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Data review leading to a conceptual model of the hydrogeology of the Combe Down area, Bath

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EXECUTIVE SUMMARY

Bath and North East Somerset Council (B&NES) has obtained funds from the Department of Environment, Transport and the Regions to carry-out stabilisation of stone mines located in the Combe Down area to the south-east of the city of Bath. There are potentially significant engineering geology and hydrogeology implications associated with the project. The British Geological Survey (BGS) has been appointed by B&NES to provide independent geological advice. In this role, BGS has undertaken a review of available data to allow a conceptual model of the hydrogeology of the Combe Down area to be developed.

Combe Down is located on a spur, formed by the incised valley of the River Avon. The aquifer system underlying Combe Down can be simplified to a three layer system, the Great Oolite limestones and the Inferior Oolite limestones separated by the clays of the Fuller's Earth. Springs issue from the base of the two main aquifer units and provide both public and private water supplies. The hillslopes have undergone a great deal of land slippage and those on the southern side of the plateau are still oversteepened.

The review has collated the following hydrogeology-related information on the Combe Down area:

- existing reports on the geology, geomorphology and hydrogeology
- geological borehole logs held within the National Geosciences Data Centre, BGS, Keyworth
- well, borehole and spring information held within the National Groundwater Archive, BGS, Wallingford
- rainfall data for the locality and Meteorological Office estimates of actual evapotranspiration for the region
- available groundwater-level, springflow and stream data collected by Halcrow and Wessex Water
- groundwater and spring water quality analyses undertaken by Halcrow and Wessex Water
- licenced abstractions, consented discharges and an estimate of mains leakage
- groundwater source protection zones, obtained from the Environment Agency

The development of the conceptual model of the hydrogeology was aided by undertaking a preliminary water balance on the shallow aquifer, as part of the review, in which known inputs to the aquifer are compared with known outputs. Total groundwater recharge and spring flow was calculated for a hydrological year from mid-August 1994 to mid-August 1995.

It is anticipated that any impacts on the hydrogeology of Combe Down due to stabilisation are likely to be the result of mine voids becoming less permeable due to their total or partial infill and/or leachate from mine infill affecting the quality of spring outflows. If infill of some or all of the existing mined areas does not allow water to infiltrate to the shallow aquifer following the present pattern, then the groundwater flow directions may alter. This could affect the location of existing springs and cause changes to the overall volumes or temporal variations in flow, possibly to the detriment of the environment and the present users.

The review has produced improved estimates of the size of catchment areas for the springs discharging from the shallow aquifer. It has shown that the delineation of the catchments of individual springs, in particular those of Prior Park and the Whittaker and Tucking Mill Springs, is very approximate, due in particular to the possible importance of structural controls and the difficulty in assessing groundwater recharge in urban areas. The review presents evidence that the deep aquifer, formed by the Inferior Oolite limestones and the Midford Sands, is not isolated from the shallow aquifer in the Combe Down area, and therefore that springs discharging from this aquifer may potentially be affected by changes to groundwater flow and quality associated with stabilisation of the mines.

Any change in the groundwater flow pattern within the shallow aquifer as a result of stabilisation may also have implications for land stability, particularly on the southern slope of the plateau where it is oversteepened. The review quotes evidence of recent and potential land instability in the area.

The review has highlighted the lack of information that is available on the hydrogeology of the Combe Down area. It is suggested that if the choice of stabilisation solution is likely to significantly affect groundwater, further investigations on the hydrogeology will be essential. Broad areas for further investigation are suggested.

1. INTRODUCTION

1.1 Background

The Great Oolite limestones of Combe Down, south of Bath, have provided stone for building dating back to Roman times. Extraction of the stone on a large scale began in the early eighteenth century. Initially quarried, the requirement for large quantities of stone for the extensive Georgian developments in Bath, lead to the opening of mines at Combe Down.

Investigations in the early 1990s raised concern by the local authorities about the stability of the mines and the apparent deterioration. Detailed underground surveys of two adjacent mines (Firs and Byfield) showed that they covered an area of approximately 18 hectares and it is suspected that in total there are as much as 28 hectares underlain by mines. There is historic information that mines also exist adjacent to other quarried areas on Combe Down.

A land stabilisation project was proposed in 1992/1994 but the options proposed were not carried through as a result of a cost-benefit analysis. In January 2000, Bath and North East Somerset Council (B&NES) were successful in their application for funds from the Department of Environment, Transport and the Regions, through English Partnerships, to carry-out a stabilisation project of the Combe Down mines.

1.2 Physical Setting

Combe Down, located to the south-east of the city of Bath, close to the Wiltshire-Somerset border, is located on a spur, formed by the incised valley of the River Avon. The plateau is approximately 1 km wide in the area of Combe Down village. The location of the area and the topography are shown in Figure 1.1.

The geology of the region is dominated by the rocks of the Middle and Lower Jurassic. The massive limestones of the Great Oolite commonly form plateau-like tracts in the region, whilst those of the Inferior Oolite give rise to bench-like outcrops on the valley slopes. The aquifer system of Combe Down can be simplified to a three layer system, the Great Oolite limestones and the Inferior Oolite limestones separated by the clays of the Fuller's Earth. Springs issue from the base of the two main aquifer units. These spring groups provide both public and private water supplies.

The hillslopes have undergone a great deal of land slippage and those on the southern side of the plateau are still oversteepened. Significant cambering has also taken place, with implications for the hydrogeology and land stability.

1.3 Aim of Data Review

The British Geological Survey (BGS) has been appointed by B&NES Council to provide them with independent geological advice on the Combe Down Stone Mines Project. There are potentially significant engineering geology and hydrogeology issues linked with the project. In this role, BGS have been asked to undertake a review of available data relevant to the hydrogeology of the area. The purpose of this review has been to:

- collate and review data relevant to the hydrogeology of the Combe Down area;
- develop a conceptual model of the hydrogeology of the Combe Down area, including the role of the mines, based on available data;
- briefly discuss the likely impacts of potential mines stabilisation options and the associated investigations and monitoring required.

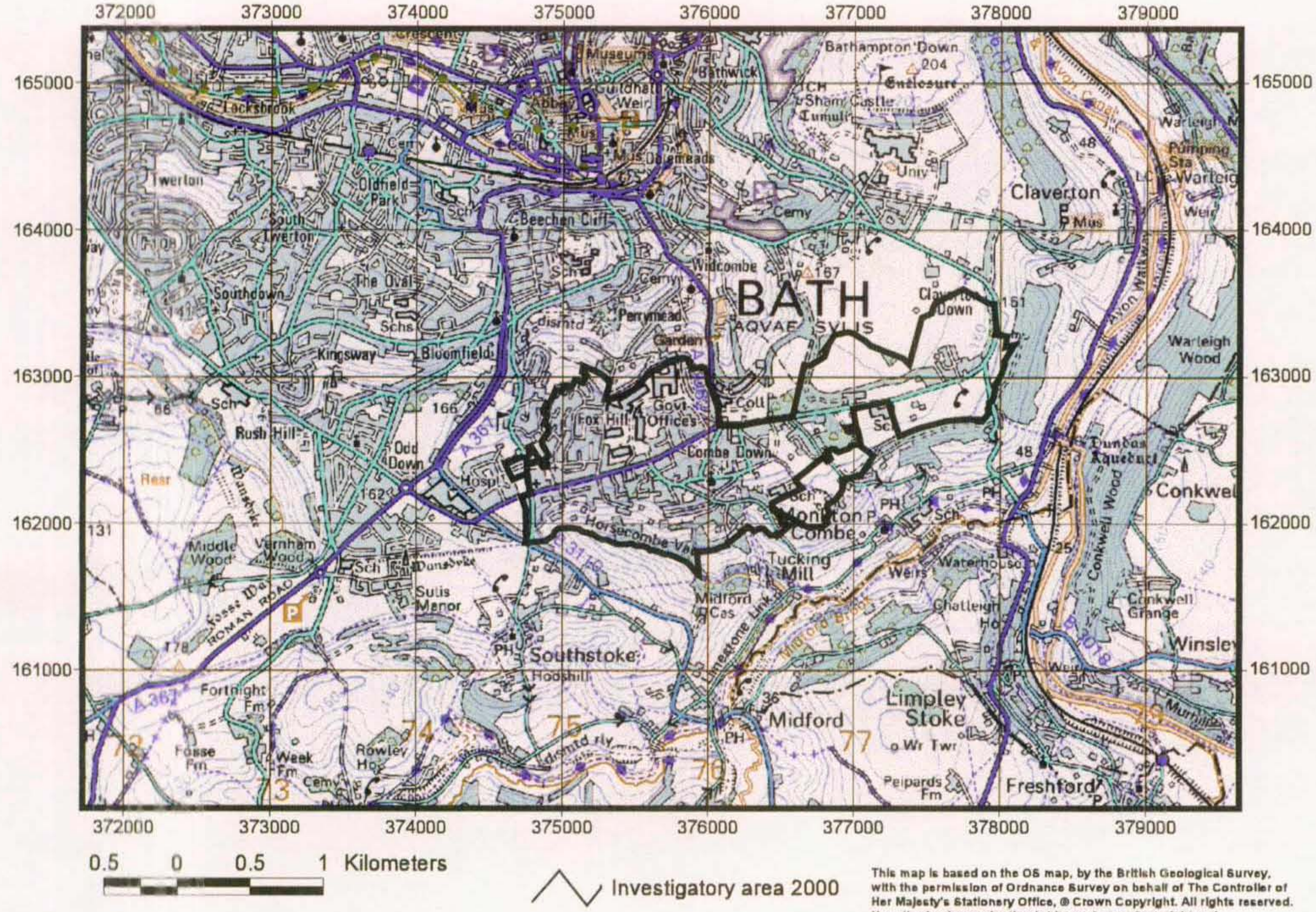

Figure 1.1 Location of the Combe Down Stone Mines Project Investigatory Area

2. REVIEW OF EXISTING INFORMATION

This chapter details existing information that is of relevance to understanding the flow and quality of groundwater in the aquifer system of Combe Down.

2.1 Geology

2.1.1 Review of existing reports

The geological sequence below Combe Down based on existing borehole records (see Section 2.1.2) is presented in Table 2.1. The outcrop geology of the area taken from the 1:10,000 geology map is shown in Figure 2.1. (Note the key for Figure 2.1 and all other figures with a geology base is given in Figure 2.2).

Table 2.1 Geological sequence beneath Combe Down.

	Description	Approximate thickness (m)
Great Oolite		*up to 20*
Twinhoe Beds		
Winsley Facies	shelly limestone	
Freshford Facies	shelly limestone and marl	
Twinhoe Ironstone	ironshot limestone	
Combe Down Oolite	oolitic limestone	
Lower Ragstone	shelly oolitic limestone	
Fuller's Earth		*40*
Upper Fuller's Earth	mudstone/clay with limestone	25
Fuller's Earth Rock	shelly oolitic limestone	5
Lower Fuller's Earth	mudstones/clays	10
Inferior Oolite		*15*
Anabacia and Doulting Limestone	oolitic detrital limestone	
Upper Coral Bed	corals in marly limestone	
Upper Trigonia Grit	shelly limestone	

The geology of Combe Down is described in detail in Hawkins (1994). Some aspects of the geology that are particularly relevant to the hydrogeology are listed here in bullet form. References used are Hawkins (1994), Halcrow (1996a) and Forster et al (1985):

- the basal 15 cm of the Freshford Facies of the Twinhoe Beds consist of a rubbly coarse, shelly material with a significant, friable, sandy silty clay component;

- the upper 1.5 to 2 m of the Combe Down Oolite is stronger, more thinly bedded, and has a different fracture pattern than the worked freestone. This horizon, known as the 'Bastard Stone', forms the roof beds over many of the mines;

- beneath the freestone of the Combe Down Oolite is the Lower Ragstone, 2 to 3 m of thinly bedded, crystalline, shelly oolitic limestone. This has greater strength and is more variable and was not extracted by miners. (Note, in the remainder of this report reference to the Combe Down Oolite includes the Lower Ragstone);

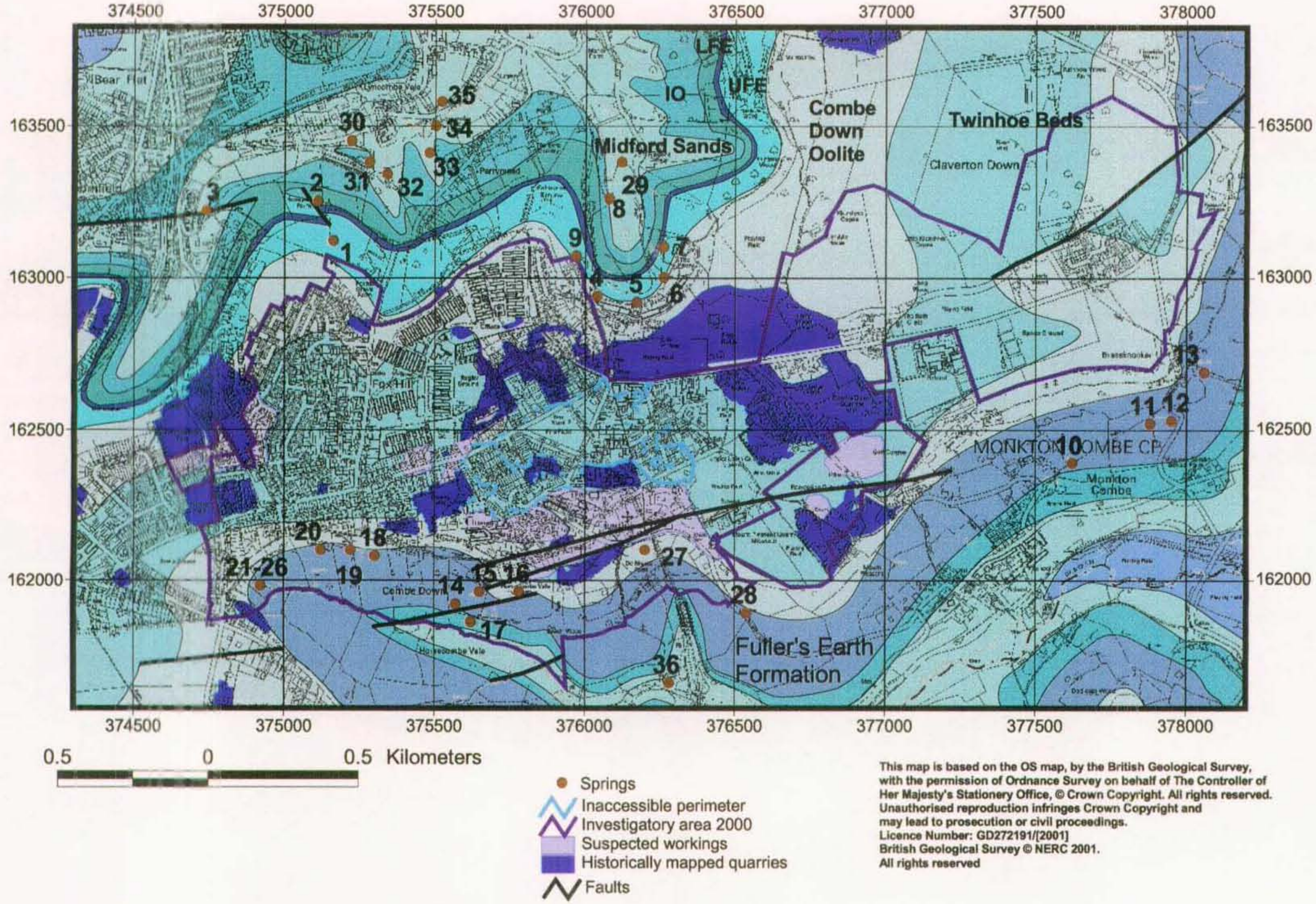

Figure 2.1 Geology, quarries, areas of suspected mine workings and springs in the Combe Down area

Figure 2.2 Key for geology in report figures

- below the Lower Ragstone are the transition beds, approximately 2 m of sparsely oolitic shelly limestones alternating with mudstone/clays, the proportion of argillaceous material increasing with depth towards the underlying Upper Fuller's Earth clays. The boundary between Combe Down Oolite and the Upper Fuller's Earth is therefore not distinct;

- the Midford Sands is a variably cemented, silty sand. A prominent ENE/WSW discontinuity pattern beneath the centre of the hill has been identified. The upper few metres of the Midford Sands are reported to be decalcified;

- Hawkins (1994) reports that the Jurassic strata in the Bath area have a regional dip of 2 to 5° to the E/SE;

- two prominent fracture sets exist in the Great Oolite limestones, N 070° (wider, more persistent) and N 140°, with an average spacing of approximately 0.8 m and widths of up to 5 cm;

- a series of normal faults is shown on 1:10,000 geology maps running along the southern edge of the Combe Down plateau. The northerly set of three are normal faults (see Section 2.1.1 for information on the throw). The most southerly fault, which extends through Horsecombe Vale, has a downthrow to the north. Some 2 km to the west of Horsecombe Vale, at the Fuller's Earth works at Combe Hay Lane, the throw is 10 m. The 1:10,000 geology map shows a further E/W trending fault to the north of Claverton Down.

2.1.2 *National Geosciences Data Centre holdings*

A search was undertaken of the National Geosciences Data Centre, located in the British Geological Survey's offices in Keyworth, for borehole records in the Combe Down area. A total of 76 records were identified that include geological information. Based on the geological logs, 46 of these are believed to penetrate the base of the Combe Down Oolite. The thicknesses of the geological layers taken from these boreholes are listed in Table 2.2. Figure 2.3 shows the location of these boreholes on a basemap of the geology of the area. The height of the estimated boundary of the Combe Down Oolite limestones and the Fuller's Earth, relative to Ordnance Datum, has been calculated from this information and plotted on a separate geology basemap (Figure 2.4). As the base of the Combe Down Oolite is not distinct, there will be some variability in the point chosen by the recorder as the boundary with the Fuller's Earth. This plot gives an approximate dip in the base of the Combe Down Oolite of 5° to the east.

Figure 2.4 suggests a significant throw in the fault set located on the southern edge of the plateau, (although this is based on only two boreholes). The boundary in borehole ST76 SE 13 is approximately 20 m below its nearest neighbour to the north and in borehole ST76 SE 23 it is approximately 32 m. Also of note is the height of the boundary in borehole ST76 SE 55 which is 122 mAOD, significantly lower than in the nearest boreholes.

