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Report on the By Brook low flow investigations

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Volume I

Report

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Executive Summary

In 1996 the Friends of the By Brook Valley (FOTBV) expressed concern to the Environment Agency about deterioration in the quality and quantity of water in the By Brook, especially since 1990. As a result, the By Brook catchment was identified as an issue in the Bristol Avon Local Environment Agency Plan (LEAP) (item 2.2.6) and also in the report 'A Price Worth Paying' (March 1998) as a subject to be investigated in the Water Companies' Asset Management Plan (AMP) 3 period.

In order to initiate the investigations, the Agency commissioned Halcrow to produce an inception report, which was published in 1998. The report's recommendations were accepted by the Agency and the FOTBV as the basis for further action as a three year strategy for the catchment (Appendix 1). At the end of that period the additional information gathered and actions implemented would be reported back to the FOTBV in spring 2001. This is the promised report on the findings of the investigations.

In the perception of the FOTBV, deterioration in the quality and quantity of water in the By Brook is caused by:

- a decrease in summer flows, resulting from groundwater abstractions;
- an increase in flashiness due to motorway runoff that drains into the Brook;
- water quality problems due to sewage treatment works, farm slurry and motorway runoff;

resulting in decreased amenity and ecological value.

It was, therefore, not sufficient to limit the study to water resources. It has examined:

- geology of the area, in order to derive a conceptual model describing the hydrogeology;
- groundwater records, for signs of general water resources deterioration;
- streamflows at a dense network of new sites, to examine catchment behaviour and estimate the impact of abstractions and discharges on flows;
- abstraction and discharge records to examine human impacts on flows;
- the impact of impoundments on water resources, water quality and ecology;
- rainfall records, to correlate with streamflow and investigate variability and trends;
- groundwater tracer results, to define the hydrogeological catchment boundary;
- River Quality Objectives and their achievement, to describe the water quality aspect of river flows;
- pollution incidents, consent compliance and their follow-up, to indicate that progress is being made to improve water quality;
- flora and fauna, by means of extended surveys.

This study has demonstrated that water resources in and around the By Brook catchment are in a very healthy state at present, with sustained high groundwater levels and above-average river flows. River flows are very variable in time, both on an annual and monthly scale, and highly dependent on concurrent rainfall. This is due to a highly fractured upper aquifer of limited thickness, which recharges, but releases quickly.

Since the start of the flow record at Middlehill in 1982, no increase in flashiness could be detected. It has not been possible to analyse the impacts of the construction of the M4 as there was no flow data available, however, it was noted that the degree of flashiness seen on the By Brook is not outside that that would be expected for a catchment with these hydrogeological characteristics. The Environment Agency has a policy of encouraging sustainable urban drainage where possible and any future proposals for works on the M4 would be subject to this policy.

The impact of abstractions within the catchment are minor and could not account for a degradation of water quality or ecology. The net impact of abstraction and discharges within the catchments is to increase flows, with some upper reaches especially experiencing higher flow due to sewage treatment works discharges.

Significant impact due to abstractions for Public Water Supply outside the catchment boundary to the east are unlikely because of the hydrogeological layout and the unchanged characteristics of groundwater level records. Impact on flows in the By Brook due to stream support abstractions to the north of the catchment are also considered unlikely due to their hydrogeological setting, though testing and analysis is ongoing on these sources to ascertain recharge mechanisms. These sources are currently operated via a Section 32(3) consent[1]. If analysis does identify that flow in the By Brook could be significantly impacted by these abstractions then conditions on future licences for these sources (i.e. abstraction rate and period of abstraction) will ensure there is no impact on the By Brook.

It has been concluded that although low flows do probably contribute to water quality and ecological problems in dry years, analysis of rainfall statistics shows that these low flows are predominately natural, due to the variability of rainfall and the hydrogeological character of the upper catchment.

Water quality improvements have been negotiated with discharge consent holders, and improvements should be observed in the next few years. However, water quality data (time series) point to a considerable part of current pollution levels originating from farmland as diffuse pollution, a problem which is much less easy to solve than the point pollution from sewage treatment works or incidents. A North Wessex Diffuse Pollution Strategy has been written with a view to furthering the work on diffuse pollution in the area. The strategy used River Quality Objectives (RQO) as a key performance indicator for identifying and prioritising work in the future. The By Brook currently shows no RQO failures, and as such is not considered a high priority catchment. The need for a full nutrient budget for the Bristol Avon has been identified as a priority for the North Wessex Area, and will be completed when resources allow. The Agency has actively targeted farms in the upper reaches of the catchment and offered advice on best management practices. The adoption of these practices and the improved operation of private waste water disposal units is an area where residents of the By Brook valley can contribute to water quality improvements.

[1] Under Section 32 of the Water Resources Act 1991 the Agency is able to issue permits (32 (3) consent) which allow the applicant to carry out drilling and test pumping for the purpose of investigating groundwater.

Glossary

abstraction licence	legal document permitting the abstraction of surface or groundwater up to a certain quantity at a certain place; conditions may be imposed, e.g. to preserve a certain flow in the river
abstraction returns	annual report on actual abstractions as measured by the licence holder
AMP3	Water Companies' Asset Management Plan no.3 (2000-2005)
aquiclude	geological layer that prevents the passage of (ground)water
aquifer	water bearing geological layer or combination of layers
aquitard	geological layer that delays the passage of (ground)water
baseflow	river flow that is thought to originate from subsurface (soil or aquifer) storage as opposed to direct rainfall runoff
bedding plane	surface in a geological layer that is parallel to the plane of deposition
benthic	living on the bottom of the stream
BFI (Base Flow Index)	baseflow as proportion of total flow (statistically defined)
confined / unconfined aquifer	exposed to the air (unconfined) or covered by other geological layers (confined); this excludes a possible thin cover (drift)
CSO	Combined Sewer Overflow
discharge consent	legal document permitting the discharge of water up to a certain quantity and quality at a certain place
drift	layer covering the solid geology
effective rainfall	proportion of rainfall that is available for recharge or runoff once evapotranspiration and soil moisture deficit have been accounted for.
fault	discontinuity in geological layers originating in horizontal and/or vertical displacement of layers
flow regime	*see river flow regime*
heterogeneity	contains properties which are unlike each other
hydraulic continuity	connection between geological layers which means that groundwater can flow from one layer to the next (but possibly with difficulty)
hydrograph	trace of river flow or groundwater levels in time
joint	fracture in a rock where there is no observable movement (crack)
lotic	running water
mBDAT	Metres Below Datum. A unit measurement given to groundwater levels, denoting the distance down from the dip point (datum) to water level
mAOD	Meters Above Ordnance Datum
MORECS	Meteorological Office Rainfall and Evaporation Calculating System. A computer package run by the Met Office which gives evaporation, effective rainfall and soil moisture deficits for each 188, 40 x 40km grid square in the UK
naturalised flow	the estimated flow of a watercourse once it has been modified to account for the influence of artificial influences such as abstractions of water from, and discharges of effluent into a watercourse.
oolitic limestone	limestone with many ooliths, i.e. spherical rock particles
perched water table	water table higher than and separate from the extensive regional water table, underlain by (nearly) impermeable layer
Q	flow (i.e. volume of water per time unit)
Q95	flow that is equalled or exceeded 95 % of the time (low flow statistic) in an average year (using all year data)
R^2	regression coefficient, i.e. the percentage of the variation that is explained

	by the equation
recession curve	part of the hydrograph that shows the depletion of storage when recharge ceases; typically spring/summer part of the hydrograph
recharge	the part of rainfall that is stored in the subsurface (soil or aquifer), i.e. after evapotranspiration and direct runoff have taken their part
river flow regime	average pattern of river flow in time, quantified e.g. in BFI and Q95
Section 32 (3) Consent	Permit issued by the Agency under Water Resources Act 1991, which allows the applicant to carry out drilling and test pumping for the purpose of investigating groundwater availability.
standard deviation	statistical measure of the dispersion of results around the average value defined as $\sqrt{(n\Sigma x^2-(\Sigma x)^2/n(n-1))}$. Informally, this may be defined as the spread or reliability of obtaining the average.
storage coefficient	amount of water released from a unit volume aquifer when the pressure drops one unit
stratum (-a)	layer (-s)
STW	sewage treatment works
transmissivity	measure of total water transport in an aquifer
variability	deviations from the average seen in time
water year	12 months running from October to September, used to represent one water cycle. e.g water year 1999 = Oct'99 - Sept'00
winterbourne	stream that only bears water in winter

Conversion factors

from	*to*	*multiply by*
mm depth	m^3/s	area (in m^2) /time (in seconds)
m^3/s (cumec)	l/s	10^3 (i.e. multiply by 1000)
	Ml/day	86.4
	m^3/day	86400

To go from the 'to' column to the 'from' column, divide by the factor indicated.

1. Introduction

1.1 History of recent By Brook investigations

In 1996 the Friends of the By Brook Valley (FOTBV) expressed concern to the Environment Agency about deterioration in the quality and quantity of water in the By Brook, especially since 1990. As a result, the By Brook catchment was identified as an issue in the Bristol Avon Local Environment Agency Plan (LEAP) (item 2.2.6) and also in the report 'A Price Worth Paying' (March 1998) as a subject to be investigated in the Water Companies' Asset Management Plan (AMP) period 3 (AMP3). The present study is lead by, and administered by, the Water Resources function of the Agency, and much of the investigations described here concerns stream flows and groundwater behaviour. However, ecological surveys and environmental protection site inspections were also included in order to discuss all aspects of public concern.

The perceived problems are mostly located in the northern half of the catchment upstream of Ford (ST 842 748). The FOTBV expressed the need for urgent investigation and remedial action. In order to initiate the investigations, the Agency commissioned Halcrow to produce an inception report which was published in 1998 (Halcrow, 1998). The report's recommendations (Appendix 1) were accepted by the Agency and the FOTBV as a basis for further action as a three year strategy for the catchment. At the end of that period the additional information gathered and actions implemented would be reported back to the FOTBV in spring 2001.

Intensive data collection has been ongoing since spring 1998. Progress reports were presented as promised to the FOTBV bi-annual meetings. This report presents the results of these investigations in the context of earlier findings, in order to draw conclusions where possible and propose remedial actions where necessary. The major challenge of the investigations has been to try to answer public concerns, as expressed by the FOTBV, translating them into scientific questions that can be answered through field investigations, and subsequently communicating the results of the investigations to the public.

1.2 Perceived problems

The perceived deterioration in the quality and quantity of water in the By Brook are expressed by the FOTBV in terms of negative signals: less clean water ('sewage instead of spring flow in our brooks'), increased weed growth but decline in water crowfoot, decline in wildlife and fish, lack of flow (or depth). In their opinion, problems are caused by:

- a decrease in summer flows, resulting from groundwater abstractions;
- an increase in flashiness due to motorway runoff that drains into the Brook;
- water quality problems due to sewage treatment works, farm slurry and motorway runoff.

resulting in decreased amenity and ecological value.

1.3 Related reports and publications

The following reports were produced as a part of the By Brook investigations. This list does not include general scientific references, which may be found at the end of the report.

BGS (2000) Stratigraphy and geological structure of the principal aquifer sequences in the catchment of the River Avon near Malmesbury. British Geological Survey. Commissioned by the Environment Agency.

Brown, A. (1999) A macro-invertebrate flow assessment of the By Brook. Environment Agency.

Environment Agency (2000) Local Environment Agency Plan: Bristol Avon Action Plan.

Halcrow (1998) By Brook Low Flow Preliminary Study. Volume 1 Main Report, Volume 2 Appendices A – E. Commissioned by the Environment Agency.

Hicklin, A. (1998) Botanical surveys of the By Brook. Environment Agency.

Smart, P. L. (2000) Hydrogeology of the Upper By Brook, Wiltshire. Commissioned by the Environment Agency.

Tatem, K. (1996) A history of the By Brook. Environment Agency.

Yeandle Whittaker Partnership (1999) Abstraction Licence Assessment, West Kington Nurseries, Chippenham. Commissioned by the Environment Agency.

2. Monitoring Network (Water Resources)

2.1 Overview

In order to fill the gaps in knowledge about the water resources system in the By Brook catchment, an intensive programme of field measurements was instigated (Map 1). This section explains briefly how monitoring was expanded from the regular programme. Results of the observations are presented in Section 3.5.

2.2 Rainfall

Three daily-read raingauges are in operation in or near the By Brook catchment; they are located at Castle Combe, Marshfield and Bathford and adequately cover the catchment (Table 1). Rainfall is expressed in mm depth, which can be in any time period, e.g. one day, one month or one year. Data are quality-controlled by the Met Office using regional consistency criteria. No climate stations are located near the By Brook catchment.

Table 1 Raingauges

Raingauge Ref. No.	Location	Start date	Weight *	Long Term Average (LTA)[1] 1961-90 (mm)	1981-2000 mean annual rainfall (mm)
53010490B	Bathford	01/01/1973	0.22	814	863
53040100B	Castle Combe	01/01/1981	0.36	829	875
53040400B	Marshfield	01/01/1975	0.42	897	934

The three rainfall sites are evenly distributed around the catchment, their observations are similar and well correlated, so they represent catchment average rainfall acceptably. The Thiessen polygon method (Shaw, 1994) was used to attribute weights to each of the three sites; the weights can be seen as the proportion of the catchment that is represented by a gauge. The formula for calculating catchment average rainfall then becomes:

$$\text{Catchment rain} = 0.22 * \text{Bathford} + 0.36 * \text{Castle Combe} + 0.42 * \text{Marshfield}$$

As the three gauges are present from 1981 onwards, this is the period that has been analysed in this report. The supporting raingauge data and calculation is shown in Appendix 2.

In addition, MORECS (Sq 158) effective rainfall data for the last 30 years has been collected and assessed to examine long term trends.

[1] This is a Met Office estimated value for all raingauge sites that is used as a standard in national comparison.

2.3 Groundwater monitoring

At the start of the investigations the groundwater level observation network was limited to three sites (Atworth 3, Colerne 1 and Allington 1), and only Colerne 1 was situated inside the catchment boundary. It was greatly expanded by:

1. re-including boreholes that had been observed in the past. This added 11 locations.
2. investigating the possibility and usefulness of including existing wells on a list provided by the FOTBV. Unfortunately none of these were found suitable.
3. investigating the possibility and usefulness of including previously unused boreholes and wells from Water Authority and British Geological Society (BGS) borehole records. From these, four sites were added to the network.

The usefulness of a borehole or well may be limited if other observation points exist nearby, or if it is shallow thus not capturing the full fluctuation in groundwater level. Some old boreholes were found to have collapsed inwards, making dipping for the level impossible, or covered over in an irrecoverable way. The new well at Burton was thought to be suitable but after a few months of monitoring, water level observations showed that no meaningful data was being obtained and monitoring subsequently ceased.

The current level monitoring points, the aquifer which they monitor and length of available record are presented in below in Table 2. The Monitoring point locations are shown on Maps 1 and 2.

Table 2 Groundwater Observation Boreholes

Name	Aquifer	Type	period of observation
Atworth 1	IO	borehole	1973-1989 and 1998-present
Nettleton ex-PWS*	IO (?)	borehole	new site
Chippenham ASR	IO	borehole	new site
Tormarton 1	IO	borehole	1973-1986 and 1998-present
Acton Turville Road	GO/FE	well	1960-1970 and 1999-present
Down Farm	GO/FE	well	1960-1978 and 1998-present
Castle Farm	GO	well	1964-1974 and 1999-present
Atworth 3	GO	borehole	1972-present
Colerne 1	GO/FE	borehole	1973-present
*Burton PWS**	*GO*	*well*	*new site (subsequently removed)*
Westfield Farm	GO	well	new site
Market Cross Cottage	GO	well	1998-present
Wick Cottage	GO	well	new site
Yatton Keynell Manor	GO	well	1975-1979 and 1998-present
Leigh Delamere Tip 1	GO	borehole	1978-1986 and 1998-present
Leigh Delamere Tip 2	GO/FE	borehole	1978-1986 and 1998-present
Allington 1	GO	borehole	1974-present
Alderton Grove Farm	FM/GO	borehole	1966-1986 and 1998-present

FM – Forest Marble
GO – Great Oolite
FE – Fuller's Earth
IO – Inferior Oolite

* See Appendix 3 for Note on this site

Monitoring of groundwater levels in the By Brook catchment and surrounding area started in 1960, with further sites being added to the network in the 1970's. Groundwater level monitoring at many sites was terminated by 1986 following a review of the network. Monitoring at many of these sites has been reinstated for the present study, and a few new sites have been established as shown in Table 2 above. The groundwater level is dipped every month at most sites, except at Atworth 3 where frequency is weekly; this is the indicator observation borehole for the down-dip public water supply abstractions. Since groundwater reacts relatively slowly, this frequency is sufficient to monitor groundwater behaviour for long term trends.

