the specific yield value obtained will represent storage within the zone isolated by the packers. Secondly, the method fails to take into account the lateral anisotropy of the Chalk; the results would therefore only indicate relative vertical variations in storage. An additional drawback is that the mathematical analysis would be very complicated. Careful selection of the tracer would be required to prevent its diffusion into hydraulically static pore spaces, and hence an over-estimate of the specific yield.

Storage values for Chalk beneath cover

Considerable difficulties were encountered when attempting to define a storage coefficient for the Chalk where it is overlain by drift or Tertiary cover. In East Anglia there was frequently no information about the type of drift cover, or whether it was in hydraulic continuity with the Chalk. Where the two formations are in hydraulic continuity, aquifer parameters derived from pumping tests represent the combined aquifer system. In such situations, the crucial questions to be asked are:

- what is the relative contribution to storage and transmissivity from the cover and the Chalk?
- how are the overlying deposits contributing to recharge of the aquifer?
- if the Chalk is currently confined, what would happen when the water level is drawn down into the Chalk; would this represent a significant decline in the volume of water in storage?

These questions might be answered by a detailed comparison between aquifer properties at sites which abstract from both the Chalk and overlying deposits, and those abstracting solely from the cover. Hydro-geochemical techniques could also be used to identify the relative quantities of water originating from each aquifer. However the large variations in both geometry and composition of the overlying deposits will make comparisons between different sites complicated.

During this summer (1992), it is probable that some currently confined boreholes will become unconfined. It is suggested that such sites are studied in detail to obtain new values of transmissivity and specific yield and a comparison made with those originally obtained.

Assessment of variables having most effect on storage coefficients

Some of the variables that could be expected to influence the calculated storage coefficient have already been discussed (Section 3.6). The collection of pumping test results, together with all the factors believed to influence the derived values of storage and transmissivity, would enable multiple regression or modelling studies to be carried out. In this way the variables having most influence on the calculations could be identified. Toynton (1983) attempted this approach, but failed to identify the factors affecting storage coefficient and transmissivity (see Section 3.6).

Future work should also concentrate on establishing routine methods to calculate confidence intervals for the derived values of storage coefficient and transmissivity. With careful evaluation of storage parameters used in the volume calculations, the resulting numbers would be much more useful.

Special catchments

The calculations were carried out on the basis of subdividing the Chalk by hydrometric area. However as the gridded data files are now available, they could be relatively easily used to calculate the volume of groundwater stored in any area under any conditions.

10. CONCLUSIONS

To summarise the material achievements of this work, the following have been produced:

- structural maps of the Chalk of England
- water level contour maps for the Chalk for four separate dates
- a model of the spatial distribution of specific yield and specific storage
- extensive appraisal of literature on Chalk
- estimates of volumes of total and 'usable' water stored in the Chalk

Numerous problems were encountered during the course of the project. As described in Section 9.1.4, little confidence can be placed in the values of storage coefficients derived from pumping test analyses. The values used in the calculations were chosen to represent the normal ranges observed in a number of different hydrogeological situations; however, this does not imply they are appropriate for this approach. A further problem is that the variation of storage coefficient at very low water levels is not known; borehole logging and pumping tests carried out at very low water levels indicate that it decreases disproportionately with depth. The number of 'unknowns' means that it is impossible to attach confidence limits to the values of storage coefficient used.

The computing difficulties arose, in the main, because of the extremely large files being manipulated. Water level data problems were severe in places; however, little could be done to remedy these. In the most extreme situations, hand contouring of the water level maps was carried out to minimise the problem.

The study identified important hydrogeological processes that need to be considered when estimating the volume of water stored in the Chalk aquifer. In particular:

- the effects of continuing infiltration through the unsaturated zone, and the significance of this effect when the unsaturated zone is thick
- the importance of delayed yield, and the inability of most pumping tests to account for this
- the importance of the contribution from specific storage
- the importance of storage in the overlying deposits.

From the volume calculations, it appears that storage between maximum and minimum water levels was generally a half or less than that between minimum water level and minimum water level minus 10 m. This would imply there is more water available below the present drought levels than has already been lost from store. The following considerations are important:

- the 'dynamic' storage is suggested to be significantly underestimated using this approach
- comparison of both volumes with estimated abstraction figures suggests that many areas have limited additional storage in relation to the volume being abstracted.

It is clear, given the importance of the Chalk aquifer resource, its sensitivity to periods of reduced infiltration, and the repercussions of lowered groundwater levels on both water supplies and river flows, that much more work is required. There are considered to be two areas where future research is particularly important: firstly, to understand the hydrogeology of the unsaturated zone of the Chalk; and secondly, to gain a better understanding of the spatial distribution of specific yield and specific storage through the Chalk aquifer. Such work would be essential in order to quantify the rate of water level decline, which, in the light of this study, would be expected to increase rapidly as the drought conditions continue.

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