2.2 Geomorphology

As a consequence of deep dissection by the River Avon and its tributaries during the Quaternary period, the slopes of the Combe Down plateau were left in an oversteepened state. Landslippage has occurred in the slopes of much of the area. As a result the slopes on the northern edge of the plateau are now thought to be in equilibrium, however this is not the case for the southern edge which are still oversteepened.

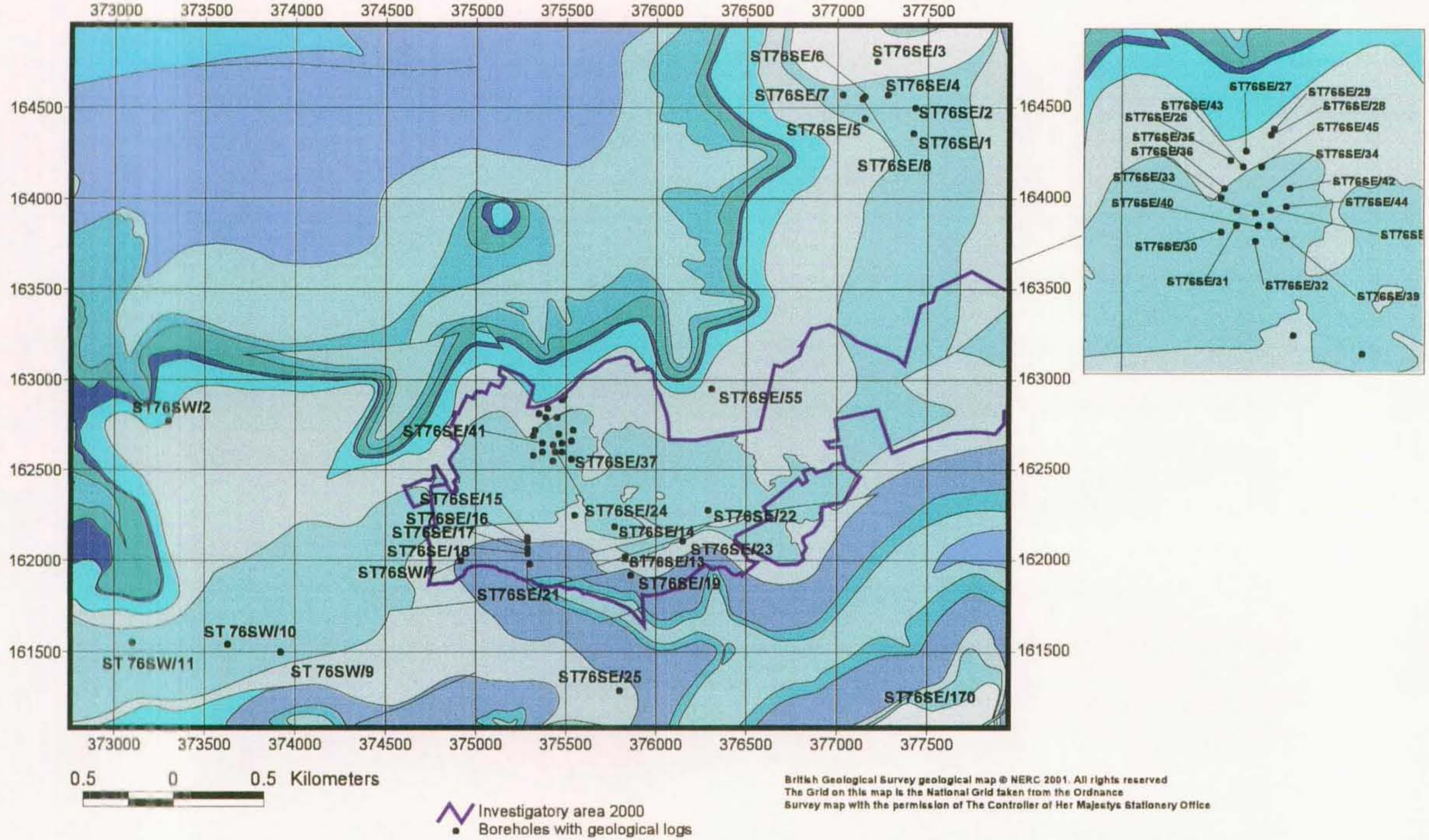

Figure 2.3 Borehole records from National Geosciences Data Centre that include geological logs

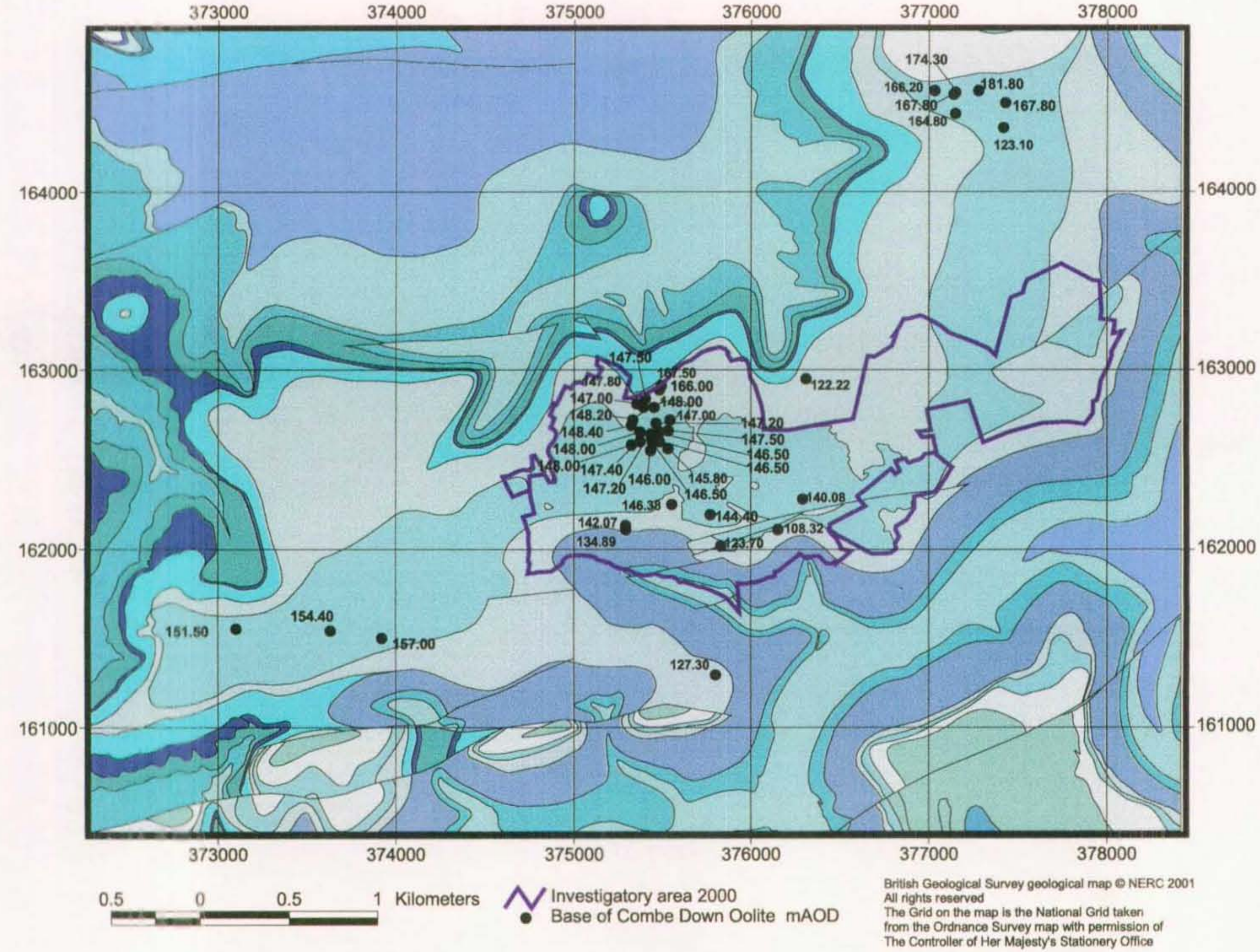

Figure 2.4 **Height of the base of the Combe Down Oolite above Ordnance Datum based on borehole records from National Geosciences Data Centre**

Table 2.2 **Information from borehole geological logs for the Combe Down area, held in the National Geosciences Data Centre. Records included are only for those boreholes which penetrate the base of the Combe Down Oolite.**

				THICKNESSES (m)							
Index number	Grid reference	Depth (m)	Height (mAOD)	Overburden	Twinhoe Beds	Combe Down Oolite[1]	Fuller's Earth undifferentiated	Upper Fuller's Earth	Fuller's Earth Rock	Lower Fuller's Earth	Inferior Oolite
ST75NW/28	ST 7213 5995	30.5	143		6.2	13.8					
ST76SE/1	ST 7742 6436	12.0	180	0.2	2.6	9.4					
ST76SE/2	ST 7743 6450	12.0	183	0.3	2.3	9.6					
ST76SE/4	ST 7728 6457	30.0	185	0.3	2.3	13.9					
ST76SE/5	ST 7715 6444	12.0	177	1.2		11.0					
ST76SE/6	ST 7714 6455	12.0	180	0.2	1.2	10.8					
ST76SE/7	ST 7703 6457	31.0	183	0.3	1.8	14.6					
ST76SE/8	ST 7715 6456	12.0	185	0.3	1.1	9.2					
ST76SE/13	ST 7583 6202	56.0	137.7		2.7	11.4	36.9	22.6	3.9	10.5	
ST76SE/14	ST 7577 6219	18.0	155.0			10.6					
ST76SE/15	ST 7529 6213	40.2	152.7			10.7		25.5			
ST76SE/16	ST 7529 6211	22.3	139.6			4.7					
ST76SE/17	ST 7529 6207	20.0	129.7					17.1			
ST76SE/18	ST 7529 6204	30.5	123.5	2.5			24.9	10.3	4.8	9.8	
ST76SE/19	ST 7586 6192	15.7	117.0	2.5				5.5	3.1		
ST76SE/21	ST 7530 6198	26.2	109.3	4.0						7.8	
ST76SE/22	ST 7629 6228	20.4	150.3			10.2					
ST76SE/23	ST 7615 6211	38.9	128.7		6.2	14.2		17.6			
ST76SE/24	ST 7555 6225	71.7	154			7.6	45.8	27.9	5.1	12.9	14.3
ST76SE/25	ST 7580 6129	14.0	130			2.7					
ST76SE/26	ST 7535 6281	12.8	155	0.2		7.0					
ST76SE/27	ST 7540 6284	57.1	155.5	0.2		7.8	42.9				
ST76SE/28	ST 7548 6289	10.5	175	0.2		8.8					
ST76SE/29	ST 7549 6291	10.0	175.5	0.2		7.8					
ST76SE/30	ST 7532 6258	14.0	160.5	0.2		12.3					
ST76SE/31	ST 7537 6260	16.2	161.5	0.2		13.9					

Table 2.2 continued

Index number	Grid reference	Depth (m)	Height (mAOD)	THICKNESSES (m)							
				Overburden	Twinhoe Beds	Combe Down Oolite[1]	Fuller's Earth undifferentiated	Upper Fuller's Earth	Fuller's Earth Rock	Lower Fuller's Earth	Inferior Oolite
ST76SE/32	ST 7543 6255	18.8	162.5	0.3		16.2					
ST76SE/33	ST 7543 6264	16.0	161	0.2		13.6					
ST76SE/34	ST 7546 6270	15.5	160.5	0.2		13.1					
ST76SE/35	ST 7533 6272	12.1	157			8.8					
ST76SE/36	ST 7532 6269	12.1	157.8			9.4					
ST76SE/37	ST 7553 6256	19.8	163.3	0.2		17.3					
ST76SE/38	ST 7548 6265	17.0	161.7			15.2					
ST76SE/39	ST 7548 6260	18.5	162.5			16.0					
ST76SE/40	ST 7544 6260	17.0	162	0.2		15.3					
ST76SE/41	ST 7537 6265	15.0	160	0.2		11.8					
ST76SE/42	ST 7554 6272	16.5	162	0.2		14.8					
ST76SE/43	ST 7539 6279	12.0	156	0.2		8.8					
ST76SE/44	ST 7553 6266	16.0	162	0.2		14.3					
ST76SE/45	ST 7545 6279	14.5	158	0.2		9.8					
ST76SE/55	ST 7631 6295	30.5	140.5			18.3					
ST76SW/2	ST 7330 6277	24.0	170					23.8			
ST76SW/7	ST 7492 6200	21.3	130.5					17.8			
ST76SW/9	ST 7392 6150	30.5	175			18.0					
ST76SW/10	ST 7363 6154	30.5	175			20.6					
ST76SW/11	ST 7310 6155	30.5	170			18.5					

[1] For some records this may include the Twinhoe Beds

Forster et al (1985), generalising for the Bath area, identifies two factors that have been the cause of much of the recent mass movement, namely the removal of support at the foot of slopes and the action of groundwater. Groundwater reduces the shear strength of the overconsolidated clays of the hillslope bedrock and of the mantle of head overlying it, causing failure of the hillslope. Forster et al go on to describe the process of land slippage. Continued input of groundwater into the slip mass saturates disrupted clays further thus promoting further movement. At the same time the hillside above the slip will have become oversteepened by the removal of material below and a second failure may occur. The sequence will continue until the angle of repose is such that the gravitational forces are in equilibrium with the strength of the slope material.

Hobbs (1980) in a study of the slope stability in the Avon Valley (Bath to Limpley Stoke) noted that the Fuller's Earth in the Monkton Combe area was potentially unstable. Hawkins (1994) reports that geotechnical properties of the mudrocks of the upper section of the Upper Fuller's Earth are such that extensive landslips and creep cambers have developed at that elevation. In comparison, the Lower Fuller's Earth has better engineering properties, as it is effectively drained by the underlying Inferior Oolite, and so landslips here are much less frequent.

The rocks of the plateau have also been affected by cambering (Figure 2.5). Superficial valleyward lowering of competent, near-surface strata has occurred such that limestones form a drape over the less competent, argillaceous horizons. The resulting cambering of competent strata has caused opening/extension of pre-existing tectonic-induced fractures to produce gulls, generally sub-parallel to the plateau edge. These features can be up to 1 m wide and may remain either as a void or be infilled with clay or rock fragments. Cambering also caused mass movement. Beds have moved valleyward through softening of the Upper Fuller's Earth clays leading to lateral creep and the near surface strata have foundered at and below the edge of the plateau. It is possible that the faults identified on the southern edge of the plateau in the Combe Down area are in fact cambering-related. Cambering of incompetent beds is commonly expressed in the Bath area in Midford Sands by marked thinning valleywards; and in the Fuller's Earth and Lower Lias clays by zones of disturbance to considerable depths below valley slopes (Forster et al, 1985).

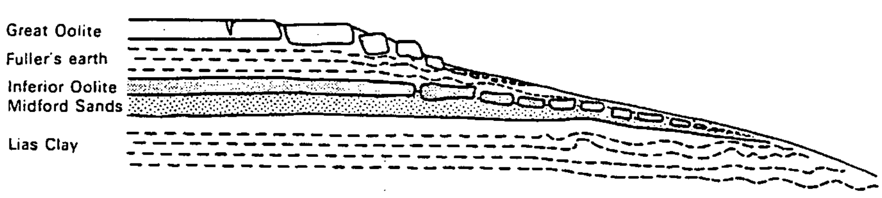

Figure 2.5 Diagramatic representation of cambering in the Bath area (Forster et al, 1985)

Cambering took place at a relatively remote time and it is reasonable to suppose is no longer actively affecting the hillsides (Forster et al, 1985). However, one of the potential problems with cambering is the existence of relic shear surfaces in deformed incompetent clays which may become reactivated. These problems are often difficult to predict due to a mantle of head deposits.

2.3 Hydrogeological Information

2.3.1 Review of existing reports

In simple terms, the aquifer system underlying Combe Down is made-up of a shallow Great Oolite limestone aquifer separated by an aquitard (Fuller's Earth) from a deeper aquifer formed by the limestones of the Inferior Oolite and the Midford Sands.

The lack of any surface watercourse on the plateau of Combe Down is evidence of the high permeability of the shallow limestones. This permeability is primarily controlled by open-jointed fractures (see Section 2.1) although rates of infiltration of rainfall are enhanced by the cambering-related gulls. Hawkins (1994) reports that increased infiltration through the roof of the mine workings on Combe Down has been noted within 3 hours of rain events. Hawkins (1994) also notes that crushed/powdered oolite or clay fallen from gulls form a lower permeability material which causes temporary ponding of water in mines. Other low lying areas of the mines may form collection points for infiltrated rainfall and therefore zones of concentrated recharge to the aquifer below. The mines may therefore have some effect on the flow pattern of the infiltrating rainfall.

The only time series groundwater level data available for the Combe Down area are those collected by Halcrow (1997) from a private well at 101 Church Road, completed within the shallow aquifer. These data were collected over the period April 1994 to May 1997. Groundwater-levels fell below the base of the well in the late summer of 1995; however, it would appear that the base of the well was close to the minimum groundwater-level at this time. Halcrow (1996a) reports that the groundwater level in the well responds very rapidly to rainfall, within 48 hours. Groundwater levels over the three-year period fluctuate from 140.3 mAOD (February 1995) to 136.1 mAOD (base of well, August 1995). The only other groundwater-level measurement referred to in the literature is 138.4 mAOD in a well located within the mines (Hawkins, 1994). No date is given for the measurement. Reference to Figure 2.4, which shows the approximate base of the Combe Down Oolite, suggests that the groundwater-levels may be fluctuating within the Upper Fuller's Earth, and possibly the transition zone at the base of the Combe Down Oolite. Hawkins (1994) reports that preferential water flow occurs along thin to medium argillaceous limestones in the upper few metres of the Upper Fuller's Earth. (Note, the base of the explored mine workings is well above the maximum groundwater-level based on these data and there is no anecdotal evidence of groundwater flooding of the mines having occurred (Hawkins, 1994)).

The clays of the main section of Upper Fuller's Earth (approximately 20 m thick) are of lower permeability and form the base of the shallow aquifer. These clays cause lateral movement of groundwater which discharges to the northern and southern edge of the plateau. Halcrow (1996a) report two types of springs that issue from the shallow aquifer. The first type appears rapidly following rainfall and forms temporary seepages. They report that these springs respond to rainfall events within 3 days (although the threshold size/intensity of the rainfall events required is not discussed). The second type have a marginally damped response to rainfall and issue from more permanent locations. They suggest that this type are outflows from the interlayered limestone and clay zone at base of the Combe Down Oolite and top of the Upper Fuller's Earth.