Hydrographs for these sites and notes are presented in Appendix 3 and 4, although it should be noted that only limited data is available for those sites noted as new in Table 2. Levels are plotted in 'mBDAT', i.e. meters below the datum point (usually at or near ground level). The data series are of variable quality for several reasons:

1. several of the monitoring sites are shallow redundant wells which become dry in summer, or stagnant where they have been dug into the Fuller's Earth clays. In these locations there are no data for low recharge periods (Acton Turville, Down Farm, Manor House Yatton, Leigh Delamere Tip 1);
2. historical records are very short and/or patchy, and there is a large gap between the last historical observation and the re-start (Acton Turville, Castle Farm, Down Farm, Manor House Yatton);
3. many wells and boreholes are, or have been pumped, and therefore water levels do not always reflect a rest situation.
4. there is uncertainty about reference levels (Alderton Grove Farm, Castle Farm);
5. historical behaviour is very different from present day behaviour i.e. since being re-instated Atworth 1 has shown water level fluctuations of 0 – 30 mBDAT, this is in stark contrast to the previous period (1973 – 1989) when water levels only fluctuated between 28 and 32 mBDAT. A reason for this variation in behaviour is yet to be determined.

The most meaningful data series were obtained at Atworth 3 (1972-present), Colerne 1 (1973-present) and Allington 1 (1974-present), where records are more or less continuous, and to a lesser degree Tormarton 1 and Leigh Delamere Tip 2. All but one (Tormarton 1) are measuring water levels in the Great Oolite. Three of the sites (Leigh Delamere 2, Allington and Atworth) are outside the catchment but in the same aquifer as most of the By Brook springs. Allington 1 and Atworth 3 are considered indicators of groundwater resource availability in the By Brook catchment over time. They are located to the south and east of the catchment, which is down slope in the aquifer and in between the By Brook and some large public water supply boreholes.

In spite of the patchy character of many records (point 2 above), they do allow some comparison between past and present water levels. As the time series are extended, more extensive analysis will become possible. Wessex Water are currently installing two further observation boreholes between the By Brook catchment and the Stream Support boreholes for Malmesbury to the North East (see sections 5.3.3 and 7.2).

2.4 Streamflow measurements

An intensive programme of streamflow observations was undertaken from spring 1998 to autumn 1999. In addition to the existing continuous flow measurement site at Middlehill (1982-present), a second site with continuous measurements was established at Ford[1]. The

[1] At these sites, water levels are measured every 15 minutes using electronic devices and data storage facilities. Flows are then calculated using a 'rating curve' which is established by doing flow measurements at the site.

Halcrow report (Halcrow, 1998) proposed the establishment of such a station at Castle Combe, however no suitable location could be found. Spot flow measurements were done on a roughly monthly time scale at an additional five sites, on tributaries and the upper reach of the By Brook. All tributaries and spring heads were monitored qualitatively for a full year, noting the starting point of the flow and any disappearances and reappearances. This method of observation is called 'winterbourne signatures'.

Continuous records of sewage treatment inflows were obtained at three out of four major plants on the catchment, data for the fourth plant is only available from July 1999. Inflows rather than outflows were measured because of the existence of measuring flumes. Over a period of a few days, inflows and outflows may be assumed to be the same.

3. The By Brook Valley: Catchment Description

3.1 Topography and Outline Description

The By Brook is a tributary of the Bristol Avon River, situated in the centre of that river's catchment. The By Brook catchment, with an area of 111 km^2, is located mainly to the south of the M4, between Bath and Chippenham. The topography drops from the high (200m AOD) and relatively flat ground in the north and west of the catchment, to a deeply incised main valley which joins the Bristol Avon at Bathford, just upstream of Bath. The steepness of the valley outcrop means that landslips are common. Land use is mixed grassland and arable on the flatter areas, with park, grassland and wooded areas on the steeper slopes.

The northern part of the catchment is dominated by the gently north-east sloping Great Oolite limestone plateau within the Cotswolds Area of Outstanding Natural Beauty. The By Brook itself starts at the confluence of two tributaries, the Burton Brook and the Broadmead Brook, at Castle Hill just upstream of Castle Combe. At Ford two further tributaries, draining the western side of the catchment, join the By Brook; the North Wraxall Stream and Doncombe Brook. Below Ford a further four tributaries join the By Brook: two draining the west side (includes the Lid brook) and two to the east side of the catchment.

Since the construction of the motorway in the 1960's, the northern Burton Brook tributary, receives some of its flow from the M4 drainage channels. In fact, the natural surface water catchment is now cut by the drainage system of the motorway, and is slightly larger in extent than the former surface catchment.

For most of its length the By Brook is a model for an ideal river, rich in varied habitats, meandering, creating pools and riffles, eroding banks for wildlife, and supporting a great variety of species. Some lengths have remained untouched for seventy years or more. However, the By Brook valley also knows a long history of use of, and interference with, the flow, as the existence of 22 mill sites proves (Tatem, 1996).

3.2 Rainfall

Figure 2 shows the annual catchment rainfall (calendar years) with the average over 1981-2000 (897mm) drawn in. It can be seen in Table 1 that the mean annual rainfall for 1981-2000 is significantly higher than for the period 1961-1990 at all three raingauges. Table 3 shows the percentage of the period average of each annual total. There is relatively little variability in these percentages, as shown by the standard deviation[1], which is 13%. 1990, 1991 and 1996 clearly stand out as the lowest values with 80%, 82% and 81% of the period average. In contrast, 1998, 1999 and 2000 recorded values which were well above average (115%, 117% and 131% respectively)[2]. It therefore follows that slightly greater variation is seen in the period 1991-2000 (standard deviation 16%) compared to the previous decade 1981-1990 where standard deviation was only 9% of the period average.

[1] see Glossary

[2] They are also the wettest years since 1961 at 5 other raingauges with data from 1961 in the area.

Table 3 Annual catchment rainfall in mm and as % of 1981-2000 period average (PA)

year	'81	'82	'83	'84	'85	'86	'87	'88	'89	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00
rain	966	921	820	896	931	947	809	910	852	713	739	862	855	1015	869	731	845	1032	1052	1178
%PA	108	103	91	100	104	106	90	101	95	80	82	96	95	113	97	81	94	115	117	131

Note: the (1981-2000) period average is 897 mm. The standard deviation of the above annual totals equates to 13 % of the period average.

Variability of monthly rainfall is much greater. Appendix 2 presents rainfall data from three rain gauges (Marshfield, Bathford and Castle Combe) as a monthly total and as a percentage of the 1961-1990 long term average[1] rainfall for that month. For information, a graph showing monthly catchment rainfall and its corresponding percentage of period average has also been included in Appendix 2 with a summary of the monthly average rainfall calculation. Monthly rainfall maybe as low as 4% of the month's period average, rising to a maximum of 286%. Although no clear seasonal trend is apparent, the greatest monthly spread can be seen to occur in August and June (Table 4).

Table 4 Standard deviation of monthly rainfall for 1981-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S.D as % *	54%	60%	52%	62%	57%	66%	51%	70%	50%	38%	48%	43%

* % of monthly period average 1981-2000

In addition to rainfall totals, MORECS data for effective rainfall has been examined. Effective rainfall is the proportion of rainfall that is available for recharge or runoff once evapotranspiration and any soil moisture deficit have been accounted for. The effective rainfall for the last 30 years is presented in Figure 3. The monthly effective rainfall figures have been summarised to give a water year[2] (October to September) total.

The water year effective rainfall[2] totals have been ranked in Table 5, to identify the "low" effective rainfall years. Table 5 shows that 1975 - 1976 recorded the lowest total. It is noted that within the top five of low rainfall years, three occurred in the 1990's, namely 1990 - 1991, 1991 - 1992 and 1996 - 1997.

[1] This is a Met Office estimated value for all raingauge sites that is used as a standard in national comparison.
[2] See Glossary

Table 5 Ranking of Water Years by Effective Rainfall Totals (1970-to present)

Ranking	Water Year	Effective Rainfall (mm)	
1	75-76	26.8	
2	96-97	59.1	
3	91-92	77.3	
4	72-73	128.5	
5	90-91	172.8	
6	83-84	176	
7	73-74	194.6	
8	79-80	204.7	
9	88-89	204.7	
10	97-98	208.7	
11	95-96	217.2	
12	71-72	220.4	
13	80-81	228.5	
14	78-79	243.9	(Mean = 246mm)
15	77-78	258.9	
16	86-87	259.9	
17	87-88	275	
18	85-86	276.6	
19	98-99	280.8	
20	70-71	282.5	
21	92-93	289.6	
22	74-75	303	
23	89-90	306.3	
24	93-94	309.6	
25	94-95	313	
26	84-85	316.5	
27	81-82	351.6	
28	82-83	356.4	
29	99-00	363.8	
30	76-77	481	

3.3 Geology

The Jurassic geological succession in the By Brook Valley comprises a repetitive pattern of clay and limestone (Table 6).

Table 6 Geology sequence as found in the area

	stratum	*rock type*	*thickness*
Youngest	Oxford Clay & Kellaways Clay	thin clays	up to 28 m
	Cornbrash	a thin shelly limestone	up to 10 m
	Forest Marble	upper: argillaceous rocks (clay, silts, marls) lower: limestone (Acton Turville Beds)	up to 35 m
	Great Oolite	limestones	20-30 m
	Fuller's Earth	upper: clays and limestones; lower: clay	up to 28 m (10 m of clay)
	Inferior Oolite	limestones	10-110 m
	Cotteswold Sand *(also known as Midford Sand)*	silty sands	approx. 60 m
Oldest	Upper Lias Clay	mudstones	up to 80 m

The geology underlying the By Brook catchment is shown in Map 2. The geological cross sections from north to south and WNW to ESE through the upper part of the catchment are shown in Figure 1 (the lines of section are marked on Map 2). More detailed geological cross sections are difficult to draw across the By Brook Valley due to the lack of more detailed geological logs.

Great Oolite limestone outcrops in the upper reaches of the catchment. To the east of the catchment due to the south-east dip of the local strata, the Great Oolite is overlain by Forest Marble. The Great Oolite outcrop forms a plateau area in the north of the catchment. Erosion of the Great Oolite by watercourses has produced steep sided relatively narrow valleys within the plateau area. Within the Broadmead Brook, Doncombe Stream, Lid Brook and Burton Brook below Gatcombe, erosion has resulted in the Fuller's Earth being exposed within the valley floors.

Due to erosion and the dip of the local strata the Burton Brook flows over Great Oolite, then is underlain by Fuller's Earth until Lapdown, where it flows over Great Oolite again, until Gatcombe where the Fuller's Earth is exposed. Within the Broadmead catchment the upper reach is underlain by Fuller's Earth, below West Kington the Brook flows over Great Oolite until the confluence with the By Brook.

The upper section of the Fuller's Earth contains several limestone bands which can be laterally extensive. These bands are persistent and regular enough for several to be named i.e. Dyrham Rock, Upper Tresham Rock, Lower Tresham Rock and Fuller's Earth Rock. These limestones are exposed and mapped along the scarp slope of the Cotswolds to the west of the By Brook. The BGS 1:10,000 Sheet (ST 77 NE) map shows the Upper and Lower Tresham Rock along the upper Broadmead Brook valley side. The lateral persistence of these limestones may be affected by faulting.

Downstream of Ford the erosion exposes the Inferior Oolite and the Cotteswold Sand (also known as Midford Sand). The foundered nature of the deposits downstream of Box does not allow differentiation of the exposed units.

A study of the geological structure has been completed for the neighbouring Malmesbury catchment (BGS, 2000). There, small faults split the aquifer into separate compartments, which may be hydraulically isolated or, on the contrary, provide continuity between layers. In the Malmesbury area, greater faults with greater throws have resulted in the Inferior Oolite being in hydraulic continuity with the Great Oolite, but in the By Brook catchment the extent of faulting is much more limited (Smart, 2000).

3.4 Hydrogeology

The alternating sequence of limestone and clays produces a multi-layer aquifer system within the catchment, with faulting possibly leading to some hydraulic connection between the separate layers.

3.4.1 Aquifer Units

There are three main aquifers within the catchment:

1. Great Oolite (Major Aquifer) - this aquifer comprises limestone beds of two formations: the Acton Turville beds (base of the Forest Marble) and the underlying Great Oolite.

2. Upper Fuller's Earth (Minor Aquifer) - the upper Fuller's Earth contains limestone units which store and transmit water, intervening clay bands acting as aquitards. These limestone bands may not be laterally persistent across the catchment and displacement due to faulting may departmentalise the limestone band into isolated units.
3. Inferior Oolite (Major Aquifer) and Cotteswold Sand (Minor Aquifer) - the overlying lower Fuller's Earth (Clay) separates the inferior limestone aquifer and Cotteswold Sand from the overlying aquifer units. The Inferior Oolite and Cotteswold Sand are in hydraulic continuity, with the limestone a more transmissive unit, hence a "major" aquifer.

To the north of the catchment the limestone bands within the Upper Fuller's Earth become thicker and more extensive. The increase in limestone is such that to the north within the Malmesbury-Avon catchment the Upper Fuller's Earth is included with the Acton Turville and Great Oolite to form the "Great Oolite aquifer". The clays within the upper Fuller's Earth are more prevalent and act as aquitards within the By Brook, hence its designation as a separate aquifer unit.

The Great Oolite aquifer is unconfined in the north-west of the catchment and becomes confined to the south and east of the catchment. As detailed below (3.4.3) karstic features within the Great Oolite means it quickly drains water following recharge events. It supports its own water table, separately from the upper Fuller's Earth by clay units which act as aquitards. These clay layers which appear to be laterally extensive give rise to the formation of spring issues from Great Oolite, at hydraulic low points, i.e. the end of dry valleys. These springs are located within the tributary stream draining east into the By Brook and along the east side of the By Brook, i.e. at Gatcombe, Long Dean and Ford. In dry periods spring flows are re-absorbed into the ground in some locations of the upper reaches of the Burton Brook.

To the west of the By Brook catchment springs emanate from the limestone units within the Fuller's Earth at Seven Springs (ST 761 791, 800m west of Tormarton). These water bearing limestones are exposed down dip in the By Brook tributary valleys and the main By Brook upstream of Ford.

The Inferior Oolite and Cotteswold Sands aquifer outcrop in the valley floor below Ford and provide baseflow to the By Brook.

3.4.2 Groundwater Catchment Boundaries

From his quantitative fluorescent dye tracing in the mid-1970's, Smart (2000) concluded that to the west, the hydrogeological catchment area of the upper By Brook is coincident with the surface water catchment (Map 3). To the north, the boundary between the By Brook and the Luckington branch of the Sherston Avon has been defined by tracer results, and was shown to lie to the north of Acton Turville (Map 2). However, a complication here is the presence of the Old Sodbury railway tunnel. Strong seepage from the Great Oolite occurs into the tunnel, which therefore acts effectively as a hydrogeological catchment divide to the north-west.

The dye tracing work also helps define the hydrogeological boundary between the Broadmead Brook and Burton Brook sub-catchments (not detailed here). To the east, the groundwater catchment divide is not known with certainty. However, the divide is believed to be close to the By Brook and is likely to be coincident with the eastern edge of the Great Oolite outcrop. Only a piezometric map can solve this question with certainty, however there are no groundwater level observations close enough to be able to draw piezometry with sufficient accuracy.

3.4.3 Flow Mechanisms

Fracture and fissure flow are the predominant flow mechanisms within the limestone units of the individual aquifers, though conduit (karstic) flow is present within the Great Oolite.

Smart's dye tracing of the Great Oolite aquifer showed that rapid fracture (conduit) flow occurs with velocities of up to 10,000m/day. However, the very long tail (of dye) indicates that considerable dispersion and temporary storage of water in the dense network of small fractures occurs (BGS, 2000).

The combination of conduit features (rapid travel times) and small fractures (slow travel times) provides a mechanism to explain the river flow behaviour. Typically river flow in the Cotswolds including the By Brook, respond very rapidly to autumn rainfall, but the recession of flow in the summer is much more gradual. The river keeps flowing when it might have been expected to dry up.

The rapid increase in river flow occurs soon after recharge, but before the aquifer is fully replenished indicating rapid transfer of water via high transmissive conduits, removing the vast majority of the recharge. Summer flows are supported by the release of residual unsaturated and saturated storage in the dense network of fractures (BGS, 2000 and Smart, 2000).

3.4.4 Recharge

The Great Oolite aquifer receives direct recharge over its outcrop area plus leakage from the overlying Forest Marble, as well as runoff from the Forest Marble onto the Great Oolite outcrop and via swallet holes through the Forest Marble.

Recharge to the upper part of the Fuller's Earth is via leakage through the clays, with faulting possibly providing a preferential route for downward leakage from the Great Oolite.

The Inferior Oolite has a very small outcrop area, along the Cotswold scarp slope to the west, which provides only a limited area for recharge. The primary mechanism for recharge is via leakage from overlying units through aquitards. Faulting may provide a direct route for flow from the Great Oolite to the Inferior Oolite.

3.4.5 Groundwater Level Monitoring

The Great Oolite is the main aquifer monitored (thirteen monitoring sites), with only four sites monitoring the Inferior Oolite (see Table 7). The boreholes outside the catchment monitor the Great Oolite, except Atworth No. 1 (Inferior Oolite). The hydrographs for the sites currently monitored are contained in Appendix 4, with supplementary well and borehole data in Appendix 3.

The aquifer monitored by each borehole and the range of water level fluctuation is given in Table 7.