The Upper Fuller's Earth is underlain by the Fuller's Earth Rock (approximately 5 m thick), a shelly oolitic limestone with significant fracturing which elsewhere can provide sufficient water for small supplies (Morris et al, 2000). Hawkins (1994) reports that the Fuller's Earth Rock drains the lower section of the Upper Fuller's Earth, implying that groundwater discharges from this minor aquifer as springs on the plateau edge. A number of the springs identified by Halcrow (1996a) when plotted on the 1:10,000 geological map (Figure 2.1) are located on areas mapped on the northern edge of the plateau as Fuller's Earth Rock and on areas likely to be Fuller's Earth Rock on the southern edge, where the Fuller's Earth is mapped as one unit (note a spring does not necessarily discharge from the layer on which it is mapped due to interflow). Spring discharges from the Fuller's Earth Rock imply that groundwater can leak through the Upper Fuller's Earth.

The Fuller's Earth Rock is underlain by the clays of the Lower Fuller's Earth, approximately 10 m in thickness. Hawkins (1994) reports these clays to have better engineering properties than parts of the Upper Fuller's Earth as they are effectively underdrained by the Inferior Oolite.

Below the Lower Fuller's Earth is the Inferior Oolite, a fractured marine limestone. It is reported to be in hydraulic continuity with the upper few metres of the Midford Sands, which tend to be decalcified. Springs, including the Wessex Water's public supply source at Tucking Mill, have been mapped as discharging from the Midford Sands. There are no groundwater-levels available for the Inferior Oolite in the Combe Down area. Hobbs (1980) reports that seasonal fluctuations of groundwater-levels in the Inferior Oolite, where confined, are typically small (1-2 m).

Halcrow (1994) describes the Fuller's Earth as a whole as 'an effective aquitard' and suggests that there is no significant vertical infiltration of groundwater to the underlying Inferior Oolite limestone. They identify the source of recharge to the Inferior Oolite/Midford Sands aquifer as distant outcrops to the north and west. It is assumed that they are referring to the outcrop approximately 4 km to the west of Combe Down (Figure 2.6). This is the only significant area of outcrop within the Inferior Oolite aquifer in the locality, the aquifer being isolated by the incised valley of the Avon and its tributaries.

Hobbs (1980) reports that where the Great Oolite limestone outcrop is deeply dissected, spring discharge often passes over the Fuller's Earth outcrop and infiltrates in to the Inferior Oolite, another mechanism for the recharge of the Inferior Oolite springs. Sinks have been mapped on the Inferior Oolite on the northern slope of the plateau. (Note, springs issuing from the Great Oolite feed streams flowing over the Fuller's Earth. The main streams are in Lyncombe Vale and Horsecombe Vale and flowing from lakes in Prior Park. All of these are accreted by springflow from the Inferior Oolite springs.) The mechanism for flow to the Inferior Oolite/Midford Sands aquifer is discussed further in Chapter 3. (Note, for brevity, the Inferior Oolite/Midford Sands aquifer and springs will be referred to as Inferior Oolite for the remainder of this report.).

Although the Lower Lias clays are likely to be an aquiclude, a railway tunnel excavated through the overlying Midford Sands does not suffer any significant leakage of groundwater from above and therefore the lower section of the Midford Sands may form a base to the aquifer system below Combe Down.

2.3.2 Data available from the National Well Record Archive

Table 2.3 lists all well/borehole and spring records from the Combe Down area, held in the National Well Record Archive, at the British Geological Survey's offices in Wallingford, Oxfordshire. None of the records contain water-level or flow information.

Table 2.3 Records for the Combe Down area held in the National Well Record Archive

Location	BGS ID	Grid ref	Depth (m)	Comments
Bath University	ST 76/5	ST 7740 6434	30.35	through Great Oolite limestone, ~13 m into Fuller's Earth
Prior Park	ST 76/18	ST 7631 6295	30.5	basic geological log
Macaulay Buildings	ST 76/22	ST 765 638	53.0	basic geological log
Tucking Mill Springs	ST 76/39	ST 763 617	-	water quality data included
Sham Castle Springs	ST 76/48	ST 766 642	-	very limited water quality data
Fuller's Earth Works, South Stoke	ST 76/56	ST 7364 6160	30.5	basic geological log, fully penetrates Fuller's Earth

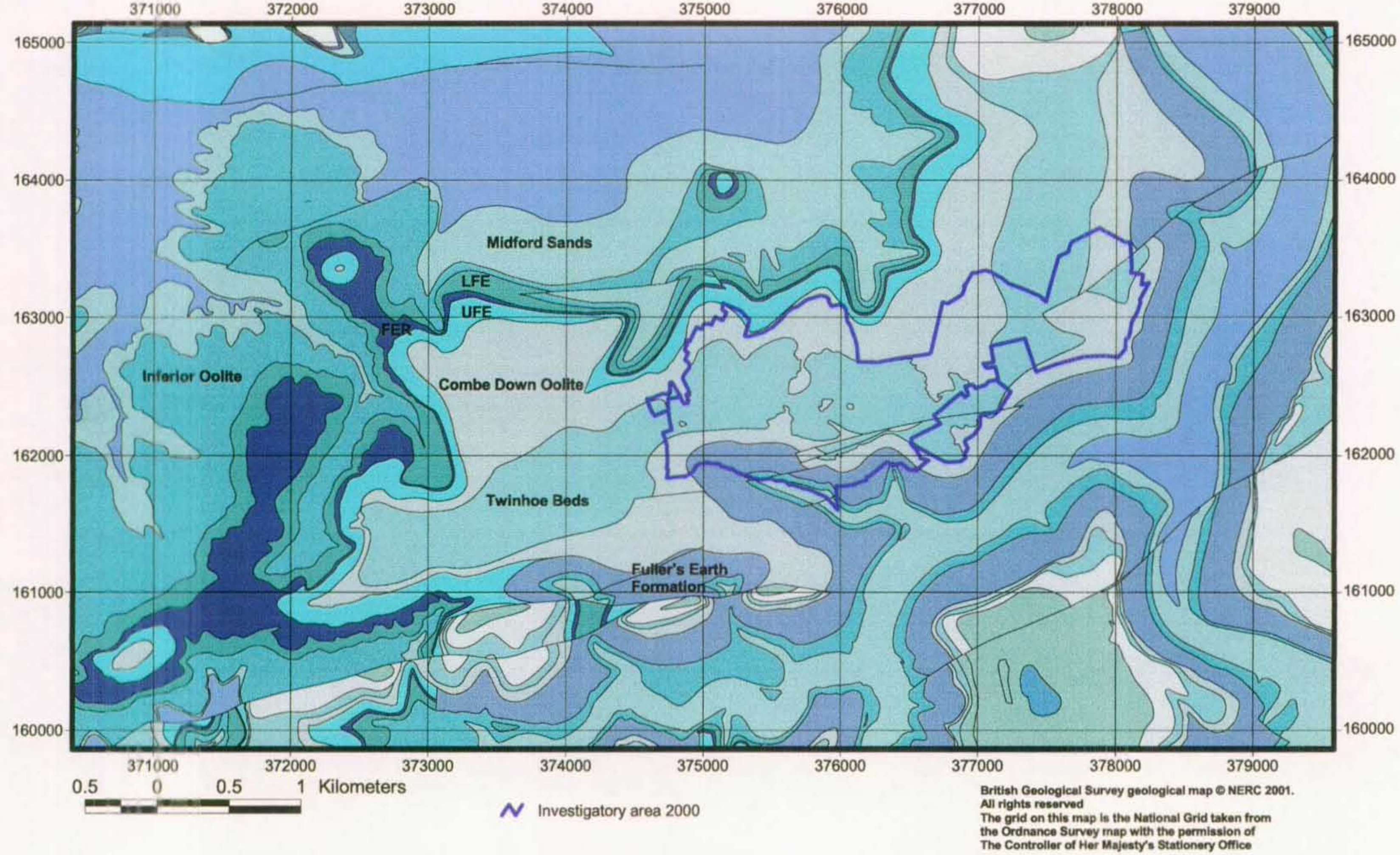

Figure 2.6 Geological map showing the relatively large outcrop of Inferior Oolite west of Combe Down

2.4 Climate Data

Rainfall is measured locally at Beechen Cliff School (ST 7510 6380). Daily data from this station for the period 1961 to present were obtained from the Environment Agency. Annual and monthly statistics for this station are given in Table 2.4.

Estimates of groundwater recharge are commonly made using rainfall and actual evapotranspiration. The Meteorological Office use climate data from Beechen Cliff School to estimate actual evapotranspiration using the MORECS system, however, the cost of these data was prohibitive for this exercise. MORECS data, averaged over 40 x 40 km squares, were made available to BGS by the Centre for Ecology and Hydrology. Combe Down is located in the bottom left corner of square 157, close to the junction between squares 158, 168 and 169. A comparison of the rainfall data for each of these squares was made with that of Beechen Cliff School, suggesting square 168 as being most similar in pattern to the rainfall in the Combe Down area. The annual and monthly ratios of rainfall to actual evapotranspiration for this square were used, along with the Beechen Cliff School rainfall data, to give an estimate of actual evapotranspiration for Combe Down.

Table 2.4 Statistics for rainfall at Beechen Cliff School and actual evapotranspiration, estimated using MORECS 40 x 40 km squares.

	Rainfall Beechen Cliff School (mm)	Estimate of actual evapotranspiration (mm)
Annual mean	778.5	504.7
Monthly Means		
January	77.1	14
February	53.7	16.2
March	60.7	34.9
April	53.7	55.5
May	61.4	83.1
June	55.5	67.3
July	51.6	64.4
August	63.1	58.1
September	75.9	48.8
October	68.4	30.5
November	74.3	18.3
December	86.1	13.4

2.5 Springflow Data

2.5.1 Data availability

As part of the previous hydrogeological survey of the Combe Down area carried out by Halcrow, a series of springs was identified (Figure 2.1) and subsequently monitored. The type and period of monitoring undertaken is summarised in Table 2.5 and given in more detail in Halcrow (1997). The data available include those for the two public water supplies of Whittaker Spring and Tucking Mill Springs. The data available for Tucking Mill Springs are those provided by Wessex Water. The data available for Whittaker Spring are derived from a combination of monitoring undertaken by Halcrow and by Wessex Water. In addition, measurements of the flow rate of a stream that runs through the valley in which both Whittaker and Tucking Mill are located are also available. The measurements were made at a point upgradient from where the stream flows over the Inferior Oolite. This stream accepts spring discharges from the Great Oolite plus any discharge from Whittaker Spring that is not captured by Wessex Water. It is also expected that the streamflow will include run-off. The streamflow is not thought to include discharges from springs that are included in the monitoring carried out by Halcrow.

Not all the raw spring data collected by Halcrow have been archived in either paper or digital form. Where raw data have not been archived, the only reference are graphs included within Halcrow's reports (Halcrow, 1997).

2.5.2 *Summary of springflow information*

An overview of the springflow data collected by Halcrow and Wessex Water is given in Table 2.6. To indicate the relative flow rates between springs and within a hydrological season for individual springs, the maximum and minimum flow rates are given. The hydrographs for Whittaker Spring and Tucking Mill Springs are shown in Figure 2.7. A full set of hydrographs can be found in Halcrow (1997). The total flow from each spring has been estimated over the hydrological year beginning mid-August 1994. The total flow is calculated by assuming the flow rate measured at any date is representative of the flow from the dates mid-way between the previous and following measuring dates. This estimate is approximate because springflow measurements for this year, for all but the Whittaker Spring, were made at an interval of two weeks or greater. As water moves through the shallow aquifer system relatively quickly, springflow will be very dependent on the rainfall in the preceding few days. Measurements made on a monthly basis are likely to miss peaks in the springflow and where a peak is measured the averaging scheme will assume that this peak is representative of the flow over an extended period.

Note, the springs in Table 2.6 are grouped on the basis of the aquifer from which they discharge. This uses the assignment made by Halcrow (1997).

Figure 2.8 shows the relative estimated annual flow from springs grouped by location (see Table 2.6). Note that summing the Whittaker Spring and stream gives a flow in this valley that is 43% of the total flow from the shallow aquifer system. Discharges from Prior Park, which is located to the north on the opposite side of the plateau, are also a significant percentage of the overall flow. The significance of structural controls on springflow in this area are discussed further in Chapter 3. Figure 2.8 also illustrates the relatively large percentage of estimated discharge associated with the Inferior Oolite aquifer, which occurs at Tucking Mill. The estimated annual flow for 1994/95 for Tucking Mill is approximately 37% of the total flow from the Great Oolite aquifer.

2.5.3 *Seasonal variations in springflow and response to rainfall*

A comparison of springflow and rainfall shows the springs discharging from the shallow aquifer to be highly responsive to rainfall events. Analysis of rainfall and springflow by Halcrow (1996a) suggested that the time required for springflows to respond to rainfall events is approximately three days. Figure 2.9 shows the seasonal variation in flow from Whittaker Spring. A comparison of the springflow and rainfall inflow over the Whittaker Spring catchment (assuming total rainfall matches spring outflow) indicates significant storage within the aquifer system both by the baseflow that occurs from the spring in summer and the imbalance in rainfall and springflow in Autumn. Such analysis is not possible for other springs discharging from the shallow aquifer during this period due to the infrequency of flow measurement. Such analysis would be informative of the processes which control the flow of water to the springs.

Table 2.5 Data available on groundwater-levels, spring flows and water quality in the Combe Down area.

	Monitored	Period	Frequency	Form of data	Comments
Great Oolite					
Groundwater					
water-level	Private well 101 Church Road	Apr 94 – Mar 96 May 94 (for 2 weeks) Mar 96 – May 97	several per week every 30 minutes several per month	raw data: Apr 94 – Aug 96? rest in graph form	well dry in summer of 95+96
water chemistry		Apr 94 – Feb 95	approx. monthly		
Springs					
flow	24 springs	Mar 94 – May 97 not all springs have flows measured for full period	approx. monthly + approx. twice monthly in summers of 95+96 datalogger used on Prior Park V	raw data: Mar 94 – Mar 96 rest in graph form no datalogger data	
	Whittaker Spring	weir-level recorder readings collected for Mar 94 –Aug 98	daily readings Apr 94 – Mar 95? approx. monthly to Jan 97 one reading Aug 98	all raw data available apart from Dec 94 and Jan 95	
water chemistry	10 springs	Mar 94 – Feb 95 all Mar 94 – Nov 96 Prior Park V Nov 96 – May 97 Prior Park I	approx. monthly	all available in paper form	monitoring point changed from PPV to I in Nov 96 due to H&S considerations
	Whittaker Spring	Apr 94 - present	approx. monthly	all available in digital form	
Stream					
flow	Whittaker Stream	Mar 94 –Aug 98	daily readings Apr 94 – Mar 95? approx. monthly to Jan 97 one reading Aug 98	all raw data available	
Inferior Oolite					
Springs					
flow	8 springs	Mar 94 – May 97 not all springs have flows measured for full period	approx. monthly + approx. twice monthly in summers of 95+96	raw data Mar 94 – Mar 96 rest in graph form	
	Tucking Mill Spring	Mar 94 – Aug 98	varies from daily to 3-monthly, less frequent from 1995 on	all raw data available	
water chemistry	3 springs	Mar 94 – Feb 95	approx. monthly	all available in paper form	S Stoke I monitored once
	Tucking Mill Spring	Apr 94 - present	approx. monthly	all available in digital form	

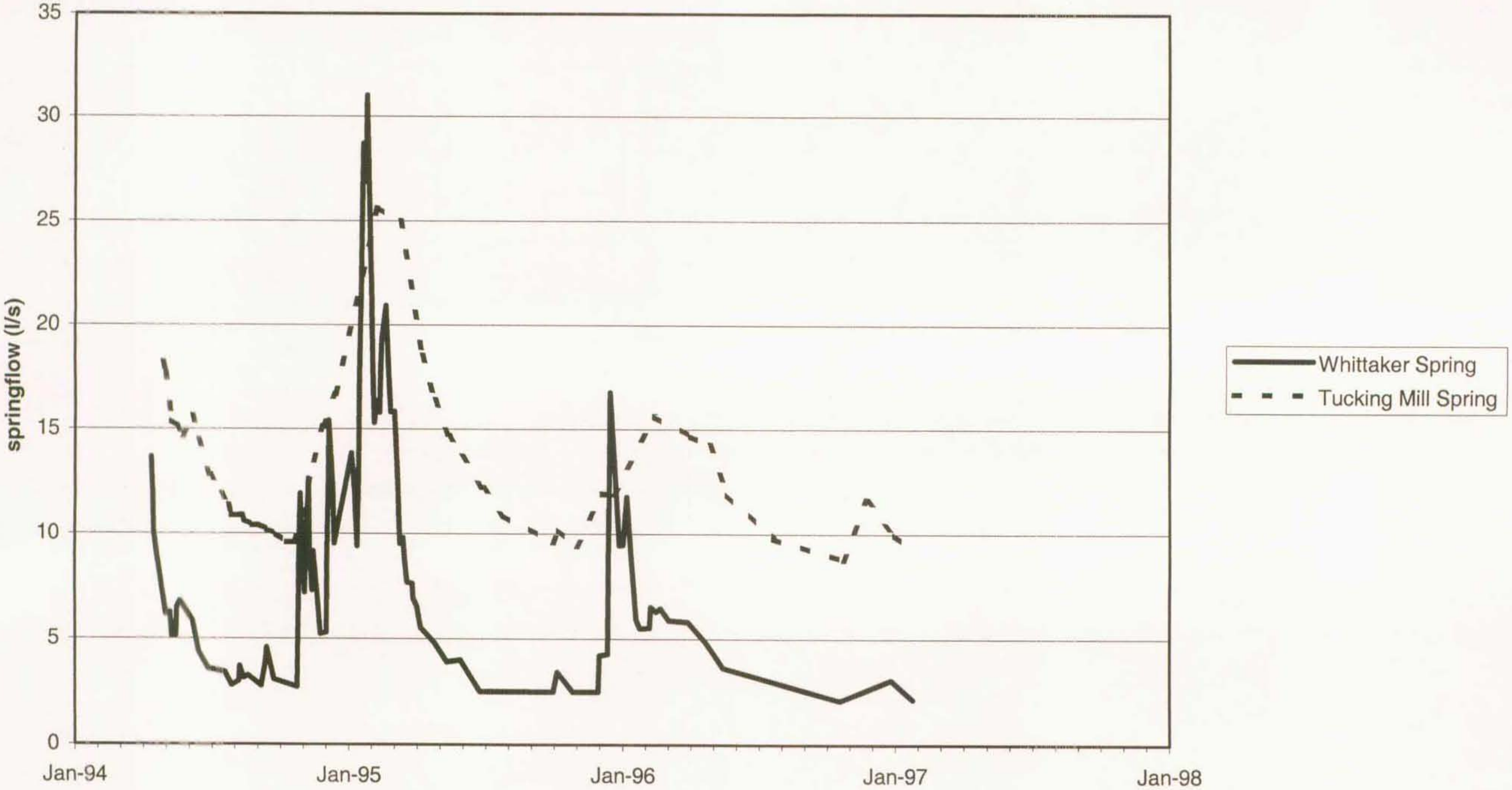

Figure 2.7 **Hydrographs for Whittaker and Tucking Mill Springs**

Table 2.6 Overview of springflow data collected by Halcrow and Wessex Water in Combe Down area, April 1994 to April 1995.