Table 7 Aquifer Water Level Fluctuation

Borehole	Aquifer	Water Level Range (m)	Period of Observation	Comment
Within Catchment				
Acton Turville	GO/FE	3.5	1960-1970 and 1999-present	base of well in FE
Down Farm	GO/FE	1.7	1960-1978 and 1998-present	base of well in FE
Tormarton 1	IO	25	1973-1986 and 1998-present	
Castle Farm	GO	11	1964-1974 and 1999-present	well is pumped
Colerne No. 1	GO/FE	2.25	1973-present	base of well in FE
Nettleton PWS	IO (?)	-	new site 2000-present	record too short
Burton PWS			*New site - data invalid*	*no longer in use*
Yatton Keynell	GO	9.5	1975-1979 and 1998-present	base of borehole in FE
Westfield Farm Well	GO	4	new site 1999-present	record too short
Wick Cottage Well	GO	11	new site 1999-present	record too short
Market Cross Cottage	Alluvium /GO	4.5	new site 1999-present	record too short
Outside Catchment				
Atworth No. 1	IO	1 (11)	1973-1989 and 1998-present	2000 data marked rise
Chippenham ASR	IO	4.5	new site 2000-present	record too short
Atworth No. 3	GO	28	1972-present	
Leigh Delamere 1	GO	9.5	1978-1986 and 1998-present	
Leigh Delamere 2	GO/FE	18	1978-1986 and 1998-present	
Allington No. 1	GO	16.5	1974-present	
Alderton Grove	FM/GO	11	1966-1986 and 1998-present	possibly dries

Notes: FM - Forest Marble
GO - Great Oolite
FE - Fuller's Earth
IO - Inferior Oolite

Monitoring shows that over the outcrop area of the Great Oolite water levels respond rapidly to rainfall. Water levels also quickly decline as the aquifer drains, leaving a residual water column in the base of the well within the Fuller's Earth, i.e. Acton Turville.

Where the boreholes monitor the full water level fluctuation the range is 16.5m to 28m in the confined aquifer.

Monitoring of the Inferior Oolite at Tormarton shows a 25m fluctuation in water level. Monitoring at Atworth No. 1 during the 70's and 80's recorded only ~1m fluctuation in level. Since being re-included in the monitoring network a fluctuation range of 30m has been recorded, currently there is no explanation for this change in behaviour available. A review of the borehole network in the North Wessex Area is currently underway and will assess the value of this and all other boreholes within the By Brook catchment.

3.4.6 Aquifer Properties

No data for aquifer properties from testing undertaken within the catchment are available. The following data were obtained from the physical properties of major aquifers in England and Wales (BGS 1997).

Great Oolite

Transmissivity (m^2/d)	Storage Coefficient	Specific Yield (%)
4 to 5,900 (mean 212)	6×10^{-5} to 4×10^{-3}	3

Inferior Oolite

Transmissivity (m^2/d)	Storage Coefficient	Specific Yield (%)
3 to 11,000 (mean 139)	7×10^{-5} to 1×10^{-4}	-

The transmissivity value particularly shows the heterogeneity of the aquifer.

3.4.7 Source Protection Zones

Groundwater source protection zones (SPZ) reflect the potential source of water, pumped from an abstraction borehole. They are the areas where pollution could endanger public water supply. The zones are conservatively drawn through modelling and/or best estimates based in the conceptual understanding of the aquifer. To the east, the source protection zones for the public water supply boreholes in Chippenham (Ivyfield), Lacock and Goodshill extend as far as the By Brook (Map 3). The boundary includes limited areas of Great Oolite at outcrop on the eastern slopes of the By Brook catchment, where some recharge to the pumped aquifer may occur. It is considered that the extension of the boundary to the edge of the outcrop is too conservative, as the groundwater divide will prevent the SPZ extending to the western edge of the outcrop. To the north-east, the source protection zones for the Malmesbury catchment boreholes (notably Rodbourne and Cowbridge) overlap with the hydrogeological catchment as defined above.

No separate source protection zones have been determined for the stream support boreholes at Lower Stanton St Quinton, Hullavington and Luckington within the Malmesbury-Avon catchment. (These are not awarded the same level of protection as the public supply boreholes).

3.4.8 Winterbourne signatures

The Agency's 'Winterbourne signature' work of the Chalk streams was applied to the By Brook valley because of similarities in the hydrogeological character of the Oolite to the Chalk aquifer. Both are primarily fracture or fissure flow aquifers, with very fast groundwater travel times. The winterbourne signature technique consists of tracking the field observations of the points (grid reference) where flows start in the tributaries, on a monthly basis. This information, when collected and studied over a period, gives an indication of the changes in elevation of the water table with time.

The April to August 1999 observations on the headwaters of the Burton, Broadmead, Doncombe and Lid Brook are reported with respect to elevation and published geology in Appendix 5. It is noted that 1999 (water year 98-99) was a relatively wet year (see Table 3). They show that groundwater is effluent from the aquifer(s) at discrete locations. These spring horizons are likely to be geologically controlled, probably where an Oolite horizon rests upon a more impermeable clay horizon (top of the upper Fuller's Earth).

Burton Brook

When monitoring commenced in April, the start of Burton Brook had already moved ~7km from the winter head water down the valley to ephemeral springs from the Great Oolite adjacent to Nettleton PWS (ST 8282 7917). By July these ephemeral springs had dried up and the Burton Brook started from the perennial Great Oolite springs at Gaulters Mill (ST 8322 7906). It is noted and discussed further in Section 5.3, that stream support abstraction at Luckington and Hullavington to the north did not commence abstraction until August in 1999.

Broadmead Brook

Upstream of West Kington, near Rownham Farm, the Broadmead Brook: northern and southern tributaries. Through 1999 the southern tributary starts flowing at ST 7494 7314 from the Fuller's Earth. The northern tributary flow commences from the Fuller's Earth at West Littleton. By July the northern tributary started to flow ~1.2km downstream of West Littleton, in August the start of the stream returned to West Littleton.

The observations show that along the upper reach (above West Kington) where the Brook flows over Fuller's Earth, the Brook is fed by minor springs which drain the Great Oolite aquifer on the valley sides and limestone units in the Fuller's Earth exposed in the valley floor and headwaters. Downstream of West Kington the Brook runs on the Great Oolite and is fed by several springs.

Doncombe and Lid Brook

During the 1999 monitoring no movement of the spring head for these watercourses was detected. Like the Broadmead Brook, these watercourses run over the Fuller's Earth.

3.5 Hydrology

3.5.1 Continuous flow record at Middlehill

The gauging station at Middlehill has been in operation since 1982 and provides reasonably accurate data at 15 minute intervals (Figure 4 and Appendix 6). In common with long term groundwater records (Section 3.4, Appendix 4), the flow record at Middlehill shows considerable variability. Features of particular interest to the present study are:

- the magnitude and length of summer low flows;
- the length of the winter high flow period;
- flashiness of the flows.
- the volume of runoff;

The first two characteristics are discussed qualitatively below; the latter two are analysed quantitatively below and in Section 3.5.2 respectively.

During 1990 and 1991, low rainfall resulted in a prolonged recession in summer 1990 and the lowest winter flows since records began; the good recovery of groundwater stored in the next four years is mirrored in four years of high peak flows and high runoff volumes. The low recharge in 1997 has equally affected river flows, with low winter runoff. Healthy rainfall in the summer of 1997 meant that aquifers started to recover, and river flows have been relatively high since. These events and their impact on recharge can also been seen in Figure 19 where effective rainfall is plotted against groundwater levels in the Great Oolite.

Despite much of the catchment being underlain by permeable limestone strata, surface water flows in the By Brook Valley are likely to be reasonably flashy. Rapid groundwater level fluctuations in the Great Oolite beds indicate that this aquifer responds rapidly to rainfall recharge. The Great Oolite beds are highly transmissive strata which are exposed at the surface and in direct continuity with the surface water regime. The net effect of these properties is that baseflow support (or groundwater outflow) to the watercourses is significant but occurs after only a short time lag meaning that a reasonably flashy response is still observed in the catchment. The Inferior Oolite are also highly transmissive beds which demonstrate a large fluctuation in annual groundwater levels. However, the Inferior Oolite beds are confined at depth and show a much smoother, seasonal response to recharge which is subsequently reflected in baseflow.

The base flow separation algorithm is a standardised method for separating the groundwater support to flows from the total flow (Figure 5) (Gustard *et al.*, 1992). The Base Flow Index is the volume of base flow, expressed as a proportion of total flow. In a very permeable catchment (e.g. Chalk) the BFI would approach 1.0 while in an impermeable catchment (e.g. clay) it is around 0.20.

There is reasonably sustained support at Middlehill, with annual Base Flow Indices (BFI) ranging between 0.61 and 0.75 (Table 8) with a mean of 0.648. These are figures expected for an 'average' catchment. This parameter also helps to investigate the alleged increased flashiness of the river. If flashiness would have increased, then the BFI should have become less. In fact, no trend in BFI could be detected (Figure 6).

Table 8 Annual BFI values

year	annual BFI	year	annual BFI
1982	0.637	1992	0.667
1983	0.695	1993	0.684
1984	0.746	1994	0.667
1985	0.643	1995	0.648
1986	0.623	1996	0.714
1987	0.703	1997	0.546
1988	0.625	1998	0.689
1989	0.557	1999	0.631
1990	0.626	2000	0.595
1991	0.619	*Mean*	*0.648*

Work carried out for the Flood Estimation Handbook (FEH), released by the Institute of Hydrology in 1999, enables us to produce an estimate of BFI based on the catchment's physical characteristics such as soil type (Boorman *et al* 1995). Using the FEH CD ROM the By Brook catchment has an estimated BFI of 0.718. Whilst the FEH estimate is higher than the mean observed at Middlehill, it is not outside the range of annual BFI values observed within the catchment. This gives support to the premise that the degree of flashiness observed is not outside that that would be expected of a catchment with the hydrogeological characteristics described above.

Another parameter that gives an indication of catchment reaction is the flow recession curve in spring, where a faster recession would indicate quicker depletion of water resources, and possibly greater flashiness. The recession slope was determined manually from a logarithmic plot of flows (Figure 7)[1]. The resulting figure covers the global spring recession, eliminating the effect of sudden peak flows. It is a very subjective measure and the plotted values should not be taken at face value. No trend can be detected in this parameter either (Figure 8) although considerable variability occurs.

In conclusion, the character of surface runoff in the By Brook as observed at Middlehill has not changed since 1982 when records began, although much variability has been observed. This variability can be linked to climatic variability, as was observed for groundwater fluctuations. No increase in flashiness could be detected since flow records began in 1982. It is not possible to investigate whether flashiness has increased since the construction of the motorway in the 1960's as there is no flow data on which to base an analysis. However, the observed Baseflow Index is in line with that estimated by the FEH using catchment characteristics and therefore does not suggest that the catchment is showing a significantly different baseflow / runoff response to that which would be expected in a catchment of this type. Where improvements to the motorway are proposed in the future, the Agency would continue its policy of encouraging sustainable drainage options to be installed where possible.

3.5.2 Rainfall-runoff comparison

Whereas rainfall is measured in mm depth, river flows are expressed as a volume per time unit (e.g. m^3/s). In order to compare them, river flows are converted to runoff by dividing by the catchment area and multiplying to the same time unit[2]. The proportion of rainfall that reaches the river (runoff as a percentage of rainfall) is the runoff coefficient. Table 9 shows that this percentage is relatively stable when calculated on an annual basis, varying from 41% to 61%.

Table 9 Annual runoff coefficients

year	runoff (mm)	rain (mm)	% runoff	year	runoff (mm)	rain (mm)	% runoff
1982	561	921	61	1995	486	869	56
1983	455	820	56	1996	356	731	49
1984	470	896	52	1997	349	845	41
1985	548	931	59	1998	558	1032	54
1986	559	947	59	1999	604	1052	57
1987	443	809	55	2000	739	1178	63
1988	502	910	55				
1989	412	852	48	min	297	713	41
1990	297	713	42	**average**	**479**	**894**	**53**
1991	364	739	49	max	739	1178	63
1992	416	862	48				
1993	415	855	49	s.d.	108	117	6
1994	576	1015	57	s.d. (%)	23%	13%	11%

[1] The parameter has no units, and its value is dependent on the scale of drawing and observer's judgement. It is not a standard parameter. To note that the recession slopes were determined on a more detailed scale than the figure that is included.

[2] 1 m^3/s on 100 km^2 catchment = (1 m^3 / 100,000,000 m^2) (m) * 1000 (mm) * 86400 per day, or * 86400 * 30 per month.

The higher percentages tend to occur in wetter years, when there is more rain available for runoff after catchment storage (aquifer and soil) has been replenished.[1] The effect of low annual rainfall on streamflow is therefore two fold: firstly, the overall volume of water (rain) available decreases, secondly the problem is exacerbated because a smaller proportion than usual flows off through the river.

The effect of storage on runoff is clearly shown in Figure 9 where monthly rainfall and runoff are plotted for the 1982-2000 period. Whereas in the long term rainfall is higher than runoff, (as it has to be to give a long term runoff coefficient of 53% -Table 9), there are several months where runoff is much higher than rainfall. This tends to occur in late winter to early spring, when groundwater reserves are full and runoff continues even when rainfall is low, although runoff does decrease as a result. The graph (Figure 9) also shows that in order to have 'healthy' summer flows, summer rainfall needs to be 'healthy'. A comparison of 1995, 1996 and 1997 shows very different rainfall patterns: a dry summer after a wet winter (1995), a wet summer after a wet winter (1996, although late summer was dry), and a dry winter with a wet summer (1997). The rainfall pattern is closely reflected in runoff, with rapidly decreasing flows in 1995, sustained spring flows in 1996 and low winter flows in 1997 but very high summer flows. These observations support the hypothesis that the catchment is sensitive to rainfall, and has relatively little storage to sustain flows when rains fail, although some is available to provide a minimum flow in dry summers, e.g. 1990.

3.5.3 Spot flow gaugings

Flow measurements (or 'spot gaugings') were carried out on the same day at several locations in the catchment (Appendix 7). The spot gaugings consist of velocity measurements across the stream using a propeller meter as well as the measurement of depth and width. This permits the calculation of average velocity (in m/s) and cross-sectional area (in m^2) which, multiplied, give the flow or discharge (in m^3/s).

The principal tributaries were measured at the confluence with the By Brook in order to obtain the flows for each sub-catchment. In addition, a flow measurement was made at West Kington to aid the abstraction review (Section 4.3).

The following three types of analysis have been carried out using this spot flow data.

Correlation analysis

Correlation between flows on the same dates and at different sites is remarkably strong (Table 10). This means that if flows are known at one of these locations, flows at any of the other sites may be estimated with reasonable confidence by using regression analysis (see below).

[1] To note that the analysis of water years (October –September) would be more appropriate as it analyses a full water cycle instead of parts of two water cycles.

Table 10 Correlations between flows at different sites

	Middlehill	Lid Brook	Doncombe Brook	Ford	Golf Course	Broad-mead Bk	Burton Brook	West Kington
Middlehill	1							
Lid Brook	0.988	1						
Doncombe Bk	0.976	0.968	1					
Ford	0.992	0.977	0.968	1				
Golf Course	0.986	0.968	0.955	0.997	1			
Broadmead Bk	0.972	0.957	0.966	0.987	0.983	1		
Burton Brook	0.969	0.960	0.912	0.969	0.973	0.914	1	
West Kington	0.964	0.946	0.971	0.979	0.974	0.995	0.904	1

Note: maximum possible figure is 1.

Flow statistics estimates - example

It should be noted that for the purposes of this study all flow statistics are based on actual observed flows (including the impacts of artificial influences such as water abstractions and discharges).

Following the correlation analysis, a regression analysis was performed on West Kington flows vs. Middlehill flows in order to estimate the Q95, a flow statistic often used for water resource analysis. The Q95 is the flow that is equalled or exceeded for 95% of the time. The resulting equation was :

$$Q\ \text{West Kington} = 0.0765 * Q\ \text{Middlehill} - 0.0101 \qquad (R^2 = 98\ \%)$$

Only low flows were used since the relationship is slightly curved when including all flows. The Q95 estimate at West Kington can now be calculated from the Q95 at Middlehill (which is derived from the flow duration curve to be 0.226 m^3/s) as follows:

$$Q\ 95\ \text{West Kington} = 0.0765 * 0.226 - 0.0101 = 0.00719\ m^3/s\ (= 7.19\ l/s)$$

This figure is used in the licence impact assessment in Section 4.3.1. The same procedure has also been used later in this report for other sites and applications, e.g. at Widdenham to estimate the impact of spring abstractions (Section 4.3.3).

Accretion profiles

An accretion profile is a graph of the increase in flows going downstream along a river on a certain date. The accretion profile follows the Broadmead Brook from West Kington to the confluence with the Burton Brook, after which the By Brook is followed down to Middlehill. West Kington was chosen as point of origin, it being the furthest upstream measurement taken. Flows were calculated for the By Brook downstream of the confluence with the Doncombe Brook and Lid Brook from the measurements on the two upstream branches. Figure 10 presents these graphs for all dates when flows were measured. On the highest graph, flows are missing in Castle Combe because water levels were so high that it was too dangerous to take measurements by wader.

The jumps in the lines indicate tributaries that join the Brook, increasing the flow suddenly. The lines between these jumps are stretches of river where no major inflows occur, although there may be small localised inflows. The accretion profiles show a regular increase in flow going down the main stream, as seen from the slope of the lines which is the same until the last stretch where the line is much steeper (Figure 10). These results suggest that the stream suffers no localised impacts (there are no decreases in flow), and that the increase in flow is regular along the length of the Broadmead Brook and By Brook up to Box Hill (i.e. confluence with the Lid Brook). A possible reason for the steepening of the line between Box Hill and Middlehill is the presence of a fault in the geology in this stretch that might provide a preferential outflow path for groundwater into the Brook; however, this is not more than a hypothesis.