	Spring (number refers to Figure 2.1)	Maximum flow rate (l/s)	Minimum flow rate (l/s)	Total flow[1] (m^3)
GREAT OOLITE				
1	Honeysuckle Farm I			3300
2	Honeysuckle Farm II	1.48	0.01	15300
3	Lyncombe Vale I			100600
-	Entry Hill			59500
	total discharging in Lyncombe Vale area			*178700*
4	Prior Park I	2.31	0.07	28700
5	Prior Park II			45900
6	Prior Park III			18300
7	Prior Park IV	1.07	0.08	10600
8	Prior Park V[2]	22.86	0.75	246100
9	Ralph Allen Drive	1.93	0.23	33600
	total discharging in Prior Park area			*279700*
10	Monkton Combe School I	2.50	0.04	25700
11	Monkton Combe School II	2.29	0.26	29100
12	Brassknocker Hill I			23500
13	Brassknocker Hill II			20200
	total discharging in Brassknocker Hill area			*98500*
14	Horsecombe Vale Farm I	0.24	0.00	1700
15	Horsecombe Vale Farm II	2.60	0.28	21600
16	Horsecombe Vale Farm III	1.00	0.02	8100
17	Horsecombe Vale Farm IV	1.31	0.01	7600
18	Horsecombe Vale I			3200
19	Horsecombe Vale II			29400
20	Horsecombe Vale III			3400
21	Valley Spring I			no data available
22	Valley Spring II			no data available
23	Valley Spring III	10.00	0.72	80600
24	Valley Spring IV			10100
25	Valley Spring V	2.21	0.58	42400
26	Valley Spring VI	1.35	0.14	23100
	total discharging in Horsecombe Vale			*231200*
27	Whittaker Spring	15.72	2.45	241800
28	Summer Lane			8500
-	Whittaker stream	18.22	3.31	334100
	total discharging in Whittaker Valley, excluding Whittaker Spring			*342600*
Total discharge in hydrological year 1994/95				**1372500**
INFERIOR OOLITE				
29	Prior Park VI	2.97	0.47	43800
30	Lyncombe House I			75200
31	Lyncombe House II			21600
32	Lyncombe House III			34400

Table 2.6 continued

Spring (number refers to Figure 2.1)	Maximum flow rate (l/s)	Minimum flow rate (l/s)	Total flow[1] (m^3)
33 Lyncombe Vale Farm I			74200
34 Lyncombe Vale Farm II			11700
35 Lyncombe Vale Farm III			very little data available
	total discharging in Lyncombe Vale		*217100*
36 Tucking Mill Springs	25.63	9.61	504900
Total discharge in hydrological year 1994/95			**765800**

1 where no maximum or minimum flow rates are given, total flow has been calculated using extrapolated estimates of flow rates for the spring

2 although not stated explicitly by Halcrow, it is assumed that Prior Park V is the sum of all springflow from the Great Oolite within Prior Park's ground and therefore includes the discharges from Prior Park I, II, III and IV

The flow from the deep aquifer springs is less peaky than those from the shallow aquifer (eg see Figure 2.7). However, the date of the measured maximum flow rate in the deep aquifer springs (apart from Tucking Mill) is the same as the shallow aquifer springs in 1994/95 hydrological year (end of January 1995). The frequency of measurement during this period is monthly. The peak in the measured flows from Tucking Mill Spring is in the middle of February but this was the first measurement for two months. The delayed response expected in a confined aquifer is not evident. This issue will be discussed further in Chapter 3. Also of note is the very high springflow at Tucking Mill in the summer months ('baseflow').

2.6 Water Quality

A detailed review was undertaken of the water quality available for the Combe Down area. This review is presented in Appendix A.

2.6.1 Comparison between groundwater from the Great Oolite and the Inferior Oolite

The temperatures of the groundwaters from the Great Oolite and the Inferior Oolite show the same strong seasonal variation, with a range of 5 to 14°C. This is a large variation for UK groundwaters, which typically have fairly stable temperatures of about 10°C. The strong reflection of seasonal air temperature variations could result from one of the following: surface water influence; samples not taken directly at the outflow; delay between sampling and temperature measurement. If one of the two latter factors is controlling the temperatures recorded, these values are probably not representative of the true temperature of groundwaters from the Great Oolite and Inferior Oolite aquifers.

Groundwaters from the Inferior Oolite are typically harder than those from the Great Oolite. This could indicate that they have had a longer residence time in the aquifer, and have dissolved a greater amount of calcium carbonate. Trilinear plots showed that groundwaters from both aquifers are predominantly Ca-HCO_3 (calcium-bicarbonate) type waters, however the Inferior Oolite samples were more calcium-rich than some of the Great Oolite waters.

The concentrations of some parameters measured in samples from the Great Oolite exceed the maximum concentration allowed by the Water Supply (Water Quality) Regulations 1989 for public supply drinking waters. The data considered in this review showed that there were no exceedences of these limits in samples from the Inferior Oolite (excluding bacteriological counts). The concentration of nitrate is generally low in both aquifers, but is higher in the Great Oolite samples (mean = 17.9 mg

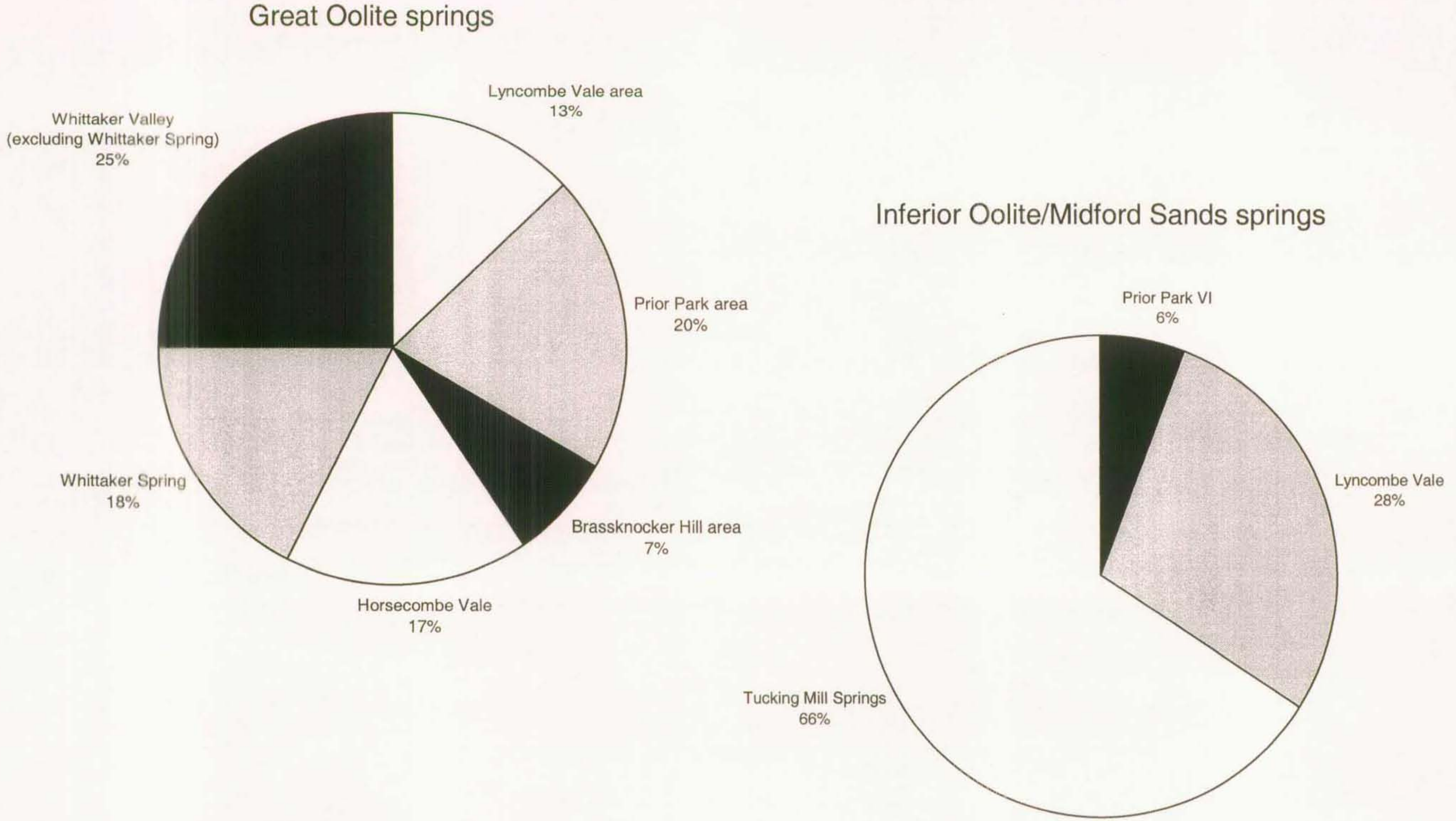

Figure 2.8 Proportions of overall springflow from individual springs and spring groupings for Great Oolite aquifer and Inferior Oolite/Midford Sands aquifer for the 1994/95 hydrological year

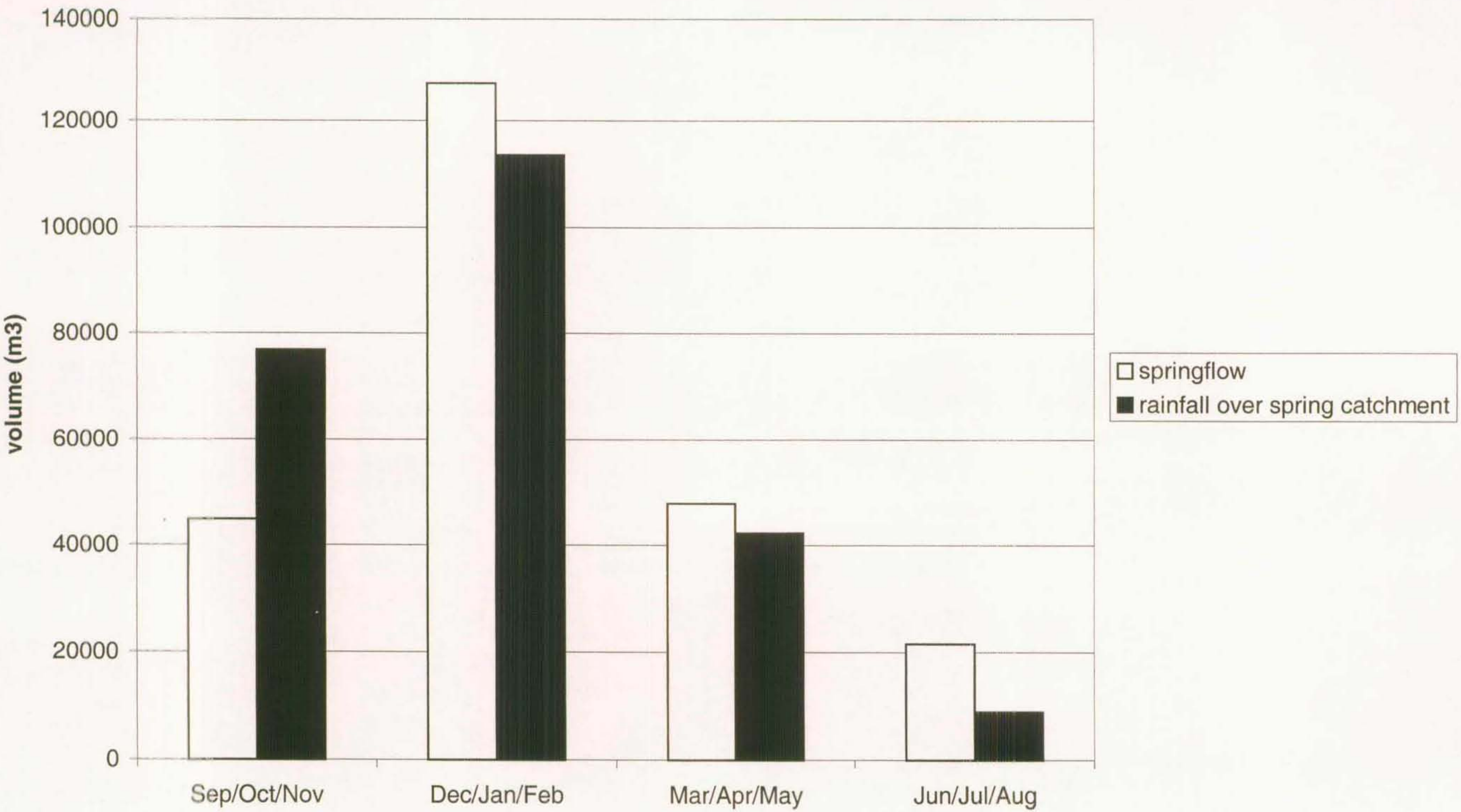

Figure 2.9 **A comparison of seasonal springflow volumes against rainfall volumes for Whittaker Spring for the 1994/95 hydrological year**

NO_3/l) than in those from the Inferior Oolite (mean = 8.1 mg NO_3/l). The groundwaters from the Great Oolite contain significantly higher levels of microbiological parameters than Inferior Oolite samples, for example, mean values of faecal coliforms were 78.5/100 ml in the Great Oolite, but just 2.7/100 ml in the Inferior Oolite.

The observed groundwater chemistry is typical of that observed in such aquifers as the Great and Inferior Oolites. For example, the calcium-bicarbonate dominated composition, with high hardness and slightly alkaline pH, is typical of limestone aquifers. The high levels of microbiological parameters observed are also common in fractured aquifers where rapid flow of groundwater can occur.

The findings of this review have also been compared to those of Halcrow (1996a, 1996b, 1997), who analysed the data collected as part of their hydrogeological survey. The results are found to be broadly in agreement, although a Durov plot produced by Halcrow (1996b) shows that some Great Oolite groundwaters have a composition dominated by calcium and sulphate as opposed to calcium and bicarbonate. This finding was not reproduced in the trilinear plots generated during the present study.

2.6.2 Indications of contamination

The major and minor ion concentrations of samples from the Great Oolite and Inferior Oolite aquifers are usually below the maximum concentrations allowed in potable water for public supply (The Water Supply (Water Quality) Regulations 1989), including nitrate which is a common contaminant in agricultural areas. There are, however, some pathogenic bacteria such as faecal coliforms, faecal streptococci and *Clostridium perfringens* in the groundwaters from these springs. This is not unusual for springwaters that originate from unconfined aquifers, or confined aquifers close to outcrop, particularly where groundwater flow is dominantly via fractures. Many bacteria, including some coliforms, occur naturally in soils and aquifers. However, the presence of faecally-derived bacteria in the aquifer is probably as a result of cesspit/septic tank discharges, sewer leaks or contamination by animal faeces. The harmful bacteria detected in the samples, many of which exceeded the maximum concentration acceptable in water for public supply, can be removed by standard disinfection practises (e.g. chlorination), so do not pose a public healththreat. Nevertheless, the sources of these bacteria may be associated with more environmentally persistent pathogens which are more resistant to chlorination.

2.6.3 Implications for developing a conceptual model of the hydrogeology of the area

The observations drawn from the analysis of groundwater chemistry data do not reveal a great deal about the hydrogeological system in the Great and Inferior Oolite aquifers. The groundwaters are of similar composition, but concentrations of calcium and bicarbonate are slightly higher in the Inferior Oolite than in the Great Oolite, suggesting a longer residence time in a carbonate aquifer. The concentrations of other parameters, such as nitrate and microbiological determinands, are typically lower in the Inferior Oolite. This could result from a lower input to the aquifer, dilution in the aquifer through mixing, or denitrification and die-off processes. The latter options of dilution and degradation could also suggest a longer residence time for groundwaters in the Inferior Oolite.

The presence of bacteria in the Inferior Oolite samples demonstrates that a significant component of the groundwater has had a short residence time in the aquifer, as the majority of bacterial pathogens die off within 50 days. However, contamination derived locally to the springs could potentially be responsible for the observed levels of bacteria.

2.7 Licenced Abstractions, Consented Discharges and Other Inputs to the Aquifer System

Details of the licenced abstractions and the consented discharges for the area were obtained from the Environment Agency. The locations of the licenced abstractions and consented discharges are shown in Figure 2.10. Licenced abstractions were requested that are located within a 4 km radius of grid reference ST 764 627, at the centre of the Investigatory Area. Those abstractions that occur within the boundary of the extent of the Midford Sands are listed in Table 2.7. No significant abstractions occur other than that at Tucking Mill. The Environmental Health Department of B&NES Council reports two non-licenced domestic water supplies in Combe Down.

Discharges may affect the quality of groundwater and/or spring waters. The analysis of groundwater and spring water undertaken by Wessex Water and as part of the previous hydrogeological survey shows significant microbiological contamination. Table 2.8 lists the consented discharges that have been provided by the Environment Agency for the area shown in Figure 2.10. Few of the discharge locations occur near the springs of interest to this study and these are unlikely to be the cause of the contamination identified. There is, however, anecdotal evidence of there being a significant number of unconsented domestic discharges of untreated sewage occurring within the Combe Down area. In addition there may be leakage from the mains sewerage network. No information on this could be provided by Wessex Water.