3.6 Water Quality

River Quality Objectives were defined for 10 stretches in the By Brook catchment (Table 11 and Map 5). The classification scheme used is focussed on river ecosystems (RE) in recognition of the need to protect the ecosystem that is sustained in a healthy river. It was defined in 1994 as a national classification. The standards for the five classes RE1 to RE5 are based on chemical water quality requirements of different types of ecosystem, and consequently the types of fisheries and uses they can support. They are set considering natural physical constraints influencing the water quality, e.g. low summer flows. Elements analysed are dissolved oxygen, biological oxygen demand, total ammonia, un-ionised ammonia, pH, dissolved copper and total zinc. If any of these fail to meet the specified environmental quality standards then the site will fail overall.

Table 11 River Quality Objectives (RQO)

Water Quality Site Ref.	LEAP Ref. No.[1]	Equivalent Biological GQA sampling site Ref.[2]	Public Stretch	RQO
Z4170201	57	NR09.6001	Burton Brook from Burton to confluence with Broadmead Brook	2
Z4170207	58	NR09.6003	By Brook confluence (Broadmead and Burton Brooks) to Rack Hill	1
Z4170214	59	NR09.6004	Rack Hill to confluence with Doncombe Brook	1
Z4170107	60		Confluence with Doncombe Brook to d/s confluence with Lid Brook	1
Z4170101	61	NR09.6007	d/s confluence with Lid Brook to Box Bridge	1
Z4170102	62	NR09.6008	Box Bridge to confluence with Avon	1
Z4180108	63	NR09.6011	Doncombe Brook: Fuddlebrook to u/s Marshfield STW	2
Z4180118	64	NR09.6010	Doncombe Brook: u/s Marshfield STW to d/s Marshfield STW	2
Z4180101	65	NR09.6005	Doncombe Brook: d/s Marshfield STW to confluence By Brook	1
Z4170202	66	NR09.6002	Broadmead Brook: West Kington to confluence with By Brook	1

The River Quality Objective (RQO) of all streams in the catchment is RE1 (very good quality) except for three stretches from u/s Marshfield STW (63) to d/s Marshfield STW (64) and d/s Burton STW (57). In the case of stretch 57 and 63 a class of RE1 could have been applied if the summer flows were sufficient to sustain the required levels of dissolved oxygen. In reality the flows are reduced in the summer in terms of both volume and velocity,

[1] This is the stretch number as identified in the LEAP (Local Environment Agency Plan).
[2] Water Quality (chemical) and biological GQA samples are not taken from exactly the same location due to the different requirements of sampling techniques, however they are very close to each other and are taken to relate to the same 'site'.

so there is insufficient agitation and "capacity reservoir" to maintain the required oxygen levels when the natural diurnal variations are considered. The short stretch 64 had an objective of RE2 because it is heavily influenced by the STW discharge, although it currently achieves RE1. It is hoped that, subject to DEFRA confirmation, in the future it will be possible to review RQOs through LEAP[1] type consultation.

Water quality monitoring is carried out monthly at 10 sites (see Map 5 and Table 12) for 'River Ecosystem' classification and the EU Freshwater Fish Directive. Details of laboratory analyses performed on the samples is presented in Appendix 11. Water samples are also taken related to discharge consent compliance monitoring; this is discussed below (Section 4.6).

Table 12 Water quality monitoring sites

Water Quality Site Ref.	Equivalent Biological GQA sampling site Ref.	Site location	Purpose
Z4170201	NR09.6001	By Brook @ Fosse Way	GQA
Z4170207	NR09.6003	By Brook @ Castle Combe	GQA
Z4170214	NR09.6004	By Brook @ Long Dean Mill	GQA, FF
Z4170107	N/A	By Brook @ Drewett's Mill	GQA,
Z4170101	NR09.6007	By Brook @ Middlehill	GQA, FF
Z4170102	NR09.6008	By Brook @ Bathford	GQA
Z4180108	NR09.6011	Doncombe Brook u/s STW	GQA
Z4180118	NR09.6010	Doncombe Brook d/s STW	GQA
Z4180101	NR09.6005	Doncombe Brook @ Ford	GQA, FF
Z4170202	NR09.6002	Broadmead Brook	GQA, FF

Note: GQA = general quality assessment
FF = freshwater fisheries monitoring

Table 13 shows the achievement of the river quality objectives since 1996. The objectives were consistently achieved in the Burton Brook, the middle and upper reaches of the By Brook (to the confluence with the Lid Brook) and the upper part of the Doncombe Brook (to Marshfield STW). Targets have not always been achieved in the lower reaches of the By Brook, in the Doncombe Brook downstream of the STW, and in the upper reach of the Broadmead Brook. An investigation into the causes of River Quality Objective failures was completed by the Environmental Protection Team (North Wessex Investigations, 2001) earlier this year and has found all failures were related to Biological Oxygen Demand, furthermore they were all marginal failures[2]. However in 2000 RQO compliance was achieved at all sites.

[1] LEAP – Local Environment Agency Plan.

[2] i.e. from the sampling results we are 50 % to 95 % certain that the river stretch failed to meet its target. A significant failure is obtained when we are greater than 95 % statistically confident that the river failed to meet its target. The calculation of the probability is based on 36 routinely collected samples, so with the current monthly sampling frequency data of the last 3 years are required. It will therefore take time for any improvement to reflect in a better RE class.

Table 13 Achievement of River Quality Objectives 1996-2000

LEAP Ref.No.	Public Stretch	RQO	Compliant Yes/No				
			1996	**1997**	**1998**	**1999**	**2000**
57	Burton Bk to confluence with Broadmead Bk	2	Y	Y	Y	Y	Y
58	Broadmead and Burton Bk conf. to Rack Hill	1	Y	Y	Y	Y	Y
59	Rack Hill to confluence with Doncombe Brook	1	Y	Y	Y	Y	Y
60	Confl. Doncombe Bk to d/s confl. Lid Bk	1	Y	Y	Y	Y	Y
61	d/s confluence with Lid Brook to Box Bridge	1	Y	N	N	N	Y
62	Box Bridge to confluence with Avon	1	N	N	Y	Y	Y
63	Fuddlebrook to u/s Marshfield STW	2	Y	Y	Y	Y	Y
64	u/s Marshfield STW to d/s Marshfield STW	2	Y	N	N	N	Y
65	d/s Marshfield STW to confluence By Brook	1	N	N	N	Y	Y
66	Broadmead Bk: West Kington to confluence	1	N	N	N	N	Y

Reasons for the historic failures were not clear-cut. In the Broadmead Brook it is likely that failures were due to a combination of:

1. septic tanks: both West Kington and Pennsylvania are unsewered and households are equipped with a variety of cess pits, septic tanks, etc. Certainly some of these were problematic in the distant past. Although there have not been any recent complaints or incidents, it is likely that some sewage seeps into the Broadmead Brook. However, if this is the cause there should be some sign of elevated ammonia concentrations, which is not the case;
2. diffuse agricultural pollution: the upper part of the By Brook catchment, including most of the Broadmead Brook sub-catchment, is largely given over to intensive arable and dairy agriculture and experiences heavy organic and inorganic fertiliser applications. Quite possibly, excess rainfall is loaded with fertiliser and infiltrates into the subsoil and aquifer, to re-emerge into the Broadmead Brook or in a watercourse further down the system;
3. very low summer flows: it was explained above that reduced flows in summer induce insufficient agitation and "capacity reservoir" to maintain the required oxygen levels. Low summer flows can be a result of climatic variation or unsustainable abstraction (see Sections 4 and 5).

The main issue for the Doncombe Brook is that there is very little flow other than from Marshfield STW. The stretch of the main By Brook to the confluence with the River Avon may have failed due to variable flows or infiltration of water from the main Avon. A full investigation would have been difficult and expensive, without a guaranteed conclusive outcome. This site is now compliant and Marshfield STW is due for improvement under AMP3 by 2005 so no further investigation is considered necessary.

3.7 Ecology

3.7.1 Ecological monitoring

In England and Wales, three main types of ecological monitoring (Macroinvertebrates, Macrophytes, and Fisheries) work is undertaken at a network of sites. Macroinvertebrate surveys are carried out as part of the GQA (General Quality Assessment) programme to determine the status of rivers every five years[1] (1990, 1995, 2000). Fisheries surveys are also carried out as part of a rolling programme, with sites being visited every five years. In addition to these monitoring programmes special studies can be commissioned as the need arises. In the case of the By Brook investigation, additional monitoring work was carried out for macro-invertebrates (1999) and macrophytes (1998/1999). Results of the following surveys are presented in the sections (as marked) below:

- GQA - macro-invertebrates (small animals including mayfly nymphs, snails, shrimps and worms) Analysis to family level carried out in 1990, 1995, 2000. (section 3.7.2)
- macro-invertebrates, detailed study carried out in 1999. (section 3.7.3)
- freshwater macrophytes ('big plants'), special study carried out in 1998 / 1999 (section 3.7.4), and Water Crowfoot survey carried out by Wiltshire Wildlife Trust in 1999. (section 3.7.5)
- fisheries: study carried out as part of a rolling programme of sampling (1998/1999). (section 3.7.6)

3.7.2 Biological quality classification

Results of the national General Quality Assessment (GQA) survey are used to classify river reaches into one of six biological classes, a (very good) to f (bad). Aquatic macro-invertebrates are used to assess the quality of the river because they:

- do not move far;
- have reasonably long life cycles;
- respond to the physical and chemical characteristics of the river;
- are differentially sensitive to organic pollution events, which occur infrequently and which are not measured by chemical spot-sampling;
- provide a picture of ecological quality over time.

For the biological quality assessment, macro-invertebrates are grouped into 83 taxa. These taxa show a range of sensitivity to organic pollution, and have been individually assigned a value on a scale from 1 (pollution-tolerant) through to 10 (pollution-sensitive). A sample containing pollution-sensitive taxa (e.g. stoneflies) indicates better water quality than a sample where only pollution-tolerant taxa (e.g. water hoglice) are found. For the classification into classes the total invertebrate score for a site is compared to a predicted score, and an Environmental Quality Index (EQI) derived. The predicted score is determined using RIVPACS computer package, which calculates the biological quality of individual sites in the absence of environmental pollution. Thus the closer to unity (i.e. 1) the EQI the higher the biological water quality of the site, and the higher the grade.

This classification system is used in the Biological GQA programme in which rivers are surveyed and their quality reported. Until recently sampling was undertaken every five years, however the system currently in place is based on a three-year rolling programme. The sites used for the biological classification are listed alongside the equivalent water quality site in Table 11 (see also Map 5). Water quality (chemical) and biological GQA samples are not taken from exactly the same location due to the different requirements of sampling

[1] The surveying frequency will be changed in the near future, resulting in a higher sampling frequency. Details of the new schedule are still being discussed.

techniques, however they are very close to each other and are taken to relate to the same 'site' and RQO stretch.

In the 1995 assessment, all stretches except the stretch around Marshfield STW obtained the 'a' grade (very good). In the 2000 assessment this trend largely continued with the exception of the Broadmead Brook and Bathford (d/s road bridge) which shifted downwards to grades b (good) and c (fairly good) respectively. A shift of one grade over a single period is not generally judged to be significant due to the degree of statistical error associated with this technique (which is designed to assess trends). However a shift of two grades is unusual and at Bathford can be explained by the fact that no Autumn sample was taken due to high flows, and that spring sampling was made difficult by a compacted river bed. On the Marshfield stretch upstream of the STW the assessment grade moved from 'c' (1995) to 'b' (2000) but downstream of the STW the opposite occurred, with the 1995 'c' grade dropping to 'd' in 2000. Again, these are only single grade shifts over a single period and thus emphasis should not be placed too heavily upon their significance. Many single-grade shifts can be attributed to factors other than notable changes in water quality, although it is important in such cases to ensure this is not the start of a trend.

3.7.3 Detailed macro-invertebrate survey 1999

Introduction
A study to investigate flows in the By Brook catchment was undertaken during 1999. The Lotic-invertebrate Index for Flow Evaluation (LIFE), is a new method for assessing river flows, based primarily on recognised flow associations of different macro-invertebrate species and families (Extence *et al.*, 1999). This method was applied to invertebrate data from a number of sites, to assess the current situation, but more importantly to provide a baseline against which future work can be compared. This will allow informed conclusions to be drawn regarding the continuing integrity of the benthic invertebrate fauna.

Survey methods
Macro-invertebrate samples were taken in three seasons from ten sites[1] (Map 7) using a standard Environment Agency protocol and preserved on-site for subsequent analysis. Samples were sorted in the laboratory and specimens identified to species level where possible. For each sample taken the LIFE score was calculated. Six processed samples were also sent to external auditors, the Institute of Freshwater Ecology, for independent quality assurance. The results from the audit indicated the work to be of high quality.

Results
Table 16 presents seasonal LIFE scores and the average score over the year for each site. The individual scores are calculated from the species present and their abundance. The theoretical range of scores is 1 – 12, higher scores reflecting higher velocities. In practice, because the LIFE score is an average figure, values at the extremes of the range are highly unlikely to be achieved.

Discussion and conclusions
The LIFE method at present has no predictive capability, although data have been collected at many different sites in Great Britain so some robust assessment of the current state of the By Brook catchment can be made, based on comparison with other catchments. For the By

[1] Four of these locations coincide with biological GQA monitoring sites, the remaining six were new sites.

Brook itself the observed results based on species identification must be interpreted in isolation for this year, but can be used as a baseline for future work. It would not be prudent to link the invertebrate species data with gauged flows either at this early stage, as the time scale would be too restrictive and any conclusions are unlikely to be meaningful.

Any LIFE value of eight or above indicates an invertebrate community generally associated with moderate to fast velocities. Most of the sites returned an average value greater than eight, with most individual scores also above this figure. The By Brook catchment therefore sustained an invertebrate community throughout 1999 that reflected a fairly high, steady flow during the year. Only the Burton Brook upstream of Burton returned results indicating low flows. This watercourse is a known winterbourne and any dry period decreases the LIFE score.

Table 16 LIFE scores

Site	Date	LIFE score	Average
Kington Down	14-05-99	7.20	
	27-08-99	5.50	6.32
	27-10-99	6.25	
U/S Burton village	14-05-99	6.60	
	27-08-99	Dry	6.60
	27-10-99	Dry	
Rownham Farm	14-05-99	8.32	
	27-08-99	8.21	8.35
	27-10-99	8.53	
West Kington	14-05-99	8.62	
	27-08-99	8.81	8.64
	27-10-99	8.50	
Nettleton Shrub	11-05-99	8.34	
	27-08-99	8.40	8.49
	27-10-99	8.75	
Gatcombe Mill	11-05-99	8.47	
	27-08-99	8.22	8.18
	27-10-99	7.85	
Long Dean	11-05-99	8.20	
	31-08-99	8.63	8.24
	27-10-99	7.90	
Slaughterford	11-05-99	8.18	
	31-08-99	7.89	8.21
	27-10-99	8.55	
Widdenham Farm	11-05-99	8.23	
	31-08-99	8.41	8.25
	27-10-99	8.11	
Middlehill	11-05-99	8.43	
	31-08-99	8.08	8.23
	27-10-99	8.18	

LIFE values are inextricably linked with the geographical location of the biological sampling sites. Upland rivers will thus support proportionally more species associated with fast current velocities and return higher LIFE scores than lower altitude rivers. The results observed from the By Brook catchment were encouragingly high, given that the area is not upland in nature.

Studies from other rivers indicate that LIFE scores respond directly to river flows. Summer flow variables are most influential in predicting community structure in most limestone streams. This is likely to be also the case for the By Brook, where the summer base flow is likely to be much more important for safeguarding the invertebrate fauna than other flow periods. It has been demonstrated (Section 3.5) that summer runoff is highly variable and strongly dependent on concurrent rainfall, so it is expected that the LIFE score will also be highly variable in time.

3.7.4 Macrophyte surveys

Introduction
One of Halcrow's recommendations (Halcrow, 1998) was to undertake a standard river macrophyte survey for direct comparison with the results from an ecological survey conducted in 1987. This section summarises the findings of river macrophyte surveys carried out over the summers of 1998 and 1999, together with a preliminary analysis of relevant water chemistry results held on the Agency's Water Quality Archive. For full results reference is made to the relevant reports in the section below.

Survey methods
The ecological survey conducted in 1987 used the best methods available at that time to map and record habitat and vegetation details throughout the catchment of the By Brook. However, it was not the objective of that exercise to collect quantitative data which might be used to monitor the long term effects of changes in land use, water quality, flow regime and the like. For this reason it was thought inappropriate to repeat the 1987 survey as recommended by Halcrow (1998), but to use the results of that survey to establish a small number of fixed sites within which quantitative data could be collected. These would be within reaches recorded in 1987 as containing significant stands of the water crowfoot, *Ranunculus*; the assertion has been that low flows have caused the replacement of *Ranunculus* by filamentous algae. The data collected in 1998 would provide an empirical measure of present day conditions and serve as a quantitative baseline for long-term trend monitoring.