2.8 Land Protection

The Combe Down area is one of great environmental significance being within the World Heritage Site of the City of Bath, a conservation area and designated as a candidate Special Area of Conservation and a Site of Special Scientific Interest.

The catchments of the Whittaker and Tucking Mill Springs (as defined by the Environment Agency) are designated as Source Protection Zones as they feed into the public water supply. These are shown in Figure 2.11. As Whittaker Spring is piped to the Tucking Mill station, the two springs are treated as one source and the protection zones are combined. Tucking Mill also taps springs that are thought to be recharged by an area to the south-west and therefore the protection zone also extends in this direction. (Note, springflows quoted in Section 2.5 do not include contributions from the springs to the south-west.) The zone to the south-west of Tucking Mill, enclosed by a blue line in Figure 2.11, is associated with another source. It is not clear why a total catchment (Zone III) is not included for Tucking Mill, even if this coincides with Zone I. Zone I, which in this situation includes most of the Investigatory Area, is designed to protect against the effects of human activity which might have an immediate effect upon the source. Zone I is defined by a 50-day travel time from any point below the water-table to the source but must be no less than 50 metres from the radius of the source.

Table 2.7 Licenced abstractions within and adjacent to Combe Down.

Ref. for Fig 2.10	Grid reference	Local Name	Type	Licence No	Annual Volume (m^3)	Daily Volume (m^3)	Purpose
1	ST 764 638	Widcombe Hill	Well	17/53/001/G/270	1659	4.5	Agriculture – General Agriculture General Farming and Domestic
2	ST 775 644	University of Bath	Borehole	17/53/001/G/443	4000	11	Agriculture – Aquaculture fish
3	ST 7603 6355	Unnamed Spring	Spring	17/53/001/S/461	3650	10.3	Industrial, Commercial and Public Services – Food and Drink Water Bottling
4	ST 763 616	Tucking Mill Springs	Spring	17/53/013/S/091	1150000	6000	Water Supply – Public Water Supply Potable Water Supply – Direct
5	ST 786 631	none	Well	17/53/001/G/419	1200	103	Agriculture, Horticulture, Spray Irrigation

Table 2.8 Discharge consents within an area encompassing Combe Down (see Figure 2.10).

Ref for Fig 2.10	NGR of Outlet	Receiving Water	Name	Permit no.	Maximum Volume (m^3/day)	Dry Weather Flow (m^3/day)
Non-Water Company, Sewage Discharges – Final/Treated Effluent						
6	ST 78390 64680	Soakaway	Manor Deer Farm	010527	1.00	
7	ST 73460 61820	Soakaway	Domestic property	011883	1.00	
8	ST 78370 63700	Tributary of River Avon	Domestic Property	012516	1.50	
9	ST 75900 61300	Soakaway	Tucking Mill Manor	020145		
10	ST 77600 61800	Surface water drain	Domestic Property	021237	16.00	
11	ST 78260 62070	Midford Brook	Somerset Coal Canal Company	100446	1.80	
12	ST 77950 62970	Soakaway	Domestic Property	101170	0.63	
13	ST 77650 64100	Soakaway	RSPCA Claverton Down	101217	50.00	10.00
Wessex Water, Sewage Discharges – Sewer Storm Overflow to River Avon						
14	ST 75690 63900			010933		
15	ST 75720 63730			010934		
16	ST 75320 62970			010936		
17	ST 74300 62650			010937		
18	ST 73810 63970			010938		
19	ST 73890 63940			010939		
20	ST 74010 63860			010940		
21	ST 74070 63750			010941		

Table 2.8 continued

Ref for Fig 2.10	NGR of Outlet	Receiving Water	Name	Permit no.	Maximum Volume (m^3/day)	Dry Weather Flow (m^3/day)
22	ST 74540 63510			010942		
23	ST 74560 63080			010943		
24	ST 74580 63800			010944		
25	ST 74600 63790			010945		
26	ST 73430 63370			010946		
27	ST 73330 62610			010952		
Wessex Water, Sewage Discharges – Sewer Storm Overflow to other receiving water						
28	ST 77260 61740	Tributary of Midford Brook		021680		
29	ST 76250 61730	Midford Brook		100502		9.00
30	ST 76350 61620	Horsecombe Brook		100509		173.00
31	ST 76230 62160	Horsecombe Brook		010961		

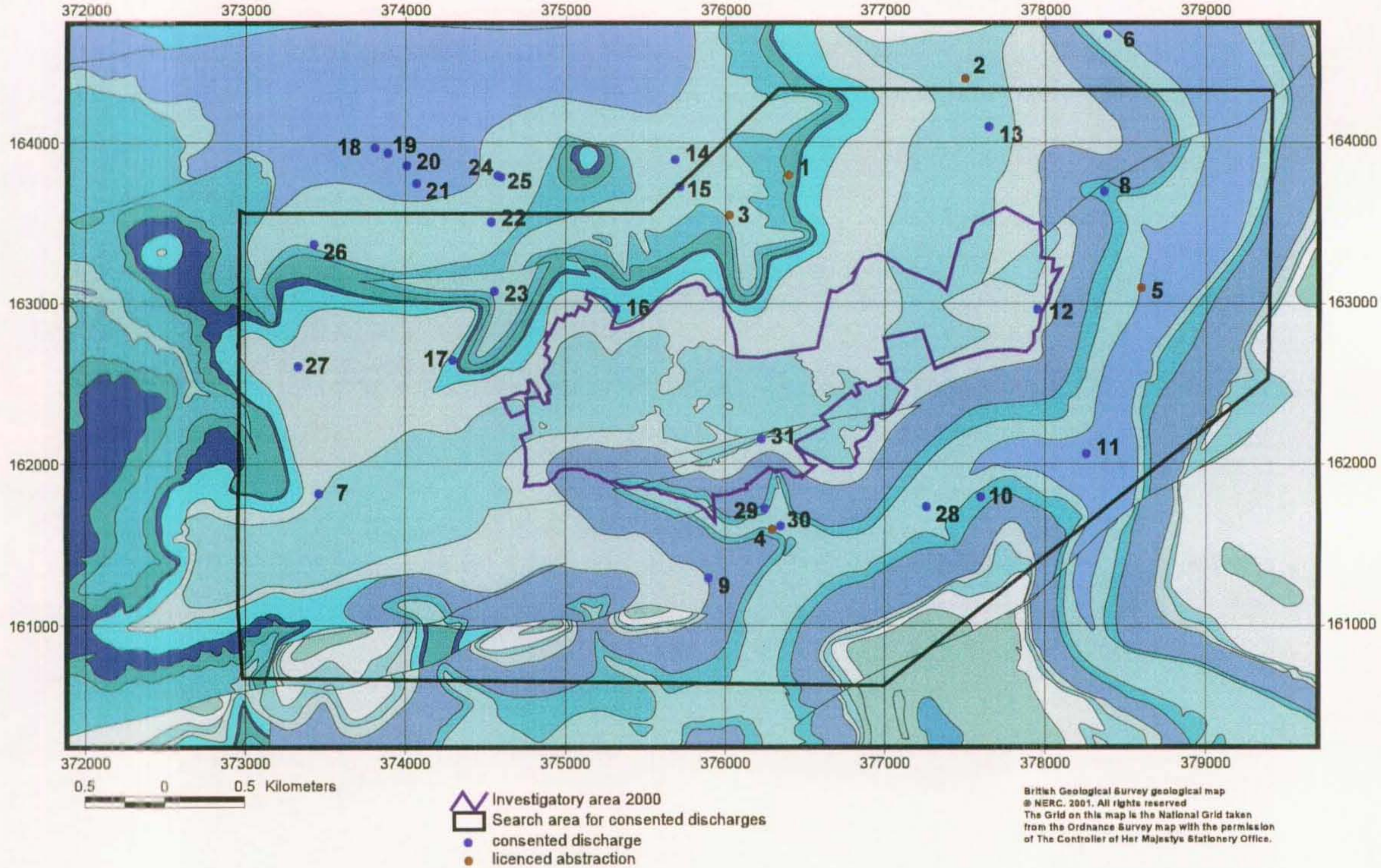

Figure 2.10 Licenced abstractions and consented discharges in the Combe Down area

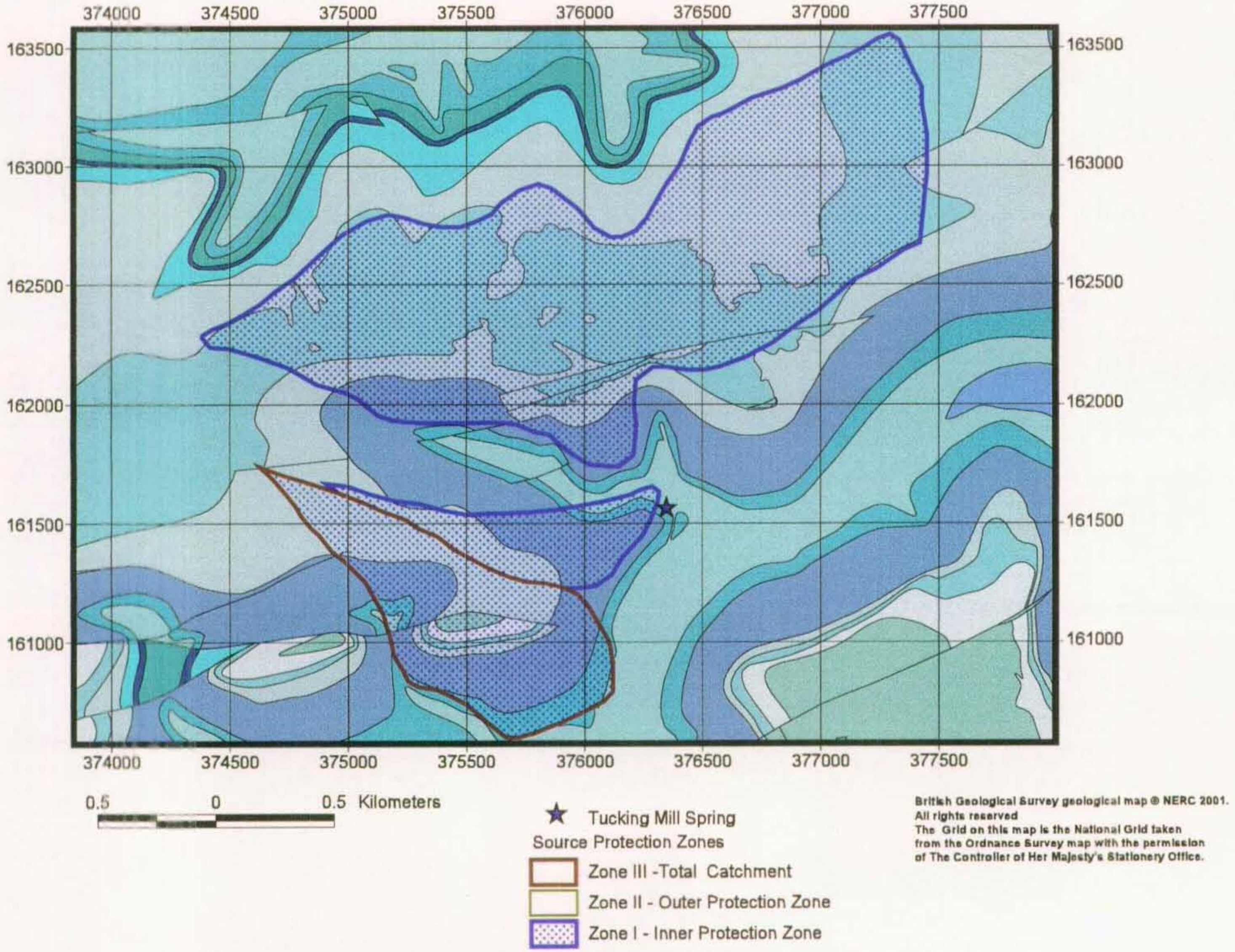

Figure 2.11 **Groundwater source protection zones for the Tucking Mill Springs (see Appendix B for terms of use of the Environment Agency groundwater source protection zones downloaded via the Internet)**

3. CONCEPTUAL MODEL OF HYDROGEOLOGY

The information gathered as part of the review presented in Chapter 2 has been used to produce a conceptual model of the groundwater flow within the aquifer system underlying the Combe Down area. Where the mechanisms of flow are not clear from the data presently available, a range of possible options are suggested. As part of the development of the conceptual model, a water balance was undertaken for the shallow aquifer.

3.1 Water Balance

A water balance has been calculated for the shallow aquifer underlying Combe Down. The known inputs to the aquifer are compared with known outputs to help understand the movement of water in the aquifer system as a whole. The water balance is based on data available for the hydrological year from mid-August 1994 to mid-August 1995. This period was chosen based on the springflow data and runs from the end of a period of sustained low springflows in 1994 to a similar time in 1995. It must be noted at the outset that this water balance is approximate and the calculations are only indicative of the volumes of flow in the aquifer system. Where there are significant error bands likely in estimates, these are noted.

The volumes of springflow from the Great Oolite Formation for the year 1994/95 are listed in Table 2.6. The total flow from the shallow aquifer, based on measured discharges, is 1,372,500 m^3. The source of error in this calculation was discussed in Section 2.5. The potential scale of the error is illustrated by comparing the flow from Whittaker Spring calculated from the flows provided by Wessex Water, 215400 m^3, with the more frequently measured flows undertaken by Halcrow, 241800 m^3, approximately 12% greater.

Calculating a groundwater recharge value for Combe Down is very difficult as it includes a significant urban area. Rain falling on roads, paved areas and buildings will tend to move rapidly to stormwater drains and it is not clear if these drains discharge to the ground or remove water from the plateau. Geomorphological structures may also significantly enhance the recharge to the shallow aquifer. However, due to the restricted time and remit of this exercise a simplification has been made that the recharge is equivalent to that occurring through grassland, the assumption made by the The Meteorological Office's MORECS system when calculating the data provided for actual evapotranspiration. Recharge has been calculated using rainfall from Beechen Cliff School and actual evapotranspiration data from MORECS system, as described in Section 2.4. The recharge is calculated by subtracting the monthly actual evapotranspiration from the monthyl rainfall for the period of the 1994/95 hydrological year. The estimate for annual recharge is 366.5 mm, 44% of the rainfall for this period. Clearly there are a number of approximations used to produce this figure and significant further work would be required to increase confidence in it. To address this issue to a degree, sensitivity analysis has been carried out on the groundwater recharge and this is reported later in this section.

There will be other inputs to the shallow aquifer in addition to rainfall. Leakage from the mains water distribution system and possibly the sewerage occurs. Consented and non-consented discharges to the ground may also take place. The only significant input for which there is an estimate is the mains leakage. Estimates of daily leakage volumes for the Combe Down area of 0.2 – 0.5 Ml/d have been made by Wessex Water (pers. comm. Luke Devial). This allows an approximate annual input to the system to be calculated assuming a mean leakage of 0.35 Ml/d (~130000 m^3).

Based on the figures provided above, recharge would have to occur over an area of approximately 3.40 km^2 to provide enough groundwater to sustain the estimated springflows that have been monitored to discharge from the shallow aquifer in the Combe Down area. This area compares with the total of the catchment areas for the main spring groups defined by Halcrow, 4.10 km^2, and the area, calculated as part of this exercise, which contains the CDSM Project's Investigatory Area, 4.59 km^2.

The volume of flow in the Inferior Oolite springs in the hydrological year 1994/95 is estimated as 765800 m^3, of which 66% discharges at Tucking Mill. One possible mechanism for recharge to the Inferior Oolite aquifer is flow through the Fuller's Earth, whether that occurs diffusely or via large faults. To aid the discussion to be developed in the next section, a comparison is made of the excess annual groundwater recharge that may occur to the shallow aquifer and the flow from the Inferior Oolite springs. Using the estimated recharge over the area encompassing the Investigatory Area, the volume of water in excess of that to sustain the Great Oolite springs for 1994/95 is 440000 m^3. This is approximately 57% of the estimated flow from the Inferior Oolite aquifer. Based on the above estimates, an increase in rainfall recharge to the shallow aquifer of approximately 20% could leave enough excess recharge to match the flow from the Inferior Oolite springs. Alternatively, a reduction in rainfall recharge by 25% would result in no excess recharge to infiltrate to the deeper aquifer.

Halcrow's hypothesis for the origin of water that discharges from the Inferior Oolite springs is recharge to the outcrop of the Inferior Oolite to the north and west. The area of this outcrop of Inferior Oolite is 4.00 km^2. If the estimate of recharge used previously is applied, the volume of recharge that would occur over this area in the period of a year is 1470000 m^3. The annual flow for 1994/95 from the Inferior Oolite springs in Combe Down is 52% of this volume. This issue will be discussed further in the next section. The figures presented in this section are summarised in Table 3.1.

Table 3.1 Summary of water balance calculations for the hydrological year mid-August 1994 to mid-August 1995.

Whittaker springflow	241800	m^3
Whittaker Valley Stream flow	334100	m^3
Other Great Oolite springflows	796600	m^3
Total spring flows from Great Oolite aquifer	**1372500**	m^3
Tucking Mill springflow	504900	m^3
Other Inferior Oolite springflows	260900	m^3
Total spring flows from Inferior Oolite aquifer	**765800**	m^3
groundwater recharge	366.5	mm
mains leakage	130000	m^3
area required to match Great Oolite springflow	3.40	km^2
Halcrow Great Oolite springs total catchment area	4.10	km^2
Area of Great Oolite encompassing Investigatory Area	4.59	km^2
volume of recharge from the above area (incl. leakage)	1810000	m^3
excess recharge that could potential feed IO aquifer	440000	m^3
IO distant outcrop area to north and west of Tucking Mill	4.00	km^2
Volume of recharge over the above area	1470000	m^3

3.2 The Conceptual Model

The mechanisms for flow in the aquifer system underlying Combe Down, presented here, are summarised in the schematic in Figure 3.1. The description summarises some aspects already discussed in Chapter 2 and develops others further.

3.2.1 Shallow aquifer

Rainfall, mains leakage and potentially mains sewerage and to a lesser extent unconsented discharges provide recharge to the shallow aquifer underlying Combe Down. Fractures, faults and gulls within the limestone aquifer of the Great Oolite Formation provide pathways for this recharge to infiltrate. The mines may play a role in distributing infiltration laterally as may units within the Great Oolite limestones in the unsaturated zone.