In 1998, the Mean Trophic Rank (MTR) system, developed through the Environment Agency R&D programme (Technical Report E38, 1997), was used to quantify vegetation at six sites (Map 6). At each location, a minimum 500m river reach was walked to select a 'typical' 100 m section for which the MTR was determined. The procedure for this is as follows. Within each 100m section the presence and abundance (percent cover) of all aquatic macrophyte species (inclusive of key algae and bryophytes) was recorded. A nine-point scale was used to categorise abundance (Species Cover Value - SCV):

C1	C2	C3	C4	C5	C6	C7	C8	C9	
< 0.1	0.1-1	1-2.5	2.5-5	5-10	10-25	25-50	50-75	> 75	%

In the R&D Report E38, each species (129 aquatic species in total) has been allocated a Species Trophic Rank (STR) ranging from 1 to 10; high scores are associated with plants typical of low nutrient, i.e. generally 'natural' and less polluted, environments, although the maximum possible score also depends on the natural chemical composition of the stream[1]. The Mean Trophic Rank (MTR) is calculated using the abundance measure (SCV) and trophic rank (STR) for each species recorded. Higher scores are associated with lower trophic status, i.e. less polluted.

In undisturbed or not degraded ecosystems, the plant community usually contains a mixture of species existing in equilibrium. Disturbance tends to cause imbalance and the dominance of a small number of generally low scoring [STR] species, which are tolerant of eutrophication or cosmopolitan in their environmental requirements. Hence, low MTR scores can also be interpreted as indicating other environmental disturbance, such as the effects of channel maintenance activities or low flows.

In 1999 the same Mean Trophic Rank (MTR) was used to quantify vegetation at the six sites surveyed in 1998. Photographs and site sketch maps were used to ensure that the same 100 m stretches were resurveyed, and the same surveyors carried out the work.

Results

1998

The river macrophyte surveys recorded significant stands of *Ranunculus* (Water crowfoot) in the middle and lower reaches of the By Brook. Two species were recorded, *R. fluitans*, and *R. penicillatus* var. *pseudofluitans*. Both species are typically found in moderately or rapidly flowing, base-rich lowland rivers, with *R.fluitans* perhaps being more common in larger, more eutrophic rivers. Although subjective, the condition of the plants appeared to be healthier in the lower reaches.

We did not record any *Ranunculus* species in the Broadmead Brook, where the vegetation was dominated by filamentous algae and other fouling organisms. Although not specifically surveyed, knowledge of other sections of the Broadmead Brook suggests this result is not atypical. The 1987 report did record *Ranunculus* (species unspecified) in several places on the Broadmead Brook.

The MTR scores reflect these observations, in general increasing from the Broadmead Brook down the catchment. The score for Burton Brook was relatively high. Expected MTRs for this type of river (based on catchment geology) are typically in the range 40-50, where actual scores were at the lower end or just below this range (Table 14).

These results show that the Broadmead Brook in particular, and to a lesser extent, the middle reaches of the By Brook, were degraded compared with the Burton Brook and lower reaches of the By Brook. This is somewhat counter-intuitive, as under normal circumstances, the cumulative impact of, for instance, sewage discharges or land run-off would be expected to increase downstream. The absence of significant point discharges in the upper catchment compounds the paradox. However, this section of the By Brook is noted as having several weirs and dams, which affect the river ecology by reducing velocity (upstream) and increased sediment deposition (see section 4.2). These observations will be discussed further, in the light of the water chemistry results, below.

[1] Upland rivers e.g. in Wales are naturally nutrient-poor. These will have plants that score 10. Rivers like the By Brook are naturally base-rich and would never support plants that score 10.

1999

Significant stands of *Ranunculus* were again recorded in the middle and lower reaches of the By Brook. The same two species as in 1998 were recorded. In addition, a rooted fragment of *R. penicillatus* var. *pseudofluitans* was found during the June survey of the Broadmead Brook at West Kington. The leaves of water crowfoot die back later in summer and during the repeat survey in September much of the top-growth had disappeared. The presence of this plant suggests that conditions in this section of the Brook at least had improved since 1998.

As in 1998, there were considerable amounts of filamentous algae and other fouling organisms, particularly on the Broadmead Brook at the time of the September survey. At this time, *Ranunculus* plants lower down the catchment had also deteriorated in condition. However, at the time of the earlier survey in June, the *Ranunculus* plants were subjectively assessed as being in very good condition.

It is probable that higher flows had restricted the growth of fouling organisms in 1999. For instance, the average depth of water at West Kington at the times of surveys in 1998 was less than 25cm. In 1999, the depth was mostly between 25cm and 50 cm. At Middlehill, the depth was less than 100 cm in 1998, 30% being less than 50 cm. In June 1999, only 10% of the surveyed length was less than 50 cm deep, 15% being over 100 cm deep. Similar differences were evident in the middle reaches. The MTR scores reflect these observations, being generally higher than achieved in 1998 (Table 14). This was particularly noticeable in the Broadmead Brook.

Table 14 Summary results of river macrophyte surveys 1998 and 1999

River	Location	MTR '98	MTR June '99	MTR Sept '99
Broadmead Brook	West Kington	34.5	38.1	37.0
Burton Brook	Gatcombe	42.7	38.6	39.0
By Brook	Lower Long Dean	33.6	38.4	29.1
By Brook	Ford	34.2	35.2	40.4
By Brook	Widdenham Mill	41.4	38.2	40.0
By Brook	Middlehill	44.4	47.6	41.7

Three other observations are of note. Firstly, *Elodea canadensis* had proliferated at Ford in 1999. This is a non-native species that indicates disturbance and/or nutrient enrichment. Secondly, conditions at Lower Long Dean deteriorated markedly between June and September, by which time filamentous algae had proliferated, and even traces of sewage fungus were evident. This points to organic pollution of this site. Finally, the cover value for *Apium nodiflorum* at Gatcombe (Burton Brook) was much reduced in 1999, the centre channel being clear of vegetation compared to the choked channel of 1998. Again, this would support the view that flows were higher in 1999 and had scoured the centre channel.

While these results support the assertion that flow affects the macrophytes of the By Brook, they do not rule out other influences. For example, during 1999, inspections by Environment Protection staff identified inadequate waste management systems at two significant dairy units in the upper Broadmead Brook catchment. Improvements at both sites have since been made.

Discussion – influence of water chemistry

If the anecdotal reports that *Ranunculus* is being replaced by filamentous algae are substantiated, the cause may be flow related, but may also be due to a change in the nutrient status of the By Brook. Increased nutrient loads (trophic status) can result in excessive growth of filamentous algae which smother and out-compete plants such as *Ranunculus*.

Water quality archive nutrients data for four sites (Map 6) were retrieved for statistical analysis. These sites were selected from the network of water chemistry sites because they maximised the data available while covering most of the catchment from the upper reaches to the confluence with the River Avon. Datasets from 1985 were merged for the four sites and analysed (Fig 12.1-12.4), data for site 2, (Broadmead Brook) was later taken out and analysed separately (Fig 12.5 &12.6). Analysis of variance was used to examine differences between sites and changes over time.

Seasonal trends in the concentration of Total Inorganic Nitrogen (TIN)[1] point to diffuse sources of nitrogen (run-off from agricultural land) because it is higher in winter when there is more surface runoff (Figure 12.1). The seasonal trends in the concentration of orthophosphate (PO4 - Figure 12.2) is typical of point source origin, e.g. sewage treatment or farm discharges, because the concentrations are higher in summer when there is less dilution. Temporal changes support this conclusion: in the time period over which data are available, TIN has broadly correlated positively with annual runoff (Figure 12.3). At the same time, a slight reduction in phosphorus concentration was observed probably through some improvements in sewage treatment (Figure 12.4).

Figures 12.1-12.4 suggest that in the By Brook catchment (inc. the Broadmead Brook) levels of phosphate and nitrate tend to be on the high side when compared with environmental quality standards (EQS). Both the Broadmead Brook (site 2 -Fig12.5) and By Brook (sites 1,3,-Fig12.5) recorded nitrate concentrations (mean and 95 percentile borderline exceedence of the EQS of 11.3 mg/l nitrate) which, if linked to diffuse agricultural sources, would qualify them for Nitrate Vulnerable Zone designation under the EU Nitrate Directive. In terms of recorded phosphate concentrations (fig 12.6), all sites except the Broadmead Brook (site 2) gave levels that would exceed the EU Urban Waste Water Directive Sensitive Area EQS for phosphate levels as indicative of being potentially eutrophic (0.1mg/l). The Lower Bristol Avon (including all its tributaries) from Chippenham downstream is currently designated as a UWWTD Sensitive Area. This designation means special protection with regard to waste water treatment and that large STWs (serving > 10,000 population equivalent), even those discharging indirectly to the Avon, are required to remove phosphate from their discharges. Other measures to reduce eutrophication in the lower Avon and upper Avon will be tackled through implementation of the EA Eutrophication Strategy and Area Diffuse pollution strategy.

Elevated phosphate would not be expected in the Broadmead Brook as it is largely affected by agricultural inputs whereas the main By Brook is impacted by a variety of inputs including STWs and agriculture. However the low level of phosphate in the Broadmead Brook is more typical of an un-impacted watercourse and is a little surprising given the type of watercourse and location of the sampling point. If resources permit and as part of the wider investigation

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[1] Total Oxidised Nitrogen + ammonia

into nutrient budgets of the Bristol Avon, the influences on the water chemistry of Broadmead Brook may be investigated further.

Conclusions

MTR scores recorded in the 1998/99 surveys were at the lower end or just below those expected of a river of this type. This could be due to the elevated TIN concentrations seen within the catchment caused by diffuse agricultural pollution. Both the 1998 and 1999 surveys show that the Broadmead Brook and the middle reaches of the By Brook are degraded compared with the Burton Brook and lower reaches of the By Brook. Analysis of water chemistry monitoring results indicate that the high nutrient concentrations (from land run-off) experienced at the Broadmead Brook could have caused the change in vegetation structure observed. It is not clear why there was a decrease in MTR scores in the middle reaches although observations in the 1999 survey suggest nutrient enrichment and organic pollution could be the cause. The impact of such pollution could also be exacerbated by the presence of several weirs and dams along this stretch (see section 4.2 & 6.1.2).

Filamentous algae and sewage fungus were observed on the Broadmead Brook in 1998 and 1999, and on the By Brook at Long Dean in 1999 suggesting organic pollution. This could be linked to the inadequate waste management systems identified in the upper Broadmead Brook in 1999, some of which have since been improved. Climatic variations will also impact the ecology seen and it is likely that the dry period experienced in 1995 / 1996 would have contributed to the conditions observed in the 1998/1999 surveys.

In addition to the nutrient status of a stretch, it has been found that physical factors such as seasonal flow patterns, water temperature and shading are also relevant and that it is the combination of these factors which determines the observed MTR score. It is unlikely, therefore, that restoration of the flow regime (if indeed it has changed) would in itself restore a *Ranunculus* dominated flora unless land use practices were at the same time modified to reduce nitrogen loading.

*3.7.5 Water crowfoot (***Ranunculus***) survey WWT*

In 1999 Wiltshire Wildlife Trust organised a volunteer water crowfoot survey which has established a baseline for future surveys. The survey points consisted of five stretches of river each 500m in length on the main By Brook (see Map 6 for NGR). Each stretch is 500m long measured downstream from the starting point. In each 100m section of these stretches, the river width was measured as well as the amount of water crowfoot covering the river (in m^2). With these two measurements the Species Cover Value (SCV) can be calculated (see Section 3.7.2). The results of this survey are shown in Table 15.

Table 15 Water crowfoot Species Cover Value

Stretch (NGR)	**1st 100m**	**2nd 100m**	**3rd 100m**	**4th 100m**	**5th 100m**
1 (ST 838783)	3	4	3	3	2
2 (ST 836777)	3	5	3	2	2
3 (ST 840724)	0	0	0	0	0
4 (ST 823688)	6	5	6	6	6
5 (ST 814687)	5	2	4	2	n.a.

According to the WWT, these results indicate that the By Brook supports a healthy population of water crowfoot. Variations between the amount of water crowfoot are possibly due to differences in the bank side, amount of shading, etc. In this context, the lack of water crowfoot in stretch 3 is probably because this is a wooded, heavily shaded section.

3.7.6 Fisheries surveys

Introduction

An electro-fishing survey was carried out as part of the Environment Agency's rolling programme of strategic fish population surveys. It has provided a reasonably accurate assessment of fish populations present. The By Brook is an important catchment within the Bristol Avon, well known for its excellent fly-fishing. North Wessex By-law 14 allows anglers to take individuals of 20cm and over from the By Brook and its tributaries, the size limit for the rest of North Wessex area is 25cm. This is subject to a daily limit of two fish (North Wessex By-law 17B). The Burton, Broadmead, Doncombe and By Brooks are designated as salmonid fisheries under the EC Freshwater Fish Directive.

Survey methods

Twelve sites were surveyed in the By Brook catchment (Map 8). BY21 was sampled during a crayfish survey in 1998 and 11 others (BY20 and BY22 to BY31 inclusive) were surveyed between March and August 1999. Sites BY27 By Brook at Drewett's Mill and BY30 Doncombe Brook at North Wraxall had never been surveyed before. The ten other sites were previously surveyed in 1992 and six of them were also surveyed in 1988 or 1989.

The sites were sampled using 240V pulsed DC electric fishing equipment over an approximately 100 m section. Stop nets were used at upper and lower ends of the site to prevent fish movement in and out of the area. Depending on depth and width of the river, a net and bucket carrier were used while wading upstream, or an inflatable rubber boat was used with all the equipment in it and net carriers would wade in front. Where pools were too deep to wade a wooden boat was used to carry all equipment and net carriers. The method is very labour intensive, with six people needed on site.

Three fishing runs were carried out at sites BY21, BY24, BY26, and BY27 and fish from each run contained separately on the fisheries vehicle before being weighed and measured. Scales were removed from the fish, except for eels and stocked trout, and sent to the Fisheries Laboratory for age and growth analysis. Minor species (stone loach, bullheads, sticklebacks and minnows) were not captured but their approximate numbers were recorded for each site. Only one fish was seen and captured at site BY29 so only one electric fishing run was necessary. At all other sites two fishing runs were carried out because the depletion rate between runs one and two was great enough to satisfactorily estimate population and biomass.

Results

The dominant species within the By Brook is brown trout since they were found at every site in the survey. Eels and brook lamprey were found in the upper main river sites and other coarse fish species were found at the two sites furthest downstream: dace, roach and gudgeon at Drewett's Mill and grayling and gudgeon at Middlehill. In total eleven species of fish were captured during the survey, those mentioned above plus the following minor species, stone loach, sticklebacks, bullheads and minnows. Native and signal crayfish were also seen. Details of the survey (population total, density and biomass) for each site are available in the survey report, a summary of results is included below.

Important nursery areas were found at BY20 and BY21 (Broadmead Brook). The Doncombe Brook (BY29) is susceptible to low flows and pollution which may limit the spawning grounds available for brown trout. This will of course vary greatly from one year to the next depending on rainfall and affect the spawning success and population dynamics at the site. Long riffle stretches, deep pools, a substrate of stones and gravel and higher flows in the Lid Brook (BY31) mean that this is a very important spawning and nursery site within the catchment. The other sites surveyed display the varied habitat, a combination of riffle and glide areas and pools, gravel substrate, marginal reed beds, in-stream vegetation and undercut banks below tree roots, that together provide excellent habitat for all age classes of brown trout.

Figure 13 and Figure 14 show summary survey results for 1999 compared to the results of similar surveys carried out in 1988/89 and 1992. The broad pattern of population distribution throughout the catchment is similar to the 1988/1989 and 1992 distributions. Comparisons of site results for the surveys show fluctuations in fish density and biomass to a varying degree, however there are several variations to the surveys technique used that could explain these differences. The 1999 results may be slightly underestimated when compared to 1988/89 and 1992 results because the cut off length chosen for total population, density and biomass calculations is 10cm whereas previously it was 8cm, meaning that more fish are excluded than they would have been before. Further differences could be due to the time of year of the survey as fish movement up or downstream will occur for spawning. Also the length of site was shorter in the 1999 survey (averaging 94m), compared with 1992 (averaging 157m). Since the stop nets are closer together in a shorter site a greater proportion of fish may be lost out of the site when the nets are being put into position. Differences in results for the Doncombe Brook may be due to low flows which may have reduced spawning success in 1999 compared to 1992. All things considered, however, most change will be due to normal population dynamics.

Conclusion
The By Brook continues to thrive with a very healthy population of brown trout. Coarse fish are important at the lower end of the catchment near the confluence with the River Avon. Spawning and nursery areas occur on the gravel substrates of the tributaries and larger fish are found in the deeper waters at Middlehill furthest downstream. Fish of all sizes and ages occur in the other five main river sites. One year old fish are found in very good numbers as far downstream as Slaughterford and Weavern.

Overall the results show that the By Brook population structure is currently stable and self-sustaining. The By Brook catchment represents one of the best brown trout fisheries in the region. It has miles of unspoilt river of high water quality and conservation value, with excellent brown trout and coarse fish habitat.

3.7.7 Conclusions: ecology

The overall outcome of the ecological surveys may be summarised as follows:

- macro-invertebrates: high LIFE scores for this type of stream except Burton Brook (due to winterbourne character).
- macrophytes: generally healthy but MTR scores are slightly lower than would normally be expected probably due to diffuse pollution; filamentous algae problems encountered in the Broadmead Brook suggesting that organic pollution may also have occurred;
- fisheries: a self-sustaining healthy population is present;

The macrophyte community does appear to be indicating less than ideal conditions. Factors involved were discussed above; they are likely to include the nutrient status of the water course, and physical characteristics such as flow rate, depth, water temperature and shade. Diffuse agricultural pollution does appear to be contributing to the slightly lower MTR scores observed. The macrophyte population seems to respond very rapidly to any changes in flows or water quality, and will be very variable in time.

4. Anthropogenic Influence on River Flow and Quality - Inside Catchment

4.1 Types of impacts

It is important to distinguish between three different aspects of river flow that are often confused when the impact of a human activity on the river is discussed: river level, river flow (volume per unit time) and water quality. Flow and level are related through cross-section and slope, so that a specific relationship only applies to a specific stretch of river, with a specific sluice setting if applicable. This means that a deep river can be stagnant (i.e. there is no flow) or water velocity can be high while being deep (the flow is then high). A shallow river can have a lot of flow (with high velocities) or none at all.

Low river levels are not necessarily a cause for concern, because the river may still exhibit a healthy flow, having a high velocity. This is typically the case in the upper reaches of UK catchments, like the By Brook. Unless the river is experiencing a flood event, high water levels in this type of river are associated with impoundments and sluggish flow, often leading to water quality problems. Flows and water quality are also linked, because the same quantity of pollutant is more diluted in a high flow than in low flow. Conversely, to achieve the same concentration, the quantity of pollutant present is higher in high flows than in low flows. High velocities provide aeration to the water, thus helping aquatic life.

In this chapter, quantitative impacts on the By Brook and its tributaries are discussed mainly in terms of river flows. This is because flows are the 'signature' of a catchment, being the result of catchment response to rainfall, other climate factors, geology and landuse, and human interference. Flows may also be easily compared with abstracted or discharged volumes, simply by dividing by the time over which the abstraction or discharge took place. Influences on water quality are discussed in Section 4.6.

Three different types of impact on the river flow regime[1] may be distinguished:

1. primarily change in timing, e.g. through impoundment (Section 4.2);
2. decrease in volume through abstraction (Section 4.3);
3. increase in volume through discharges (Section 4.4).

The first and last also have an impact on water quality, and the first usually increases water levels. The net effect of these impacts will be calculated in Section 4.5. Lastly, the construction of the Bristol-Swindon railway and the M4 motorway resulted in small modifications to the catchment area, for both the surface and hydrogeological boundaries (Sections 3.1 & 3.4.2). No increase in flashiness could be detected since flow records began in 1982. Unfortunately it has not been possible to quantify the possible impacts of the construction of the motorway (1960's) as there is no flow data available. The Agency will continue its policy of encouraging sustainable drainage options to any motorway improvement proposals in the future.

[1] See glossary.

4.2 Mills and ponds, hatches and sluices

All along the By Brook, sluices and hatches are operated by landowners and fishing organisations. These are mostly remnants of old mill installations. There is evidence of 22 mill sites down the Brook, and the valley's history is very much the history of these mills, some of which are now in disrepair and none of which is used commercially any more (Tatem, 1996). At present, the most extensive impoundments caused by sluice operations are located between Castle Combe and Ford, but there are other impounded reaches at West Kington, Doncombe Mill, Gatcombe Mill and Goulters Mill. Many of these sites pre-date regulatory control initiated through the Water Resources Act 1963 and thus because of their long existence these sluices do not require any permissions (impoundment licence or land drainage consent). However, because of its construction date, there is one exception to this: the fishing lakes near Goulters Mill Farm (ST 830791) where the licensed impounded quantity is 11,000m^3. The hydrograph of flows at Middlehill shows an example of the distinct pattern of flows resulting from sluice operations (some of which are annotated on Figure 11): there are distinct sudden peaks and troughs where sluice boards were opened and shut respectively. A natural flow would exhibit a smoother curve.

The existence of so many mills on such a small brook has caused many inter-neighbourly disputes historically, about water level management and use of resources. Wildlife habitat can be affected by the created water levels. In winter, sluices and hatches are generally open, or should be, so as not to increase flooding. This flushes out and cleans gravels on the river bed, allowing invertebrates to thrive and trout to spawn. In summer, sluices and hatches may restrict flows, particularly during periods of drought, thereby decreasing water quality and quality of the habitat. Increased nitrogen and phosphorus concentrations in the impounded reaches may lead to excessive vegetation growth and algae bloom, which could be prevented if the streams were free-flowing.

The effect on streamflows is not just to reduce water velocity. Impoundments do cause losses to the streams in two ways:

1. increased evaporation: an open water surface on a sunny summer day evaporates around 3-4 mm, i.e. 30-40 m^3/ha (or 12-16 m^3/acre). This is a flow reduction of 0.3-0.4 l/s per ha impounded water surface;
2. increased infiltration into groundwater: the rate of loss depends on the soil, but infiltration rates of 10 mm/day for moderately permeable soils are usual, i.e. 100m^3/ha per day. The infiltrated water may be lost to the catchment as it recharges the aquifer to be kept in storage, re-emerging as springs elsewhere.

In summary, there are reasons why impoundments in the By Brook can be harmful to the water environment. They cause water loss, water quality degradation and proliferation of unwelcome plants. Some impounded reaches may benefit fisheries, but it is important to manage them well to counter the detrimental effects mentioned above. Appendix 8 presents an example from the neighbouring Malmesbury Avon describing recent improvements that included re-creating natural reaches from impounded sections.

4.3 Surface water and groundwater abstractions

There are four major current abstraction licences in the By Brook catchment (Table 17) and ten minor ones with a daily maximum abstraction rate of less than 0.05 Ml (not listed). The latter are principally used for general farm activities and spray irrigation. The Portals licence (008) allows the abstraction of water from the stream near the confluence with the Avon, and does not impact on the flows in the By Brook. This leaves three licences which may have a significant impact on the By Brook: 025, 048 and 054. An assessment of the impact of each of these abstractions can be found below (sections 4.3.1 – 4.3.3).

Table 17 Abstraction licences inside the catchment with licensed quantity (Ml)

Licence No	Licence Holder	Daily Quantity	Annual Quantity	source
175304S008	PORTALS (BATHFORD) LTD	1.364	409.15	surface
175304S025	WESSEX WATER PLC (WIDDENHAM)	2.7	800	surface
175304G048	WEST KINGTON NURSERIES	0.23	38.2	ground
175304S054	MANOR HOUSE GOLF CLUB	0.72	50	surface

Note: Licensed quantities are maximum volumes per day or per year. 1 Ml = 1000 m^3

The major abstraction boreholes in the area surrounding the By Brook catchment are listed in Table 18. An assessment of the potential impact from abstractions outside the catchment is more complex and has been addressed separately in Section 5.

Table 18 Major abstraction licences outside the By Brook catchment

Licence No	Licence Holder	Annual Licensed Quantity
175301G201	WESSEX WATER PLC – GOODSHILL	500
175301G207	WESSEX WATER PLC – IVYFIELDS	6820
175301G405A	WESSEX WATER PLC – HOLT1+2	7515
175301G405B	WESSEX WATER PLC – LITTLE CHALFIELD	401.5
175301G405C	WESSEX WATER PLC – SOUTH WRAXALL	730
175301G410G	WESSEX WATER PLC – LUCKINGTON (G)	900
175301G410J	WESSEX WATER PLC – HULLAVINGTON (J)	900
175301G410K	WESSEX WATER PLC - L.S.S.Q. (K)	900
175301G415	WESSEX WATER PLC – LACOCK	3320

4.3.1 Impact of the West Kington abstraction on flows and groundwater

The groundwater abstraction at West Kington Nurseries was licensed in 1985. In order to assess its impact on flows in the Broadmead Brook, a Q95[1] for the Broadmead Brook at West Kington has been estimated (using the regression technique described in Section 3.5.3), and compared to the maximum daily licenced quantity. The Q95 is estimated at 7.19 l/s (Section 3.5.3) and the licensed daily quantity is for 0.23Ml/d (2.66 l/s). This means that if it is assumed that 100% of the abstraction is a direct loss from the Brook then the naturalised[1] Q95 (modified to account for this abstraction only) would be 37% higher than observed. This is therefore a potentially significant abstraction, however its actual impact on the By Brook catchment is thought to be negligible due the hydrogeology.

The aquifer tapped by the West Kington abstraction is the Inferior Oolite, which is isolated from the aquifer feeding the river (Great Oolite): *[The following is copied from Smart, 2000 – and refers to the West Kington abstraction]* "There is no direct abstraction from the Great Oolite, which is isolated in the borehole by solid casing. Perforated casing is placed over a 6 m interval in the upper Fuller's Earth, which may have some lateral continuity with the Great Oolite or with outcrops in the floor of the Broadmead Brook upstream. During test pumping this upper perforated section was dewatered, and the yield was apparently derived only from a second perforated zone 82m - 101m below casing level (Inferior Oolite).

The rest, and pumped, water level of the West Kington borehole is below that of the Great Oolite aquifer, and significant leakage between the two aquifers is unlikely due to the thickness and low permeability of the Fuller's Earth clays, and the limited extent of faulting in the By Brook catchment. Any effect of abstraction from the Inferior Oolite is more likely to extend to the numerous small springs in the deeply incised St Catherine's Brook or the By Brook downstream of Ford where the Inferior Oolite is exposed. Although recharge to the Inferior Oolite aquifer is small because of the limited outcrop area, given the relatively small abstraction at West Kington borehole it is unlikely that this will be a problem, as there is adequate flow in the By Brook at Ford" *[end quote]*.

It can, therefore, be concluded that the West Kington borehole abstraction does not significantly impact on flows in the Broadmead Brook, nor on any other river in the catchment.

4.3.2 Impact of Castle Combe Golf Course abstraction on flows

The abstraction licence at Castle Combe was granted in 1996 and allows the filling of a reservoir in winter (October to March) for subsequent spray irrigation use in summer. The maximum abstraction rate is 16.7 l/s, and the inlet is constructed in such a way that abstraction stops when flows in the By Brook are 288 l/s or less. This means that the abstraction into the lake is never more than 6% of flows in the Brook[2]. Average flow at Castle Combe is estimated at 650 l/s, using the regression technique[3], and Q95 as 54 l/s. Flows in the Brook are therefore more than adequately protected from over-abstraction by this licence: the Q95 is often used in licence determination as a 'hands-off' flow, and here the protected flow (288 l/s) is five times as high .

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[1] See Glossary

[2] 16.7 / 288 = 6%

[3] The equation to calculate flows at Castle Combe from flow at Middlehill is : Q Castle Combe = 0.4863 * Q Middlehill - 0.1039 (R^2 = 0.97) This is applicable to average flows. For low flows another equation should be used : Q Castle Combe = 0.2977 * Q Middlehill – 0.0129 (R^2 = 0.88)

4.3.3 Impact of Widdenham abstraction on flows

The Widdenham abstraction licence allows Wessex Water to collect outflows from the local springs opposite Widdenham Farm on the eastern bank of the By Brook. The licence has been in operation since December 1966. Flow statistics for upstream of Widdenham have been estimated using the regression technique[1] (described in section 3.5.3) and the spot gauging results from downstream of the confluence with the Doncombe Brook. The analysis of actual monthly abstractions compared to estimated monthly river flows (Appendix 9) shows that in the past 10 years, the abstracted volume compares to an average of 2.1% of monthly flows in the By Brook. A maximum was reached in July and August 1995 when the captured spring flows represented 9% of the flows in the By Brook, i.e. in these months the Brook would have had 9% extra flow downstream of the abstraction if the springs had been allowed to flow freely. Abstraction during this period equated to <7% of the Q95 in an average year. The licence allows Wessex Water to abstract more water, as only 30% of the licensed volume (on average) is actually taken. However, the actual abstracted volume is limited by the natural output of the springs, and the volume cannot be artificially increased. For the same reason there is no impact on groundwater levels.

During the driest period in the last 10 years (summer 1995), the abstracted volume is not negligible compared to river flows (9%), and extra water would probably be of benefit to river ecology in low flow periods; however, this benefit needs to be balanced against the benefit of having public water supply secured in a relatively extreme event such as this.

4.4 Consented discharges

There are around 70 current discharge consents in the By Brook catchment. Consent conditions comprise both water quality standards (see Section 4.6) as well as volumetric design parameters.

Consent criteria can include both or either[2] of:

- dry weather flow (DWF), legally defined as the average daily flow to the treatment works during seven consecutive days without rain (excluding a period which includes a public holiday) following seven days during which the rainfall did not exceed 0.25 mm on any one day;
- maximum flow.

The majority of the discharge consents are for domestic properties, with, for example septic tanks discharging to soakaways, or small sewage treatment plants discharging into soakaways or watercourses. They may or may not discharge a small volume into a stream. Discharge consents for residential dwellings do not have DWF conditions but have maximum flow rates based on the population figure of the household[3]. They are all below $5m^3/d$, and are not listed here. All discharges with a maximum daily flow of 5 m^3/d or above are monitored on a regular basis by the Agency. Those discharges within the By Brook catchment are shown in

[1] The equation to calculate flows u/s Widdenham from flow at Middlehill is :
Q Widdenham = 0.7256*Q Middlehill - 0.1486 (r^2 0.99). This is applicable to average flows. For low flows another equation should be used: Q Widdenham =0.4779* Q Middlehill - 0.0162 (r^2 0.93)

[2] With the exception of some small, very old consents where no numerical constraints were included.

[3] In the absence of accurate population data it is calculated assuming 1 person per bedroom plus 0.5 person per household. A per capita volume of 180 litres per head per day is used for this calculation.

Table 19 and are plotted on Map 4. Further details on the water quality monitoring arrangements for these consents can be found in Section 4.6.

Table 19 Consented discharges with maximum daily flows of 5m³/d or above

Number	location	dry weather flow (m^3/d)	maximum flow (m^3/d)
	Sewage Treatment Works (public)		
010011	Burton STW (Wessex Water)	32	190
010054	Long Dean STW (Wessex Water)	210	
010528	Box STW (Wessex Water)	580	1728
011339	Marshfield STW (Wessex Water)	272	907
011590	Colerne STW (Wessex Water)	527	
101513	Ford Deane (North Wilts) *		6.5
101512	Nettleton STW (North Wilts) *		6.5
	Consented discharges (private)		
011502	The Salutation Inn		5
012814	White Hart PH		9
012509	RAF Rudloe Manor		60
021672	Tormarton rest area		6
100592	*Slaughterford Housing Devt.* #		*10*

** consents relating to the new sewage treatment units due for installation early 2002*
 # consent no. 100592 is currently under review by the Secretary of State

4.4.1 Impact of discharges from sewage treatment works on flows

At Long Dean, Marshfield and Colerne, sewage treatment inflows were measured continually over a one-year period in order to obtain information about flow rates (Appendix 10). The discharge from the works was assumed to be similar to the inflow, which will be the case over a time period of a few days. Flows from Burton STW are very low and absorbed into the, mostly dry, stream bed within 10 m; therefore they were not measured. At Box technical problems were experienced with the data collection and it is not possible to provide data for the period the gaugings were completed.

The STW inflows were compared with the spot gauging results downstream of the STW[1]. The percentage of the flow in the river that originates from the treatment works was calculated (Table 20). It should be noted that only at times of heavy storm runoff the discharges from sewage works contain untreated sewage (Section 4.6), at other times all sewage is treated to the agreed standards. These flow figures need to be considered in conjunction with water quality observations (Section 3.6). Flows at Long Dean indicate that it is close to its volumetric consent limits, but there is no evidence that these are being exceeded.

It can be seen that as a percentage of the flow in the By Brook at Ford, the STW discharges from Long Dean are negligible. The outflow from Marshfield STW is a large proportion of the flow just downstream of the works on the Doncombe Brook, but this proportion diminishes going downstream to the confluence. In summer the flow from Colerne STW is a

[1] The exception is Marshfield STW where there was no spot gauging data available between Sept'98 and April'99.

considerable proportion of the flow in the Lid Brook; however, the discharge point is very near the confluence with the By Brook and as a percentage of the By Brook flow it becomes negligible.

The effect of STW discharges is not just negative. Flows in the upper reaches of the Doncombe Brook would have been reduced by 75% in summer 1999 if the STW had not discharged. In dry summers it is likely that without flow from the STW discharge the stream would have been dry. Significant improvements to Marshfield STW treatment process and capacity are programmed within the AMP3 programme to be in place before March 2004 (Section 4.8). However, even when treatment and effluent quality is improved, the volume discharged to the Brook will not be reduced and in fact could be considered a benefit to the Brook. The new Marshfield discharge consent is likely to impose strict Ammonia, Biological Oxygen Demand (BOD) and Suspended Solids (SS) constraints. The quality of the effluent required under AMP3 will therefore be very good, and during low flows the high quality effluent will form a base flow for the brook which would otherwise go dry or have very low flows. The impact of flows from the new North Wilts District Council (NWDC) sewage treatment units at Ford and Nettleton is negligible since their maximum discharge is very small and effluent quality will be good.