The only groundwater-level information available shows the water-table to fluctuate within the transition beds at the base of the Combe Down Oolite and the upper few metres of the Upper Fuller's Earth beds. Lateral movement of groundwater occurs due to the relatively impermeable clays of the main section of the Upper Fuller's Earth. Groundwater moving laterally is discharged at the plateau edge as springs. The dip of the limestone beds to the south and east means that the greater proportion of spring flow occurs on the southern edge of the plateau (67%). Water moves relatively quickly through the aquifer system. Response to rainfall has been noted in springflows within three days of rainfall events. However, the fact that the major spring flows are sustained during summer months is an indication that the system does store (as well as transmit) water. A comparison of rainfall volumes and spring volumes (Figure 2.9) shows that there is also a delay in rainfall moving to springs in autumn months, presumably as the storage of the system is replenished. There is also some evidence for springs issuing from the Fuller's Earth.

Geological and geomorphological structures would appear to have an influence on the movement of groundwater and the locations of springs. It is significant that major springflows occur at a similar easting on opposite sides of the plateau in the Prior Park area and the valley of the Whittaker Spring. Approximately 63% of the measured springflow (in 1994/95) occurs in this zone. Hawkins (1994) refers to a topographic low that occurs in the plateau at this easting and suggests that this may be associated with north-south faulting that exists regionally. One borehole geological log for this area (Section 2.1) shows the base of the Combe Down Oolite to be lower.

WSW-ENE trending faults that are identified to the south of the plateau on the 1:10,000 geology map of the area may also have an influence on the occurrence of springs, and therefore the movement of groundwater. (Note, it is possible that these are not faults but cambering-related structures). The Horsecombe Vale Farm springs are located approximately on these faults which occur to the south of the plateau. The borehole geological information (Section 2.1) suggests that the throw of these faults is significant, possibly as much as 35 m in total. These faults may cause the damming of north-south flowing groundwater, and possibly in combination with other structures may provide pathways for water to be funnelled to high-flowing springs eg Whittaker Spring. (Note, based on figures used in Section 3.1, the area required to capture the water necessary to sustain the springs discharging in the Whittaker Valley over the period of a year is 1.57 km^2, assuming the flow in the Whittaker Stream is all spring-fed).

3.2.2 Deep aquifer

A number of mechanisms for flow to the Inferior Oolite springs are possible:

- water could recharge distant outcrop areas to the west and flow downslope;
- groundwater could leak over a wide area from the shallow aquifer through the Fuller's Earth via fractures;

- groundwater could pass from the shallow aquifer through the Fuller's Earth via major faults;
- run-off over the outcrop of the Fuller's Earth, originating as springflow from the shallow aquifer, could sink back into the Inferior Oolite;
- a weathered/disturbed zone on the hillslope could allow interflow within the Fuller's Earth which recharges the Inferior Oolite.

Halcrow suggested that the origin of the water was the distant outcrop areas to the west only. In Section 3.1 it was shown that, based on the estimated recharge for 1994/95, enough rainfall could be recharged to sustain the Inferior Oolite springs in the Combe Down area, however, this would require over half of the water recharged at the distant outcrop to reach these springs.

The water balance in Section 3.1 showed that it is possible that enough water could recharge the shallow aquifer to sustain spring discharges from this aquifer and still leave sufficient water to maintain the deep aquifer springs. Simple flow calculations based on text book estimates of hydraulic conductivity of clays (Freeze and Cherry, 1979) show that, were the Fuller's Earth unfractured ($K=10^{-6}$ m/day), it would not allow the necessary leakage to sustain the deep aquifer springs (calculated using Darcy's Law, assuming a gradient of 1 and an area equal to that encompassing the Investigatory Area). Were the Fuller's Earth fractured ($K=10^{-3}$ m/day), it is possible that the necessary leakage could occur.

However, referring back to Section 2.5, the peak in the Inferior Oolite springflow does not lag significantly behind that of the springs from the shallow aquifer. The frequency of flow measurement at Tucking Mill means that it is not possible to say whether the peak in the flow here is concurrent with that in the Whittaker Spring or lagging by 2-3 weeks. Either way this implies that the flow of springs from the deep aquifer is relatively responsive to rainfall. The relatively high microbiological count in the Inferior Oolite springs may be additional evidence for rapid flowpaths. The highly responsive flow in the Inferior Oolite springs suggests that flow to the deep aquifer is unlikely to be due to diffuse recharge through fractures in the Fuller's Earth, since the travel time will be too long, particularly as this water must then pass through the unsaturated zone of the Inferior Oolite. It is possible that if the Inferior Oolite is significantly transmissive, that the recharge to the outcrop to the west could travel the distance in a few weeks. No transmissivity data are available for this area. This highly responsive element of the flow in Tucking Mill points to the latter three of the mechanisms identified above in the bulleted list. As already discussed above, there is evidence of structural features in this area that could provide rapid flowpaths for recharge and sink holes have been mapped on the northern side of the plateau.

In combination with the highly responsive element of the Tucking Mill flow, the hydrograph shows a 'baseflow' component of approximately 10 l/s (Figure 2.7) that is consistent over the three years of monitoring carried out by Halcrow (note, this is not seen in the other monitored Inferior Oolite springs in the area). This baseflow component could be provided by recharge at the distant outcrop, by diffuse leakage through the Fuller's Earth or by any of the other mechanisms listed above, assuming there are slow as well as fast pathways. It is also notable that the throws in the WSW-ENE trending faults to the south of the plateau are comparable with the thickness of the Inferior Oolite and as such they may cause the Inferior Oolite here to be dammed and flow to be funnelled.

In summary, it is possible that flow in the Inferior Oolite springs, particularly Tucking Mill, may be caused by a number of mechanisms contributing fast and slow flowing recharge.

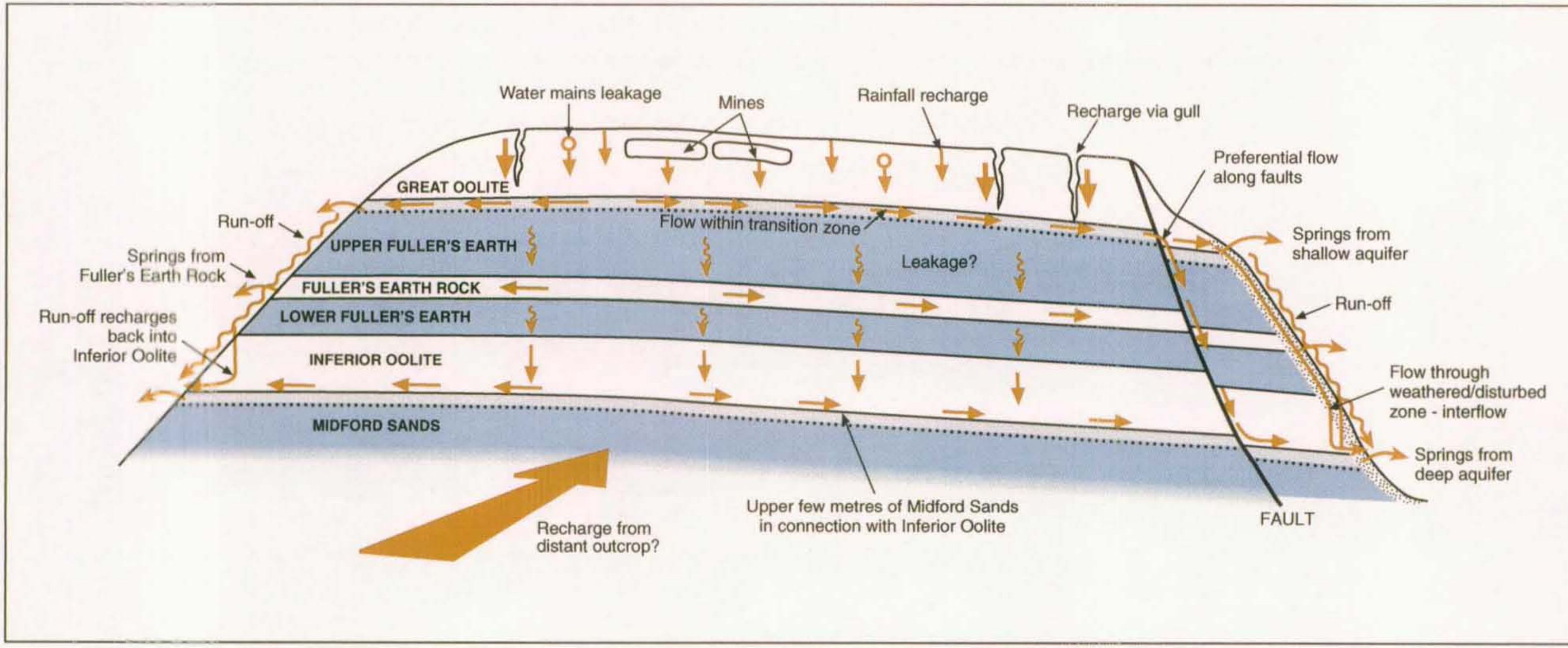

Figure 3.1 Conceptual flow model for the aquifer system underlying Combe Down

4. IMPLICATIONS FOR THE MINE STABILISATION PROJECT

Phase 1 of the present Combe Down Stone Mines Stabilisation Project is yet to be completed and therefore the preferred solution for stabilising the mines has not yet been identified. However, it is anticipated that any potential impacts on the hydrogeology of Combe Down due to stabilisation are likely to be the result of:

- mine voids becoming less permeable due to their total or partial infill;
- leachate from mine infill reaching spring outflows.

If infill of some or all of the existing mined areas would not allow water to infiltrate to the shallow aquifer following the present pattern, then the groundwater flow directions may alter. This could affect the location of existing springs or cause changes to the overall volumes or temporal variations in flow, possibly to the detriment of the environment and the present users. As the groundwater flow mechanisms within the aquifer system underlying Combe Down are not fully understood, the degree to which any stabilisation solution will impact is still unclear.

This review has produced improved estimates of the size of catchment areas for the springs discharging from the shallow aquifer but these remain approximate. It has shown that the delineation of the catchments of individual springs, in particular those of Prior Park and the Whittaker and Tucking Mill Springs, are very approximate, due in particular to the possible importance of structural controls and the difficulty in assessing groundwater recharge in urban areas.

The review presents evidence that the deep aquifer, formed by the Inferior Oolite limestones and the Midford Sands, is not isolated from the shallow aquifer in the Combe Down area, and therefore that springs discharging from this aquifer may potentially be affected by changes to groundwater flow and quality associated with stabilisation of the mines.

Changes in the groundwater flow pattern within the shallow aquifer as a result of stabilisation may also have implications for land stability, particularly on the southern slope of the plateau where it is oversteepened. The review has highlighted evidence of recent and potential future land instability in the area. Land instability is an issue because inputs of groundwater can reduce shear strength of the material on the hillslopes and can reactivate relic shear surfaces associated with cambering.

This review of available hydrogeological information for Combe Down has identified a number of aspects of the groundwater system for which additional information would be beneficial. As some of the potential stabilisation options could affect the groundwater regime, further investigations will be necessary to provide better information relating to the following issues:

- Groundwater and springflow mechanisms and delineation of spring catchment areas

  An understanding of groundwater flows in the aquifer system is essential to be able to predict the impact of any stabilisation solution and in particular will improve the delineation of spring catchment areas. These should be compared with areas which may be infilled, to help predict whether the total area of infill and location might impact on springflow.

- Groundwater recharge: mechanisms, volumes and spatial and temporal variability

  Estimates of the volumes, mechanisms and spatial and temporal variability of groundwater recharge are required to help understand the groundwater flow in the shallow aquifer and springflow responses to rainfall and to help define spring catchments.

- Geological structure of the Combe Down area

  Geological structure appears to be an important control on groundwater flow routes to springs.

- Baseline of groundwater level, springflow and water quality data

  This is valuable information for understanding the hydrological system and also provides a baseline (although limited) against which stabilisation impacts can be measured.

- Mechanisms for groundwater to flow to the springs of Inferior Oolite/Midford Sands aquifer

  An understanding of how groundwater flows to these springs will help identify the degree to which stabilisation of the mines will impact on their flow and quality.

- Land stability issues

  The risk of any stabilisation solution causing land slippage must be assessed. It is recommended that surveying is undertaken to examine geotechnical aspects of the geology of the area, particularly in the southern slopes in the vicinity of the known mine workings.

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APPENDIX A THE GROUNDWATER QUALITY OF COMBE DOWN, BATH

A1 OBJECTIVES

This appendix describes a review that was undertaken of the water quality data available for the Combe Down area. The objectives of this review were:

(i) To provide a summary of the composition of the groundwater in the area prior to any stabilisation works, which will enable any impacts of those works upon the groundwater quality to be evaluated in the future.

(ii) To determine whether or not the observed groundwater chemistry fits the current conceptual models of the hydrogeological system of Combe Down, and consider the implications of any inconsistencies.

(iii) To aid the planning of the future water quality monitoring programme.

A2. DATA SOURCES AND DATA ANALYSIS METHODOLOGY

The data used in this review came from two sources:

(i) The groundwater quality monitoring programme undertaken by consultants to Bath and North East Somerset Council. These data were obtained from three reports by the consultants (Halcrow 1996a, 1996b, 1997). Samples from a number of springs from the Great Oolite (a total of 104 samples from 11 springs) and Inferior Oolite (a total of 21 samples from 4 springs) were taken between 1994 and 1997. Due to limited time to complete the review, only the twenty-two parameters of greatest interest were input into a spreadsheet for interpretation. The aquifer from which these springs originate is not always well known as landslipping in the area complicates the surface geology.

(ii) Wessex Water provided time-series data for two sources: Whittaker Springs, a Great Oolite source; and Tucking Mill Springs, an Inferior Oolite source. Over 90 samples were taken from each of these sites between 1994 and 2000, however the full suite of determinands was not always analysed.

Basic descriptive statistics were calculated in a spreadsheet. There is no definitive technique for including values above or below detection limits in such statistical calculations, however such values cannot be omitted without hugely biasing the results. For this review, values given as greater than detection limit were input as the value of the detection limit (e.g. > 3000 was input as 3000) and values below detection limit were input as zero (e.g. < 0.02 was input as 0).

A3. DESCRIPTION OF CURRENT GROUNDWATER QUALITY

A3.1 Groundwater Temperature

The temperature of the groundwaters from the Wessex Water springs varies from 5°C to 14°C, with a mean value for both springs of 10.5°C. The time-series graph below (Figure A1) shows the seasonal fluctuation in temperatures, and that there is very little difference between the samples from the Great Oolite and the Inferior Oolite.

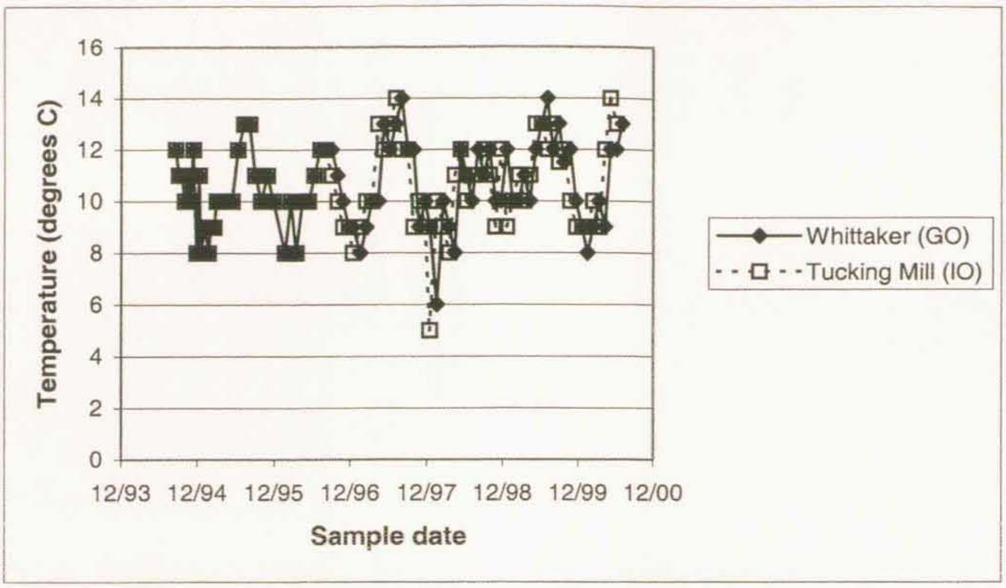

Figure A1 **Temperature variations in Whittaker (Great Oolite) and Tucking Mill (Inferior Oolite) springs.**

A3.2 Major Ions and Water Types

The maximum, minimum and mean values of the major ions and other non-microbiological parameters are shown in Table A1. The pH of the groundwaters varies between 7.1 and 8.3, with a mean of 7.6, i.e. the waters are slightly alkaline. Groundwaters from the Great Oolite and Inferior Oolite have very similar pH. The groundwaters range from hard to extremely hard, with a range of total (calcium and magnesium) hardness from 167 to 990 mg/l (as $CaCO_3$), with a mean value for both aquifers of about 300 mg/l (as $CaCO_3$). The Inferior Oolite groundwater is typically harder than that of the Great Oolite, although the highest value of total hardness was for a sample from a spring attributed to the Great Oolite. However, this value of 990 mg/l (as $CaCO_3$) is an outlier and may represent an analytical error.

The major ions (calcium, sodium, potassium, magnesium, sulphate, chloride, bicarbonate and carbonate) are the dominant dissolved species in groundwaters, and most of the dissolved solids content of groundwater results from the presence of these ions. In waters with slightly alkaline pH, such of those of Combe Down, the carbonate system will be predominantly represented by the bicarbonate ion.

The major ion concentrations are generally below the maximum concentration allowed in waters for public supply (The Water Supply (Water Quality) Regulations 1989). However, one sample had a calcium ion concentration in excess of the maximum of 250 mgCa/l, and four samples had greater than 250 mgSO_4/l (sulphate). All samples exceeding the maximum concentrations of calcium and sulphate were taken from springs attributed to the Great Oolite aquifer.

The major ion data are represented on trilinear plots (Figures A2 and A3). These plots demonstrate that groundwaters from both the Great Oolite and the Inferior Oolite are typically of the calcium-bicarbonate (Ca-HCO_3) type. Figure A2 shows that the anions for samples from both aquifers mostly plot in one area, however, there is a possible trend towards lower bicarbonate, higher chloride which is most apparent in the Great Oolite samples. The cation plot (Figure A3) again shows the samples from both aquifers plotting in a particular area of the graph, however, the Inferior Oolite samples are restricted to compositions with a higher proportion of calcium and lower proportions of magnesium, sodium and potassium than many of the Great Oolite samples.