Table 20 Discharge from sewage treatment works as percentage of streamflow

	Colerne STW as % Lid Bk	Marshfield STW as % Doncombe Bk at STW [1]	Marshfield STW as % Doncombe Bk at confluence	Long Dean STW as % By Brook at Ford
18/09/98	28.8%		6.1%	
25/09/98	46.0%		10.0%	
14/10/98	26.5%		4.8%	1.1%
19/11/98	7.0%		1.0%	0.3%
04/12/98	13.4%		3.1%	0.3%
18/12/98	14.3%		2.7%	0.3%
29/01/99	4.5%		0.8%	0.3%
05/02/99	6.6%		1.4%	0.4%
10/03/99	4.8%		1.0%	0.3%
22/03/99	9.9%		3.5%	0.4%
28/04/99	4.9%		0.7%	0.3%
12/05/99	7.8%	32%	3.4%	3.2%
15/06/99	15.2%	35%	2.1%	0.5%
19/07/99	36.0%	74%	11.0%	1.7%
20/08/99	32.5%	74%	8.5%	0.9%
17/09/99	37.4%	76%	8.9%	1.5%

4.4.2 Impact of discharges from private discharge consents on flows

Maximum discharge volumes from all but one private consent (012509) are negligible. The discharge from RAF Rudloe enters the Lid Brook near the confluence with the By Brook, at approximately the same location as the outflow from Colerne STW. Its consented maximum discharge is small compared to that from the Colerne STW, which had already been assessed above as having no noticeable impact on flows in the By Brook as a whole.

[1] Unfortunately there are no spot gaugings available for Marshfield STW between Sept'98 and April'99.

4.5 Net effect of abstractions minus discharges

Table 20 shows clearly that the overall net impact on river flows of abstractions and discharges is to increase the river flow at Middlehill. Virtually all water which discharges through sewage treatment works is sourced from outside the catchment as it originates from public water supply. The net impact at other sites will be different depending on the location. The greatest impact is in the upper part of the Doncombe Brook, where the flow depends to a large extent on discharges from the STW. A significant proportion of summer flow on the Lid Brook is also discharged from Colerne STW, however this is then diluted at the confluence with the By Brook where again it becomes negligible. At most other sites the impact from either abstractions or discharges is in the order of 10 % of summer flows at the highest (see Sections 4.3 and 4.4).

Table 21 Net effect of abstraction and discharges (in m^3/s)

m3/s	sum STW[1]	sum abs[2]	abs-STW[3]	abs/STW[4]	Q Middlehill[5]	% abs[6]	% STW[6]
Oct-98	0.0346	0.0086	-0.0260	0.25	2.05	0.42	1.69
Nov-98	0.0476	0.0105	-0.0371	0.22	4.138	0.25	1.15
Dec-98	0.0385	0.0104	-0.0281	0.27	2.614	0.40	1.47
Jan-99	0.0707	0.0167	-0.0540	0.24	5.412	0.31	1.31
Feb-99	0.0266	0.0110	-0.0155	0.42	1.752	0.63	1.52
Mar-99	0.0326	0.0109	-0.0217	0.34	2.394	0.46	1.36
Apr-99	0.0291	0.0096	-0.0195	0.33	1.661	0.58	1.75
May-99	0.0247	0.0091	-0.0156	0.37	1.448	0.63	1.71
Jun-99	0.0290	0.0104	-0.0186	0.36	1.314	0.79	2.21
Jul-99	0.0244	0.0099	-0.0145	0.41	0.481	2.06	5.08
Aug-99	0.0277	0.0107	-0.0170	0.39	0.575	1.86	4.82
Sep-99	0.0334	0.0106	-0.0228	0.32	1.306	0.81	2.56

Notes:
1. The discharge from Box was estimated from the average proportion of DWF at the other three STW, times the DWF at Box (Table 22).
2. = sum abstracted quantities from abstraction returns forms. The abstraction returns for West Kington for 1998/99 is missing and maximum observed monthly quantities have been assumed.
3. = sum abstracted quantities – sum discharged quantities
4. abstraction as proportion of discharges
5. monthly mean flow
6. total abstracted and total discharged quantities as percentage of flow at Middlehill

Table 22 Monthly STW outflow as a multiple of DWF

* DWF	Long Dean	Marshfield	Colerne	average
Oct-98	1.30	1.63	1.06	1.33
Nov-98	2.58	1.61	1.09	1.76
Dec-98	1.88	1.53	1.11	1.51
Jan-99	3.64	2.04	1.19	2.29
Feb-99	1.47	1.28	0.84	1.20
Mar-99	1.82	1.48	0.88	1.39
Apr-99	1.50	1.45	0.88	1.28
May-99	1.23	1.43	0.79	1.15
Jun-99	1.53	1.14	1.02	1.23
Jul-99	1.15	1.10	0.99	1.08
Aug-99	1.49	1.28	0.90	1.22
Sep-99	1.79	1.40	0.97	1.39
average	1.78	1.45	0.98	1.40

4.6 Impact of discharges from sewage treatment works on water quality

The perception that raw sewage spills into rivers following storms is partially true though an over-simplified presentation of the state of affairs. All sewerage systems and sewage treatment works are built to a finite volumetric capacity. Occasionally this capacity may be exceeded due to:

- surface water (rain) entering drainage systems that carry both foul discharge and surface runoff from rain (combined systems). Virtually all sewerage systems built before 1945 are combined, as are most sewerage systems in the By Brook. Modern practice is to build separate systems for foul discharge and surface runoff.
- infiltration of surface and groundwater into the sewerage pipes.

If sewerage systems were built without an allowance for relieving hydraulic overload, the result would be sewage flooding of land and/or property in the first instance and flooding of the sewage treatment works (and attendant treatment failure) in the second. To overcome this, sewerage systems are provided with so-called combined sewer overflows (CSO) at strategic points. Sewage treatment works are provided with storm tanks, which take the first flows of sewage above the plant's normal capacity to treat. These tanks have overflows which will ultimately operate. After storm conditions pass, sewage in the storm tanks is returned to treatment.

Although, as explained above, both sewers and storm tanks do overflow from time to time, the effect is generally minimal because:

- the sewage is much more dilute than usual because of the surface runoff/infiltration;
- the river is in storm flow conditions with maximum dilution available;
- both CSO and storm tanks offer a modest degree of treatment. CSOs usually have screens or some device to retain sewage solids. Storm tanks allow some settlement prior to discharge.

The effect of permitting sewage to discharge during storm events has been the subject of extensive research and has been found to have minimal impact, if properly modelled and designed. In summary, the approach to allow infrequent overflows is universal. Wherever there are sewage collection and treatment systems, there will be overflows of some sort, these are minimised as much as possible. The alternative is sewage flooding of land and/or property. Two CSOs in the By Brook catchment, near Box, are due for improvements under the AMP3 period and are scheduled for completion by March 2004.

Consented discharges with a maximum daily flow above 5 m^3/d or a DWF above 1.67 m^3/d are monitored on a regular basis by the Environment Agency to verify compliance with consent conditions. Samples are analysed e.g. for biochemical oxygen demand (BOD), ammonia and suspended solids. The frequency of the sampling depends on the size of the discharge (see Table 23). There have been no significant issues of water quality consent non-compliance in the By Brook catchment in recent years, and in the latest assessment (2000) all RQOs in the catchment were achieved (section 3.6, table 13).

Table 23 Discharge consent monitoring

number	location	frequency
	Sewage Treatment Works (public)	
010011	Burton STW	monthly
010054	Long Dean STW	monthly
010528	Box STW	2-weekly
011339	Marshfield STW	monthly
011590	Colerne STW	2-weekly
101513	Ford Deane (North Wilts)	quarterly
101512	Nettleton (North Wilts)	quarterly
	Consented discharges (private)	
021388	Bathford paper mill	monthly
021672	Tormarton rest area	quarterly
012814	White Hart PH	quarterly
012509	RAF Rudloe Manor	2-weekly
011502	The Salutation Inn	quarterly

4.7 Other potential sources of pollution

Motorway runoff

Samples were taken from various points of motorway drainage into the Burton Brook in 1998 on an ad hoc basis following rainfall events. Analysis of samples showed there is no evidence to suggest any water quality deterioration from this source.

Farmyard pollution

The Agency has undertaken a campaign of farm visits in the Broadmead Brook to evaluate the quality issue there as mentioned in the LEAP (Action 7.7.2). Most, if not all, farms in the catchment (approximately 20) were visited. A number of farms were identified that could have been causing occasional trickles of brown water to enter the watercourse. Improvements were warranted at two of the farms on the Broadmead Brook and these have since been made. For the most part, however, there were very few problems identified.

Septic tank overflow
Several comments have been received in the past that septic tanks in Pennsylvania, at the head of the catchment, may be contributing to water quality issues. The absence of elevated ammonia concentrations in water quality samples at site Z4170202 suggests that this is not a significant problem and to date resources have not allowed this to be investigated further.

Diffuse pollution from agricultural land
It is recognised that diffuse pollution from agricultural land is an issue for the By Brook catchment, however it is also very difficult to resolve. 'An Integrated Strategy for Diffuse and Point Source Pollution' for North Wessex Area has recently been written, with a view to specifically addressing the issue of diffuse pollution in North Wessex Area. The extent of the problem (in North Wessex) and a list of target catchments and actions (based on RQO failures) is currently being drawn up and prioritised. It is likely, that any future resources for diffuse pollution work will be targeted towards catchments with RQO failures, since this is the key performance target for Water Quality. The need for a full nutrient budget for the Bristol Avon has been identified as the next step forward for this catchment in the strategy. Greater awareness and the adoption of best management practices is the key to reducing this pollution source, and is an area where residents of the By Brook can contribute.

Reported incidents
The Agency has a duty to deal with all incoming reports of pollution incidents. Records are kept of all incidents and the follow-up. Recently, there have been cases of oil pollution, which have been traced to their origin and resolved.

4.8 On-going improvements to water quality

Several projects to improve to water quality in the catchment have been made and are planned for the future. Examples are:

1. The impact from Marshfield STW has been reviewed by the Agency as identified in the LEAP (Action 7.1.6). As a result of this and our ongoing liaison with Wessex Water, capital improvement is being carried out under AMP3, which will be completed by March 2004, and will allow this STW to meet strict Ammonia, BOD and SS consent conditions.
2. Following liaison with North Wilts DC two old STWs (Ford and Nettleton) will be replaced with modern sewage treatment units in early 2002, which will provide a much better level of treatment.
3. Two CSOs in the Box area are due for improvement under AMP3 and will be completed by March 2004.
4. Liaison with Colerne Airbase re. oil pollution (resolved by better on-site operating practices).
5. At Slaughterford Paper Mill, a potential flood and pollution hazard of 700 tonnes of waste paper was removed from site.
6. Following non-compliance with consent conditions in 1998, improvements have been made to the waste treatment system at the White Hart PH by the new owner in summer 1999, after which all samples have passed the tests.

7. Environment Protection Officers carried out a number of farm visits in 1999 in order to investigate farm effluent containment facilities and spreading methods to help us assess their impact. Agricultural inputs may be diffuse or point sources or most likely a combination of both. There have been further investigations into farm inputs as well as follow-up farm visits in summer 2000.

8. When resources allow, an investigation is planned to determine whether the unsewered population of Pennsylvania is impacting on water quality in the Broadmead Brook.

9. The need for a full nutrient budget of the Bristol Avon has been identified and will be carried out when resources become available.

4.9 Conclusions: water quality

Water quality objectives in the By Brook and its tributaries are in the highest grade (RE1 – very good) except in three stretches. Monitoring of water quality has shown that these objectives were historically achieved in most stretches, but not all. Due to the very low or zero summer flows on the Burton Brook and sewage discharges on the Doncombe Brook the RQO is RE2 (good), which was achieved in 2000.

There have been many improvements negotiated with dischargers, and improvements in the quality of discharges is already being demonstrated by helping to achieve RQO compliance last year. However, a considerable part of current pollution levels originates from farmland as diffuse pollution, a problem which is much less easy to solve sustainably than the point pollution from sewage treatment works or pollution incidents. This, as well as improved private waste water disposal operation, is an area where best management practices need to be applied. There are opportunities here for the residents of the By Brook valley to contribute to water quality improvements.

5. Impact on Stream Flow Due to Abstraction in Neighbouring Catchments

5.1 Introduction

Concerns have been raised that groundwater abstraction outside the By Brook catchment could reduce flow in the By Brook by intercepting groundwater that would have otherwise discharged to the By Brook via springs and as baseflow. Six large abstraction sources for public water supply and stream support are located to the east and north of the catchment which could potentially impact flows in the upper section of the By Brook. There are a further three major abstractions which lie to the south of the By Brook catchment (175301G405A / B / C), however these have not been considered here since they are too far south to potentially impact flows in the Upper By Brook. The location of the six sources to be assessed, their historical usage and the aquifer they utilise are detailed in Section 5.2. The hydrogeological setting of the abstraction sources is assessed in Section 5.3 to determine whether the abstraction could impact flow in the By Brook. The assessment particularly addresses whether the perceived derogation in flow described by FOTBV in the early 1990's can be attributed to these abstraction sources.

5.2 Abstractions outside the catchment

The location of the six abstractions to the east and north of the catchment are shown on Map 4 with a summary of licence details presented in Table 24.

5.2.1 History of Abstraction

The commencement of abstraction and any changes in abstraction rate for the six sources are detailed below.

Goodshill
Goodshill is licenced to abstract 500 Ml/year (2.5 Ml/day) and was used throughout the 1970's for public supply. Actual abstraction ceased at the end of 1979 and has not been operated since, but the licence is still in existence.

Lacock
The boreholes at Lacock have been used for supply since 1976. The daily licenced abstraction 9.1 Ml/d (which equates to 277 Ml/month) is equivalent to a flow of 105 l/s. The available monthly abstraction returns from 1980 to 2000 are plotted on Figure 15[1]. Figure 15 shows that the full licensed quantity is not normally taken, with the abstraction rate typically 125 Ml/month (125,000 m^3/month) pre 1994 and ~200 Ml/month post 1994.

Chippenham (Ivyfield)
Abstraction for public water supply has been occurring at Ivyfield since before 1970. The daily licensed abstraction 18.7Ml/d (which equates to 567Ml/month) is equivalent to a flow of 216 l/s. The available monthly abstraction returns from 1980 to 2000 are plotted on Figure 15[1]. Figure 15 shows that the full licensed quantity is not normally taken, with the

[1] The gaps shown for Dec 1996- March 1997 in this figure are due to missing data, and do not represent the absense of abstraction in these months.

abstraction rate typically fluctuating between 250 and 500 Ml/month. A decline in abstraction rates is observed since 1994 to a fluctuation of between 100 to 400 Ml/month. The combined (Lacock and Ivyfield) abstraction rate shows no discernible trend in the level of abstraction.

Lower Station St Quinton (LSSQ)
Abstraction from the Great Oolite aquifer at LSSQ for stream support (Rodbourne Brook) commenced in 1982 and is licenced for 2.5 Ml/day (900 Ml/year). The monthly abstraction returns from 1982 to 2000 are shown in Figure 16 (Ml/month). Annual abstraction volumes are shown on Figure 17: individual total and annual cumulative total, including Luckington and Hullavington. Annual abstraction rates typically fluctuate between 100 and 525 Ml/year, which is just over half the licenced quantity.

Table 24 Major Abstraction Licences - East and North of By Brook

Name	Licence No	Holder	Purpose	Aquifer	Daily Quantity (Ml/d)	Annual Quantity (Ml)
Goodshill	17/53/01/G/201	WW Plc[1]	PWS (ceased in 1979)	Great Oolite	2.5	500
Lacock	17/53/01/G/415	WW Plc[1]	PWS	Great Oolite	9.1	3320
Ivyfield (Chippenham ASR)	17/53/01/G/207	WW Plc[1]	PWS	Great Oolite	18.7	6820
LSSQ[2]	17/53/1/G/410K[3]	WW Plc[1]	Stream support	Great Oolite	2.5	900
Hullavington	17/53/1/G/410J[3]	WW Plc[1]	Stream support	Inferior Oolite	2.5	900
Luckington	17/53/1/G/410G[3]	WW Plc[1]	Stream support	Inferior Oolite	2.5[4]	900

Note:
[1] Wessex Water Plc.
[2] Lower Stanton St Quinton.
[3] Currently operating via Section 32(3) Consents (see Glossary).
[4] Under the current 32 (3) Consent the daily licenced quantity has been increased by 7.5 Ml/d to 10Ml/d

Hullavington
Abstraction from the Inferior Oolite aquifer for stream support (Gauze Brook) commenced in 1978. The monthly abstraction returns from 1978 to 2000 are shown on Figure 16. The annual abstraction totals are plotted on Figures 17. The maximum annual abstraction achieved was 400Ml in 1990, less than half the permitted quantity. The stream support abstraction operates to ensure river flow targets are met at specified gauging points, consequently abstractions occur for longer in 'low' recharge years, such as 1990.

Luckington
As for Hullavington, the abstraction from the Inferior Oolite aquifer for stream support at Luckington (Luckington Brook) commenced in 1978. The monthly abstraction returns from 1978 to 2000 are shown on Figure 16. The permitted daily rate of abstraction of 2.5Ml/d was increased to 10Ml/d from 1995 onwards for testing purposes during stream support trials for the Malmesbury groundwater investigations. An abstraction of 10Ml/day is equivalent to a continuous flow of 116 l/s. The annual abstraction totals are plotted on Figure 17. In 1996,

~1,000Ml was abstracted, though typically through the 1990's the annual abstraction total was less than 300Ml. Higher rates of abstraction occurred in 1998 and in "low" rainfall years (1990, 1995 and 1996).