Determinand	Units	Limit[1]	Great Oolite + Inferior Oolite			Great Oolite				Inferior Oolite			
			Max	Mean	Min	Max	Mean	Min	No of values	Max	Mean	Min	No of values
pH		5.5 to 9.5	8.3	7.6	7.1	8.3	7.7	7.2	196	7.9	7.4	7.1	112
Total hardness	$mgCaCO_3/l$	n/a	990.00	300.58	167.00	990	292.66	167	117	414	327.06	225	35
Calcium	mgCa/l	250	357.00	113.47	64.00	357	109.58	64	118	250	127.00	85	34
Sodium	mgNa/l	150	39.30	18.52	9.60	39.3	18.92	9.6	119	29.3	17.20	11.3	36
Potassium	mgK/l	12	12.16	2.73	<0.20	12.16	2.90	<0.20	119	4.31	2.14	0.67	35
Magnesium	mgMg/l	50	23.48	4.60	1.70	23.48	4.54	1.7	118	7.26	4.79	2.53	35
Chloride	mgCl/l	400	84.00	31.25	15.00	60	31.39	15	196	84	30.99	23	112
Sulphate	$mgSO_4/l$	250	526.00	82.18	21.00	526	78.04	25	190	120	89.60	21	106
Nitrate	$mgNO_3/l$	50	62.00	14.40	2.40	62	17.93	2.4	196	33.7	8.14	3.91	112
Ammoniacal nitrogen	$mgNH_4/l$	0.5	0.50	0.02	<0.01	0.5	0.02	<0.01	124	0.19	0.01	<0.01	45
Orthophosphate	mgP/l	n/a	0.28	0.03	<0.02	0.28	0.03	<0.02	190	0.08	0.02	<0.02	106
Acid soluble aluminium	mgAl/l	0.2	0.96	0.01	<0.02	0.96	0.02	<0.02	94	0.12	0.01	<0.02	87
Manganese	mgMn/l	0.05	0.40	0.01	<0.002	0.4	0.01	<0.002	119	0.004	0.00	<0.002	35
Iron	mgFe/l	0.2	4.30	0.10	<0.02	4.3	0.12	<0.02	118	0.18	0.02	<0.02	36
Strontium	mgSr/l	n/a	39.90	0.94	<0.10	31.1	0.93	<0.10	184	39.9	0.96	<0.10	101
Barium	mgBa/l	1	0.04	0.01	<0.01	0.04	0.01	<0.01	30	0.032	0.01	<0.01	17

Table A1 Statistics for inorganic parameters.

[1] The 'limit' is the maximum concentration or value which may be present in water supplied for public consumption in the UK (The Water Supply (Water Quality) Regulations 1989)

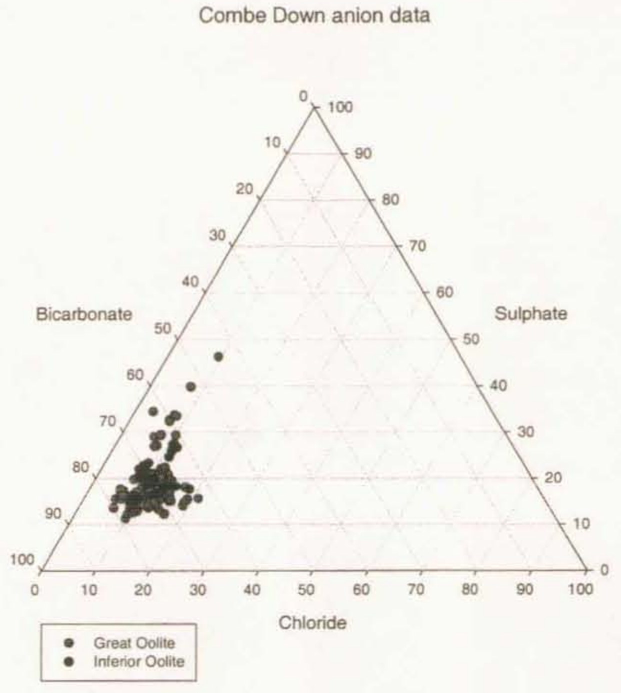

Figure A2 **Trilinear plot of anion data.**

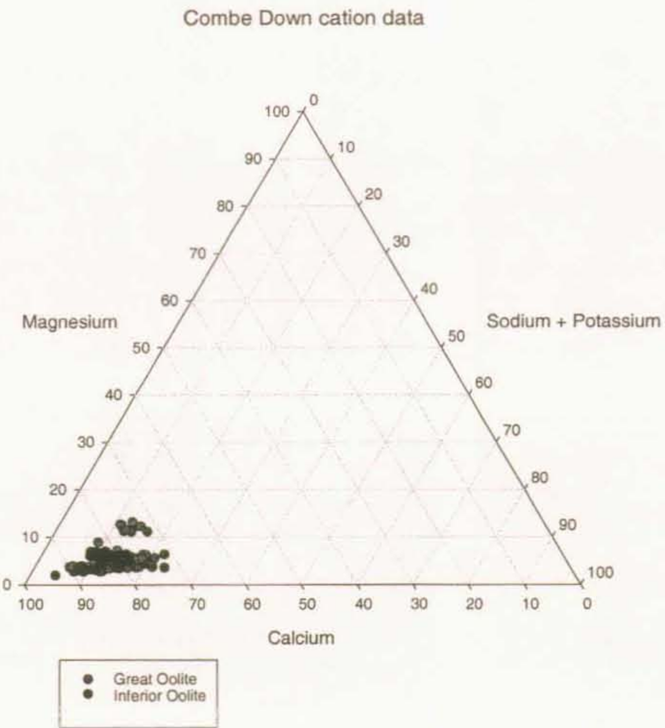

Figure A3 **Trilinear plot of cation data.**

A3.3 Minor Ions

All of the minor ions and trace elements considered in this review are present in detectable concentrations, and some exceed the maximum concentration given in The Water Supply (Water Quality) Regulations 1989 (Table A1). The concentration of nitrate ranges from 2.4 to 62.0 mg/l in the samples from both aquifers; concentrations are typically higher in the Great Oolite groundwater, with a mean of 17.9 mg NO_3/l, compared to a mean of 8.1 mg NO_3/l in the Inferior Oolite samples. The maximum concentration of 50 mg NO_3/l is exceeded in four samples, all of which are believed to originate from the Great Oolite. A histogram (Figure A4) shows that the majority of the 308 samples contain less than 10 mg NO_3/l.

Other minor ions and trace elements exceeding the maximum concentration (The Water Supply (Water Quality) Regulations 1989) are aluminium (1 sample), iron (10 samples) and manganese (1 sample); all these samples were taken from Great Oolite springs.

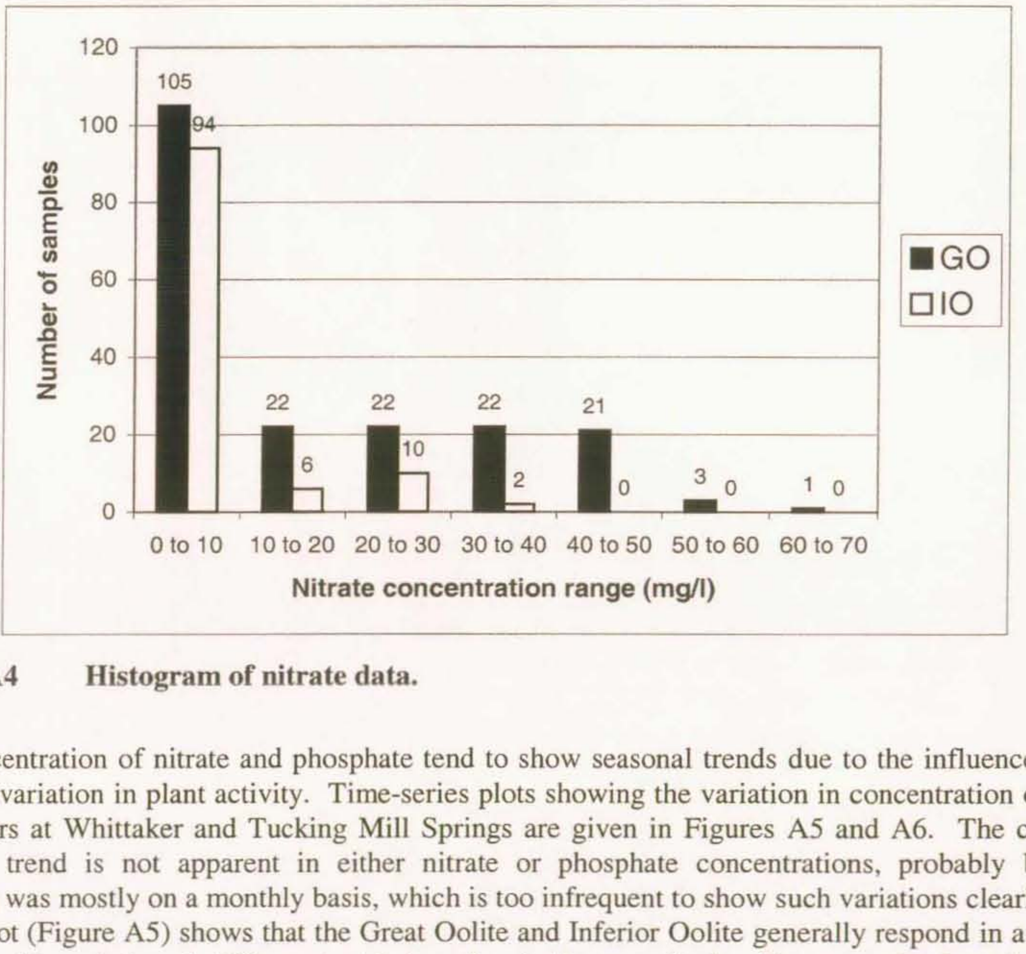

Figure A4 Histogram of nitrate data.

The concentration of nitrate and phosphate tend to show seasonal trends due to the influence of the seasonal variation in plant activity. Time-series plots showing the variation in concentration of these parameters at Whittaker and Tucking Mill Springs are given in Figures A5 and A6. The classical seasonal trend is not apparent in either nitrate or phosphate concentrations, probably because sampling was mostly on a monthly basis, which is too infrequent to show such variations clearly. The nitrate plot (Figure A5) shows that the Great Oolite and Inferior Oolite generally respond in a similar manner, with variations in NO_3 content being of a similar magnitude. However, the data also show that this magnitude of variation has varied significantly over time, indicating either that the hydrogeological system has changed, or that the sampling and analytical procedures have not been consistent. The phosphate plot (Figure A6) also shows similar behaviour in the two aquifers.

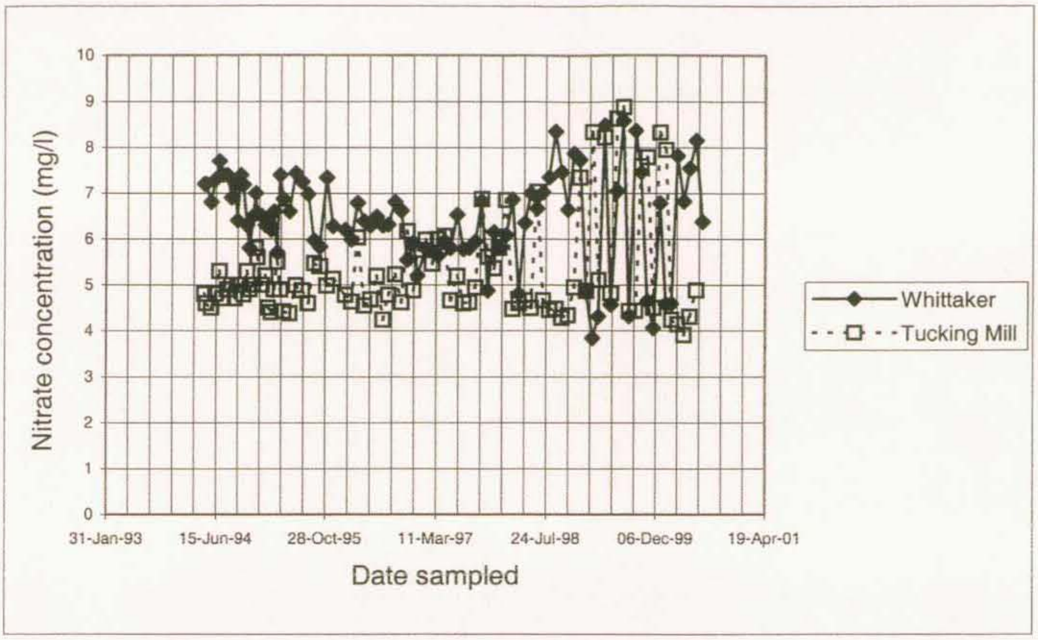

Figure A5 Variation in nitrate concentration over time.

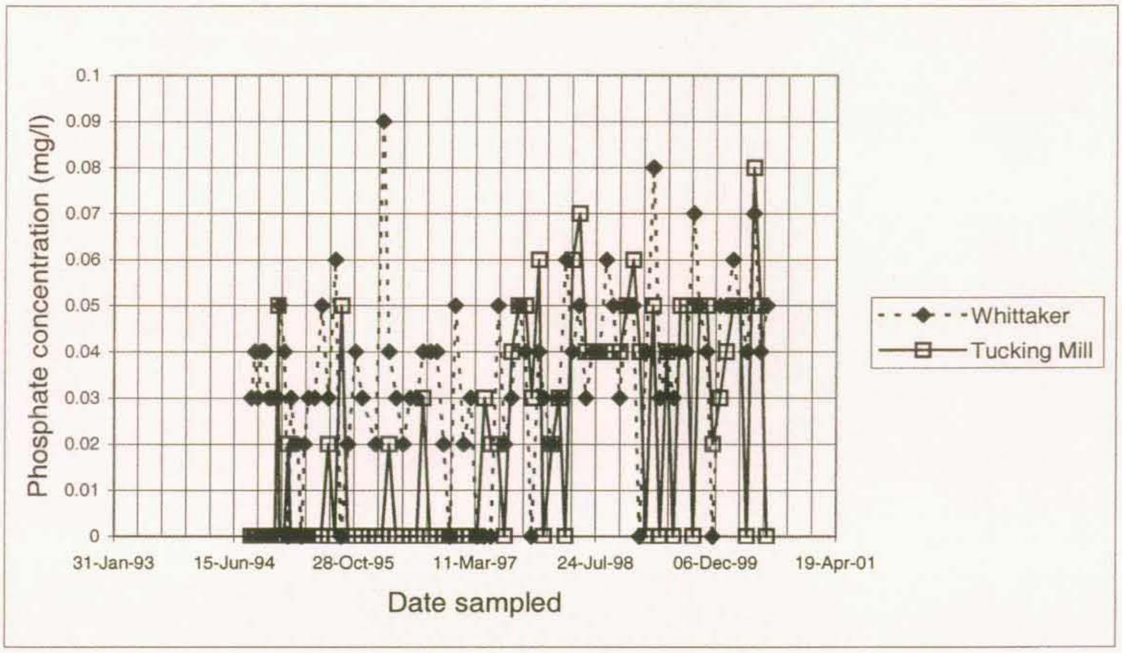

Figure A6 Variation in phosphate concentration over time.

Note: values shown as zero were below the analytical detection limit of 0.02 mg/l.

A3.4 Microbiological Parameters

The microbiological quality of the groundwaters is fairly poor, with high concentrations of faecal coliforms, *Clostridium perfringens* and faecal streptococci.

The maximum, minimum and mean concentrations of microbiological parameters are shown in Table A2. Concentrations are lower in the Inferior Oolite than in the Great Oolite, for example, the mean concentration of faecal coliforms in the Inferior Oolite is 2.7/100 ml compared to 78.5/100 ml in the Great Oolite.

The Wessex Water data was analysed to see if any correlation existed between the numbers of coliform in the Great Oolite and those in the Inferior Oolite, see for example Figure A7, however none was found.

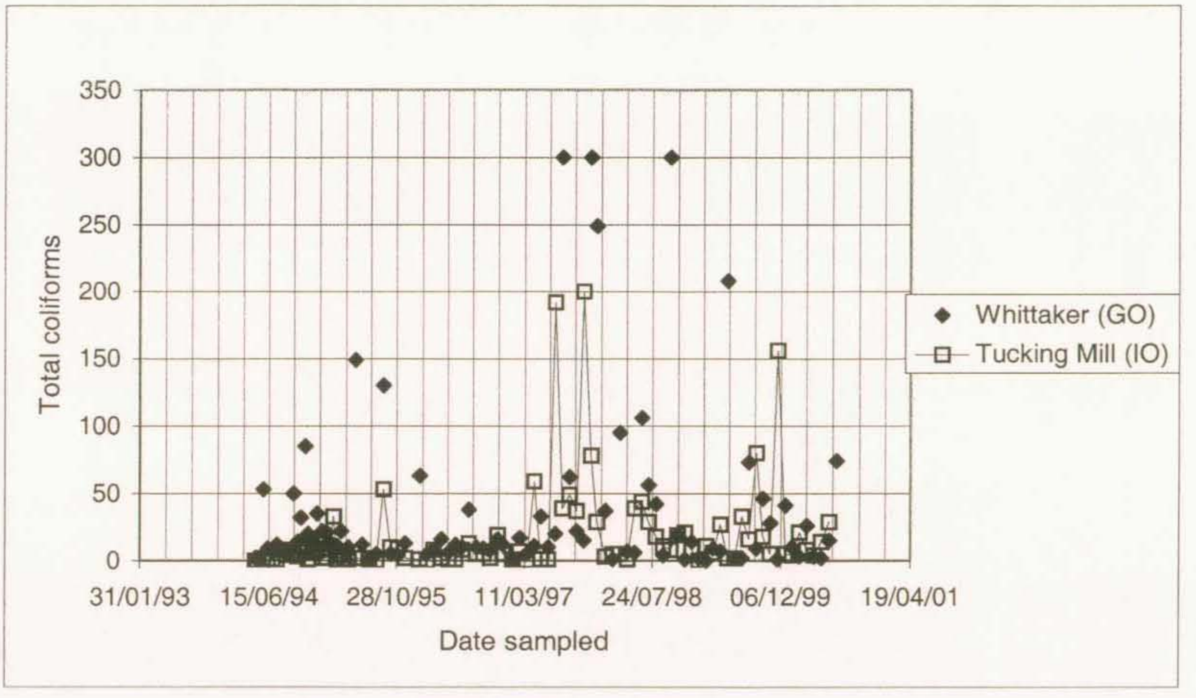

Figure A7 Comparison of total coliform concentrations in Whittaker Springs (Great Oolite) and Tucking Mill Springs (Inferior Oolite).

A3.5 Correlations Between Parameters

A correlation matrix was produced for all parameters considered in this study, and apparently significant correlations highlighted by italics (Table A3). This showed several obvious correlations, e.g. the relationships between the counts of total and faecal coliforms and between total hardness and major cation concentrations, and some commonly observed relationships, e.g. between iron and manganese concentrations.

The correlation matrix also shows a number of more unusual relationships. X-Y plots were generated for these to check whether the apparently strong relationships were 'real' or were an artifact of the method used to calculate the correlation statistics. These plots showed that several of the relationships were artificial, e.g. coliforms against aluminium, and manganese against aluminium. However, the x-y plots proved that some relationships were 'real', e.g. total hardness with sulphate (R^2 = 0.67), sulphate with magnesium (R^2 = 0.74) and magnesium with potassium (R^2 = 0.69). An example of an x-y plot, of sulphate versus magnesium, is shown in Figure A8.

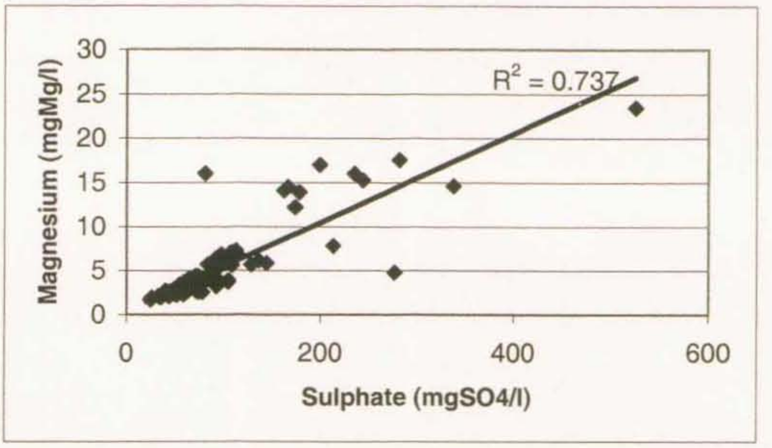

Figure A8 X-Y plot of sulphate concentration against magnesium concentration.

A3.6 Organic Chemicals

A visual inspection of the data for organic chemical parameters reported in Halcrow (1996b) was undertaken to give an idea of the concentrations of these parameters encountered in groundwater from the Combe Down area. Of the parameters that had been determined, only one detection of a chlorinated solvent, trichloroethene was made. The concentration of trichloroethene detected was 0.25 μg/l, well below the 30 μg/l maximum concentration specified in The Water Supply (Water Quality) Regulations 1989.

Low but measurable concentrations of several trihalomethanes (THMs) were also detected in some samples, including bromoform and bromodichloromethane.

The Wessex Water data set did not contain any data for organic chemicals.

A3.7 Summary of Current Groundwater Quality

The non-microbiological quality of the groundwater is generally good, with few exceedences of the Water Supply (Water Quality) Regulations 1989. Groundwaters from both the Great Oolite and Inferior Oolite aquifers are hard to extremely hard, dominated by calcium and bicarbonate, and have slightly alkaline pH. The temperature of the groundwaters varies seasonally from 5 to 14°C.

Conversely, the microbiological quality of these samples was found to be fairly poor, with high concentrations of pathogenic bacteria.

There is no evidence of contamination by chlorinated solvents.

The Great Oolite and Inferior Oolite groundwaters require disinfection to remove potentially harmful microbiological constituents, but otherwise are of good quality for potable supply.

Determinand	Units	Limit*	Great Oolite + Inferior Oolite			Great Oolite				Inferior Oolite			
			Max	Mean	Min	Max	Mean	Min	No of values	Max	Mean	Min	No of values
Plate count 1 day 37°C	/ml	n/a	>3000	194	0	>3000	231.72	0	96	39	3.32	0	19
Plate count 3 day 22°C	/ml	n/a	3832	968	1	3832	1151.05	19	188	3280	672.97	1	110
Total coliforms	/100ml	0	>300	102	0	>300	120.36	0	96	110	11.16	0	19
Faecal coliforms	/100ml	0	>300	66	0	>300	78.52	0	96	34	2.74	0	19
Clostridium perfringens	/100ml	n/a	180	15	0	180	16.46	0	95	88	6.47	0	19
Faecal streptococci	/100ml	0	>300	25	0	>300	29.66	0	95	10	1.47	0	19

Table A2 Statistics for microbiological parameters.

*The 'limit' is the maximum concentration or value which may be present in water supplied for public consumption in the UK (Water Supply (Water Quality) Regulations 1989)

	PC 1 day 37oC	PC 3 day 22oC	T. coli.	F. coli.	Clostr. perf.	F. strep.	pH	T. hard-ness	NH4	NO3	PO4	SO4	Cl	Na	Mg	Al	K	Ca	Mn	Fe	Sr	Ba
Plate count 1 day 37oC	1.00																					
Plate count 3 day 22oC	0.59	1.00																				
Total coliforms	0.24	0.41	1.00																			
Faecal coliforms	0.16	0.40	*0.84*	1.00																		
Clostridium perfringens	0.28	0.26	0.42	0.37	1.00																	
Faecal streptococci	0.07	0.31	0.39	0.38	0.40	1.00																
pH	0.05	0.19	0.38	0.41	0.13	0.19	1.00															
Total hardness	-0.20	-0.15	-0.36	-0.28	-0.14	-0.11	-0.38	1.00														
Ammoniacal nitrogen	0.10	0.06	-0.09	-0.04	-0.11	-0.02	0.01	0.01	1.00													
Nitrate	0.12	0.01	0.03	-0.07	0.08	-0.06	0.33	-0.05	0.07	1.00												
Orthophosphate	0.53	0.35	0.36	0.21	0.40	0.04	0.16	-0.29	-0.05	0.20	1.00											
Sulphate	-0.08	-0.06	-0.20	-0.18	-0.08	-0.10	-0.33	*0.82*	-0.01	0.09	-0.15	1.00										
Chloride	-0.03	0.03	-0.02	-0.02	0.05	0.03	0.21	0.22	-0.15	0.23	0.09	0.24	1.00									
Sodium	0.11	0.24	0.04	0.02	0.06	0.05	0.12	0.36	0.03	0.27	0.30	0.52	0.69	1.00								
Magnesium	-0.07	-0.07	-0.18	-0.15	-0.04	-0.09	-0.34	*0.83*	0.01	0.14	-0.07	*0.86*	0.27	0.52	1.00							
Acid soluble aluminium	0.60	0.00	*0.87*	*0.97*	0.03	0.53	0.14	-0.13	-0.08	0.03	-0.10	-0.07	-0.19	-0.08	-0.13	1.00						
Potassium	0.16	0.18	0.01	-0.02	0.10	-0.07	-0.20	0.48	-0.05	0.34	0.33	0.68	0.27	0.60	*0.83*	-0.22	1.00					
Calcium	-0.21	-0.17	-0.38	-0.30	-0.16	-0.12	-0.39	*0.93*	0.00	-0.08	-0.31	0.72	0.17	0.27	0.71	-0.12	0.35	1.00				
Manganese	0.06	0.06	0.03	0.01	-0.01	0.02	0.06	-0.05	0.01	0.18	0.13	-0.02	0.03	0.13	-0.03	*0.80*	0.04	-0.05	1.00			
Iron	0.15	0.15	0.07	0.04	0.07	0.03	0.08	-0.07	0.04	0.23	0.24	-0.03	0.02	0.15	-0.03	-0.12	0.09	-0.08	*0.97*	1.00		
Strontium	-0.08	-0.11	-0.17	-0.14	-0.10	-0.10	-0.06	0.16	-0.02	0.16	-0.08	0.12	0.11	0.17	0.15	0.02	0.09	0.14	0.31	0.27	1.00	
Barium	-0.26	-0.16	-0.32	-0.16	-0.38	-0.03	-0.04	0.57	0.19	0.20	-0.27	0.48	0.28	0.50	0.72	0.31	0.70	0.53	0.08	0.08	0.68	1.00

Table A3 **Correlation matrix of all parameters.**

A4. DISCUSSION OF CURRENT GROUNDWATER QUALITY

A4.1 Comparison Between Groundwater from the Great Oolite and the Inferior Oolite

The temperature of the groundwaters from the Great Oolite and the Inferior Oolite show the same strong seasonal variation, with a range of 5 to 14°C. This is a large variation for UK groundwaters, which typically have fairly stable temperatures of about 10°C. The strong reflection of seasonal air temperature variations could result from one of the following: surface water influence; samples not taken directly at the outflow; delay between sampling and temperature measurement. If one of the two latter factors is controlling the temperatures recorded, these values are probably not representative of the true temperature of groundwaters from the Great Oolite and Inferior Oolite aquifers.

Groundwaters from the Inferior Oolite are typically harder than those from the Great Oolite. This could indicate that they have had a longer residence time in the aquifer, and have dissolved a greater amount of calcium carbonate. Trilinear plots showed that groundwaters from both aquifers are predominantly Ca-HCO_3 (calcium-bicarbonate) type waters, however the Inferior Oolite samples were more calcium-rich than some of the Great Oolite waters.

The concentrations of some parameters measured in samples from the Great Oolite exceed the maximum concentration allowed by the Water Supply (Water Quality) Regulations 1989 for public supply drinking waters. The data considered in this review showed that there were no exceedences of these limits in samples from the Inferior Oolite (excluding bacteriological counts).

The concentration of nitrate is generally low in both aquifers, but is higher in the Great Oolite samples (mean = 17.9 mg NO_3/l) than in those from the Inferior Oolite (mean = 8.1 mg NO_3/l).

The groundwaters from the Great Oolite contain significantly higher levels of microbiological parameters than Inferior Oolite samples, for example, mean values of faecal coliforms were 78.5/100 ml in the Great Oolite, but just 2.7/100 ml in the Inferior Oolite.

A4.2 Comparison with other Data Sets in Similar Geological Settings

The observed groundwater chemistry is typical of that observed in such aquifers as the Great and Inferior Oolites. For example, the calcium-bicarbonate dominated composition, with high hardness and slightly alkaline pH, is typical of limestone aquifers. The high levels of microbiological parameters observed are also common in fractured aquifers where rapid flow of groundwater can occur.

The minimum, median and maximum concentrations of some determinands measured by Edmunds et al. (1989) in samples from the Lincolnshire Limestone, which is an Inferior Oolite aquifer, are given in Table A4. These samples were all taken from the aerobic part of the Lincolnshire Limestone aquifer, as these are believed to be more comparable to the Combe Down samples.

A comparison of values in Tables A1 and A4 shows that concentrations are typically considerably lower in the Lincolnshire Limestone samples than in either the Great Oolite or Inferior Oolite groundwaters of Combe Down. However, the dominance of the calcium and bicarbonate ions is evident in both data sets.

Parameter	N (no. in sample)	No. below detection limit	Minimum	Median	Maximum
Na	8	0	11.9	13.4	16.2
K	8	0	0.8	2.5	3.5
Ca	8	0	138	143	153
Mg	8	0	6.0	6.7	9.2
HCO_3.fld	8	0	258	274	278
SO_4	8	0	67	125	146
Cl	8	0	28.5	31.2	39.2
NO_3	7	1	1.65	4.2	14.1
Sr	8	0	0.21	0.34	0.75
Ba	8	0	0.013	0.017	0.021
Fe.Total	8	0	0.0006	0.0200	0.1140
Mn	6	2	0.0017	0.0029	0.0143

Table A4 Minimum, median and maximum concentrations (mg/l) in Lincolnshire Limestone groundwaters west of the redox boundary (in aerobic conditions). From Edmunds et al., 1989.

The findings of this review have also been compared to those of Halcrow (1996a, 1996b, 1997), who analysed the data collected as part of their hydrogeological survey. The data collected by them has been reviewed in the present study. The results are found to be broadly in agreement, although a Durov plot produced by Halcrow (1996b; Figure A9) shows that some Great Oolite groundwaters have a composition dominated by calcium and sulphate as opposed to calcium and bicarbonate. This finding was not reproduced in the trilinear plots generated during the present study (Figures A2 and A3).

A4.3 Indications of Contamination

The major and minor ion concentrations of samples from the Great Oolite and Inferior Oolite aquifers are usually below the maximum concentrations allowed in potable water for public supply (The Water Supply (Water Quality) Regulations 1989), including nitrate which is a common contaminant in agricultural areas.

There are, however, some pathogenic bacteria such as faecal coliforms, faecal streptococci and *Clostridium perfringens* in the groundwaters from these springs. This is not unusual for springwaters that originate from unconfined aquifers, or confined aquifers close to outcrop, particularly where groundwater flow is dominantly via fractures. Many bacteria, including some coliforms, occur naturally in soils and aquifers. However, the presence of faecally-derived bacteria in the aquifer is probably as a result of cesspit/septic tank discharges, sewer leaks or contamination by animal faeces. The harmful bacteria detected in the samples, many of which exceeded the maximum concentration acceptable in water for public supply, can be removed by standard disinfection practises (e.g. chlorination), so do not pose a great public threat. Nevertheless, the sources of these bacteria may be associated with more environmentally persistent pathogens which are more resistant to chlorination.

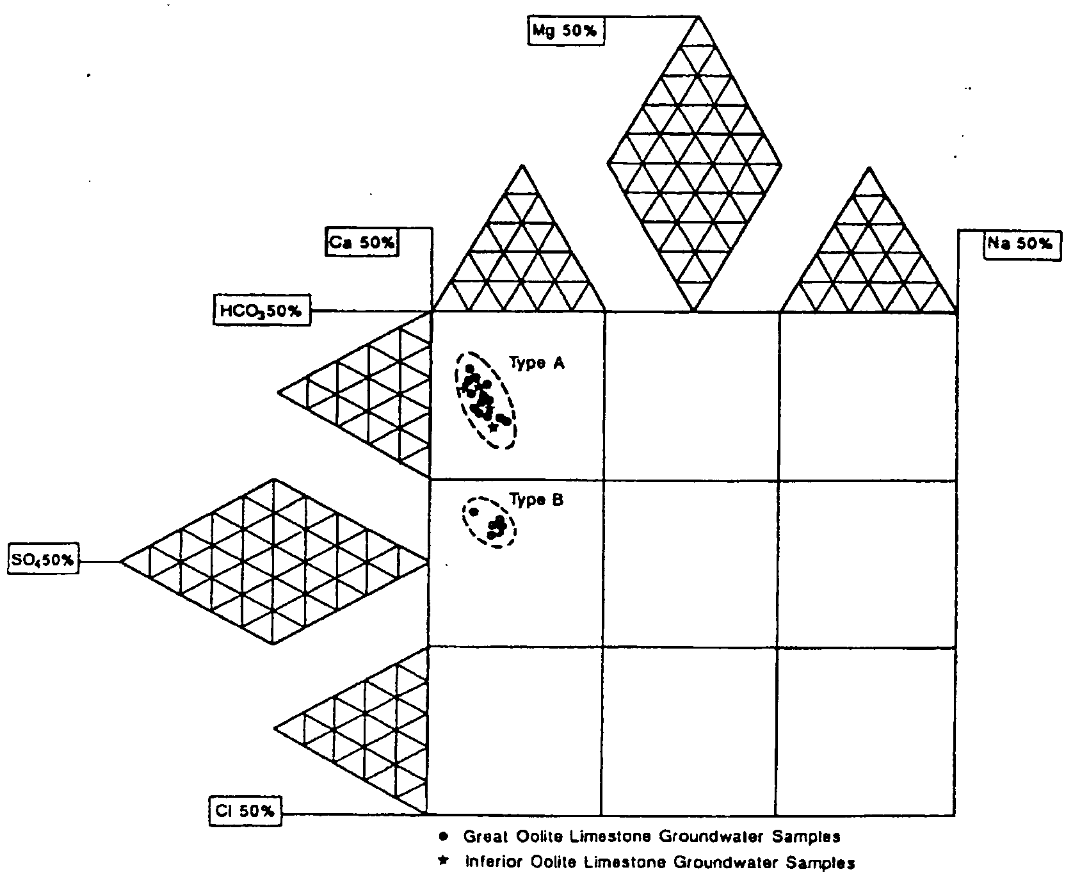

Figure A9 **Durov plot from Halcrow (1996b).**

A5. IMPLICATIONS FOR DEVELOPING A CONCEPTUAL MODEL OF HYDROGEOLOGY OF THE AREA

The observations drawn from the analysis of groundwater chemistry data does not reveal a great deal about the hydrogeological system in the Great and Inferior Oolite aquifers. The groundwaters are of similar composition, but concentrations of calcium and bicarbonate are slightly higher in the Inferior Oolite than in the Great Oolite, suggesting a longer residence time in the carbonate aquifer. The concentrations of other parameters, such as nitrate and microbiological determinands, are typically lower in the Inferior Oolite. This could result from a lower input to the aquifer, dilution in the aquifer through mixing, or denitrification and die-off processes. The latter options of dilution and degradation could also suggest a longer residence time for groundwaters in the Inferior Oolite.

The presence of bacteria in the Inferior Oolite samples demonstrates that a significant component of the groundwater has had a short residence time in the aquifer, as the majority of bacterial pathogens die off within 50 days. However, contamination derived locally to the springs could potentially be responsible for the observed levels of bacteria.

A6. CONCLUSIONS

The groundwaters sampled from springs discharging from the Great Oolite and Inferior Oolite aquifers of Combe Down, Bath, have similar compositions, strongly reflecting the calcium carbonate composition of the aquifers. The quality is typically good apart from significant levels of bacteria. The current data set does not reveal much about the hydrogeological system of Combe Down, except that rapid flow occurs in both aquifers. However, the composition of springwaters can be greatly influenced by the local conditions around the spring, particularly in fractured aquifers, so it is difficult to draw conclusions from the limited data considered in this study.

APPENDIX B TERMS FOR USE OF ENVIRONMENT AGENCY GROUNDWATER SOURCE PROTECTION ZONES

Downloading **Groundwater Source Protection Zones**, in **Shape Mapping Format (SHP)**, for **Bath & North East Somerset Council**.

Please note and agree to the following terms of use of the data:-

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