5.3 Impact Assessment

5.3.1 Introduction

In order to assess impact, the six sources have been divided into two groups: public water supply (PWS) sources (all year round) and stream support abstractions (seasonal). There is also a hydrogeological rationale for the division, as the PWS sources are located to the east of the catchment and obtain water from the confined Great Oolite aquifer, whereas the stream support abstractions are located to the north and with the exception of LSSQ (Great Oolite), take water from the Inferior Oolite.

5.3.2 Public Water Supply Sources

To assess the potential for impact the following approach is taken in this section:

- Determine the hydraulic mechanism for impact.
- Assess the sensitivity to impact.
- Assess the likelihood of occurrence.
- Conclusions.

Mechanism

These sources (Goodshill, Lacock and Ivyfield) obtain water from the confined Great Oolite to the east of the By Brook catchment. The Great Oolite rises up dip to the west of the abstraction boreholes outcropping partly within the By Brook catchment along the eastern valley side. Several springs and seepages are known to issue from the Great Oolite along the eastern valley side, which discharges into the By Brook.

Abstraction from the confined Great Oolite aquifer could reduce the outflow from springs draining the unconfined outcrop area of the Great Oolite into the By Brook, hence reducing flow in the By Brook. Flow in the tributaries (Burton Brook and Broadmead Brook) draining the western side of the catchment cannot be impacted by the PWS abstractions as erosion by the Brook exposing the Fuller's Earth has hydraulically divided the Great Oolite into two separate units, either side of the By Brook.

Sensitivity to Impact

Stream flow data has been examined to quantify the contribution to flow in the By Brook provided by springs and seepages along the east side of the valley, upstream of Ford. This information will allow the importance of this flow to be assessed and therefore the sensitivity of any loss of flow.

Data from the 1998-1999 spot gauging exercise has been used. Monthly spot flow data is available for the following sites (Appendix 7):

- Burton Brook - prior to confluence with Broadmead Brook.
- Broadmead Brook - prior to confluence with Burton Brock.
- By Brook at Ford - prior to confluence with North Wraxall Stream.

The flow in the By Brook measured at Ford is a sum of the:

- Flow in the Burton Brook.
- Flow in the Broadmead Brook.
- Gain in flow in the By Brook between the confluence of the Burton and Broadmead Brook (Golf Club) and Ford (3 km reach).

The contribution of each tributary and reach of the By Brook provides the total flow at Ford during 1998 and 1999 and is shown on Figure 18. Figure 18 presents the data in litres per second, the same data is also presented as a percentage contribution.

It can be seen that between 72% and 86% of the flow at Ford is due to the flow in the Burton and Broadmead Brook (western side of the By Brook, draining the Great Oolite). On average the By Brook reach, upstream of Ford, provides 23% of the flow in the By Brook measured at Ford.

The Great Oolite outcrops either side of the By Brook reach upstream of Ford, therefore, the 23% gain in flow is a combination of flow from the eastern and western portion of the Great Oolite in the By Brook catchment (see section 3.4). It is considered a reasonable starting assumption to estimate that the 23% gain is sourced equally from the two portions of the Great Oolite. In reality the catchment area to the west is greater than to the east, therefore, the gain from the east will be less than 10%.

It is noted that abstraction at Lacock and Ivyfield was ongoing during the 1998-1999 monitoring period, therefore, if an impact is occurring the contribution from the eastern portion under natural conditions would be greater. This influence is considered below.

Figure 18 shows that during the winter months (flows >500 l/s at Ford) the contribution from the By Brook reach averaged 21.4% (approximately 10.5% from the eastern portion). If the PWS abstractions were causing an impact, it is reasonable to assume that winter recharge would reduce this effect to a minimum, i.e. groundwater levels have risen, reducing the drawdown induced by the PWS abstraction. Hence the winter contribution from the eastern portion of the Great Oolite, with the potential impact from abstraction at its minimum, remains similar to the overall average.

It is concluded that the eastern portion of the Great Oolite contributes less than 10% of the flow in the By Brook at Ford. Therefore, the maximum possible reduction in flow due to the PWS abstraction is less than 10% of the flow at Ford.

Likelihood of Occurrence

The most northerly PWS borehole, hence closest borehole to the upper reach of the By Brook is Ivyfield. Ivyfield has the largest permitted abstraction rate and has been abstracting from the Great Oolite since before 1970. Consequently Ivyfield potentially poses the greatest threat to the By Brook.

Although the Ivyfield PWS is the closest borehole to the Upper By Brook, it is located ~7km east of the By Brook at Ford. As detailed in Table 24 the Ivyfield PWS obtains water from the confined Great Oolite. Following a review of aquifer properties (BGS 1997) the BGS concluded that abstractions from the confined Oolite aquifer take only a small percentage of water from the unconfined aquifer with most of the yield supplied by vertical flow through the overlying confining beds, with a small contribution from confined storage. Given that the

Ivyfield abstraction is located 7km from the outcrop area it is concluded that the vast majority of the yield will be obtained from vertical leakage near the borehole.

An examination of long term trends and whether water levels are being lowered by PWS abstractions, (which could result in a gradual worsening of flows in the By Brook) can be found below.

The Environment Agency has a long record (1974 – to present) for the observation borehole monitoring the Great Oolite aquifer at Allington (No 1) located 2.5km north-west of Chippenham, up dip of the abstraction (see Maps 1 & 2). The hydrograph for Allington is shown on Figure 19 and Appendix 4. Also plotted on Figure 19 are the effective rainfall (MORECS[1]) totals in water years for Oct 1974 – Sept 2000. The vertical grid lines on Figure 19 mark the start of October and show that water levels typically start to rise with the onset of winter rains in October. It should be noted that abstraction from the Ivyfield site was already occurring when monitoring began at Allington in 1974, meaning that there is no opportunity to assess the 'before and after' impact of this abstraction.

Figure 19 shows a close relationship between annual effective rainfall (recharge and runoff) and groundwater in the aquifer, for example the below average effective rainfall totals in 90-91 and 91-92 result in the lowest groundwater since 1976. The following three years of above average effective rainfall results in the annual maximum and minimum water level rising year on year. Therefore the 26 year record shows no long term trends i.e. no evidence of unsustainable abstraction.

Conclusions

These PWS abstractions have been occurring for over 25 years at a reasonably constant rate, therefore, their 'impact' on the water environment is well established. The hydrograph for Allington shows no long term trend of decline, but does show a close relationship between effective rainfall and groundwater level.

Analysis has shown that the maximum impact these abstractions could impart is less than 10% of the flow at Ford. However, more importantly, examination of the recharge mechanism for these boreholes concludes that the likelihood of a measurable impact occurring is low.

Following analysis of river flow and groundwater level records, and the hydrogeological setting of the boreholes, it is concluded that these abstractions are not responsible for the low flows in the By Brook observed in the 1990's and are unlikely to have significantly exacerbated these low flow conditions.

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[1] See Glossary

5.3.3 Stream Support Boreholes

Mechanism

The LSSQ borehole obtains water from the Great Oolite aquifer and is located ~7km north east of the By Brook topographical catchment divide. Abstraction from the borehole could move the groundwater catchment divide between the By Brook and Malmesbury Avon, such that less water from the Great Oolite aquifer flows into the By Brook. Test pumping and monitoring detailed below is ongoing to establish whether the stream support boreholes at LSSQ would impact the By Brook (see also Section 7.2)

The Luckington and Hullavington boreholes abstract water from the Inferior Oolite aquifer. As detailed in Section 3.3 the Inferior Oolite outcrops in the By Brook Valley downstream of Ford. The overlying lower part of the Fuller's Earth is predominately clay and forms a confining layer between the Great Oolite and overlying Upper Fuller's Earth and Great Oolite aquifer. Therefore, abstraction from the Inferior Oolite should not impact the upper reach of the By Brook (upstream of Ford), the focus of low flow concerns. However, as detailed in Section 3.3, faulting, if present, may provide a route for hydraulic connection between the Inferior Oolite aquifer and the Fuller's Earth/Great Oolite aquifer. If this recharge mechanism exists then stream support boreholes could intercept baseflow to the By Brook. Test pumping and monitoring outlined below is designed to establish how the stream support boreholes receive recharge e.g. from storage and/or leakage from the Fuller's Earth/Great Oolite.

Sensitivity to Impact

The current authorisations permit the abstraction of 15 Ml/day from the three stream support boreholes, equivalent to a flow of 174 l/s. The nearest watercourse in the By Brook catchment to the abstractions is the Burton stream. Figure 20 shows that in 1998, summer flows in the Burton Brook were ~25 l/s, which is equivalent to 14.4% of the maximum stream support abstraction total. 1998 was a relatively wet year, so flows would be lower in drier years. Therefore, it is estimated that if 10% of the stream support abstraction is taken from the Great Oolite aquifer which drains to the By Brook, then a significant impact on flows in the By Brook would occur. The head water flows in the By Brook are small compared to the size of the stream support abstraction, therefore the By Brook would be sensitive to an impact from the abstractions.

Likelihood

Until the hydrogeology and recharge mechanisms are fully understood it is not possible to confirm the likelihood of an impact. Two new boreholes are being installed in Autumn 2001 between Luckington and the By Brook. It is intended that this will enable us to establish recharge mechanisms and confirm the impact of abstraction for stream support on the By Brook.

Initial findings suggest that the risk of exacerbating natural low flows is low due to the following points:

i. Our initial testing has shown evidence of leakage between the Great Oolite and Inferior Oolite, the implications of which would suggest that the cone of influence to the abstraction borehole is restricted to the Sherston Avon catchment.
ii. The seasonal nature of the abstraction and the separation distance between the borehole and By Brook will restrict impact.

iii. The lower Fuller's Earth is an aquitard, restricting leaking, though faulting may increase the leakage quantity, however, faulting is less common in the southern part of the Malmesbury-Avon catchment.

Evidence in partial support of point (ii) is obtained from the spot gauging flow data collected for the Burton Brook and Broadmead Brook during 1998 and 1999. The gauging data is presented on Figure 20, also plotted on the figure are the monthly stream support abstraction totals. Apart from a small quantity abstraction from LSSQ in July, stream support commenced in August 1998. The abstraction rate during August, September and October 1998 averaged ~ 330 Ml/month (125 l/s). The stream hydrographs show no discernible change in the rate of recession once abstraction has started. Rains in September cause flow in the Burton Brook to rise and slows the rate of recession in the Broadmead Brook. No impact on the rate of flow recession is observed during 1999, though abstraction rates were much lower averaging ~135 Ml/month (50 l/s) due to the "wet" summer.

1998 and 1999 received above average rainfall and effective rainfall total, consequently stream support abstraction did not commence until July/August. No impact was observable in an "above average" recharge year. Further testing is required and is ongoing to assess whether an impact could occur in a "low" recharge year when stream support abstraction commenced earlier in the year and at higher abstraction rates.

Conclusion

The currently available data indicates that the risk of impacting the By Brook is low. However, the installation of two further boreholes monitoring groundwater levels in both the Inferior and Great Oolite will provide valuable information, to prove or disprove these initial findings. Installation is planned for the Autumn 2001, but it will not be until 12 – 18 months later that we will have gained any meaningful data and can start to draw initial conclusions.

6. Conclusions

This report has sought to answer concerns from members of the public regarding low flow and water quality problems in the upper reaches of By Brook during the 1990's.

6.1 Low Flow and Water Quality issues

The study has identified seven possible causes of Low Flow and Water Quality problems in the By Brook catchment:

1. Abstraction (groundwater and surface water) within the catchment.

2. River control structures - sluices and weirs.

3. Abstraction for public water supply outside the catchment.

4. Abstraction for stream support outside the catchment.

5. Climatic variability.

6. Septic Tanks and Diffuse Agricultural Pollution

7. Discharges from Sewage Treatment Works

Data has been provided on each of the seven possible causes and an assessment of the likelihood that they could be a principal cause of low flows or poor water quality. A summary of the conclusions reached is given below:

6.1.1 Abstractions within the catchment

There are only two licensed abstractions greater 0.05Ml/d present in the upper reach of the By Brook. One licence authorises spray irrigation directly from the By Brook and could therefore significantly affect flows. However, this is a winter only abstraction and a prescribed flow condition ensures abstraction ceases when flow in the Brook fall below 288 l/s and the abstraction cannot therefore contribute to low flows.

The second licence, for West Kington Nurseries, takes groundwater from the Inferior Oolite. The study shows (section 4.3.1) that groundwater within the Inferior Oolite is unlikely to be in hydraulic continuity with spring discharges and baseflow to the By Brook above Ford. The By Brook above Ford is principally fed by springs and baseflow from the Great Oolite and hence the West Kington Nurseries abstraction is not likely to impact flow in the brook. The abstraction is in any case relatively small representing <10% of the Q_{95} in an average year.

There is also one PWS abstraction licence in the lower reaches of the By Brook below Ford. Analysis of returns data shows that the abstracted volume compares to an average of 2.1% of monthly flows in the By Brook, and is therefore insignificant. In periods of extremely low flow, the impact can be greater (up to 9% of flows in August 1995). However in events such as these, an abstraction of this order is not deemed unacceptable for the purposes of securing public water supplies at this site.

It is concluded that abstractions within the catchment are not the principal cause of low flows in the 1990's and are unlikely to have significantly exacerbated the problem.

6.1.2 Sluices and Weirs

Manmade control structures creating impoundments can cause a reduction in river flow due to increased evaporation and leakage. However, it is concluded that the volume of flow loss is relatively low and therefore the structures are unlikely to be the principal causes of low flow but may have marginally exacerbated the problem. Structures that impound reaches of river can have an adverse effect on the river ecology due to reduced velocity and increased sediment deposition. An increase in water depth can also have a significant impact on the occurrence of species that require shallow water, such as Water Crowfoot.

6.1.3 Abstraction for PWS Outside the Catchment

The two current PWS abstractions, located to the east of the By Brook catchment, have been occurring for over 20 years at a relatively consistent rate. Their impact on the water environment is therefore established and there is no evidence that the impact of the abstractions on groundwater levels and spring discharge was any greater in the 1990's and hence they are unlikely to be the principal cause of the low flows.

In addition, the study has shown that due to their hydrogeological setting the abstractions are unlikely to have a significant impact on flows in the By Brook. The boreholes are located at least 7km to the east of the brook and are in a different groundwater catchment. Water from this catchment discharges to the east of the boreholes instead of the By Brook. Analysis has shown that the maximum theoretical reduction in flow at Ford is likely to be considerably less than 10% of the flow.

It is therefore concluded that these abstractions were not the cause of the low flows and are unlikely to have significantly exacerbated the problem.

6.1.4 Abstraction for Stream Support outside the catchment

Three abstractions for stream support have been occurring to the north of the By Brook catchment since 1978, with a marked increase during the 1990's to support low flow in the Malmesbury Avon catchment. The study has identified that there is currently insufficient data and analysis to state categorically whether these abstractions are likely to be the cause of low flows in the By Brook in the 1990's. However they are very large abstractions in comparison to summer flows in the upper By Brook, with a total abstraction equivalent to 174 l/s. Even if they derive a small proportion of their flow from the By Brook catchment they represent a significant potential impact.

Notwithstanding the size of the abstractions it is concluded that, based on the current understanding of the catchment, these abstractions are unlikely to be the principal cause of low flows. This is because the abstractions are principally from the Inferior Oolite formation which is thought to be at least partially hydraulically isolated from the Great Oolite, the principal source of flow in the By Brook, by clayey strata. This assumes that faulting in the By Brook does not provide significant hydraulic continuity between the Great and Inferior Oolite formations. The Environment Agency is currently undertaking further assessment into the source of water to these boreholes, as part of an assessment of the Malmesbury Avon catchment. This will provide a greater understanding of the potential impact on flows in the By Brook.

In summary it is concluded that, although at present there is insufficient data to be categorical regarding the impact of these boreholes, it is unlikely that they were the principal cause of the low flows in the By Brook in the 1990's. The installation of two additional boreholes between the By Brook and Malmesbury Avon in autumn 2001 will provide valuable information about recharge mechanisms and allow a better understanding of the potential impacts from stream support abstraction boreholes in the Malmesbury Avon catchment.

6.1.5 Climatic Variation

Analysis has shown that flows in the upper By Brook are very responsive to rainfall due to the transmissive nature of the Great Oolite aquifer that provides base flow to the brook. Although a summer base flow occurs from the Great Oolite via springs, a 'healthy' summer flow is maintained only by regular rainfall throughout the summer months.

Examination of rainfall and effective rainfall data shows that the early1990's had particularly low recharge; three years in the 1990's being in the top five of the lowest effective rainfall totals in the last 25 years. Rainfall during these summer periods was particularly low. Conversely, the 1990s have also seen particularly high rainfall (>115% Period Average), so it follows that there is a significantly higher variation in the annual rainfall for the period 1991-2000 than that seen in the previous decade (1981-1990).

It is concluded that based on the current understanding of the hydrology and hydrogeology of the By Brook catchment, low rainfall due to climatic variability was the principal cause of the low flows observed in the By Brook during the early 1990's. There is however still uncertainty regarding the influence of the stream support boreholes in the Malmesbury Avon catchment. Further work is currently being undertaken by the Environment Agency to confirm the impact of these abstractions. Climatic variability and the natural occurrence of dry years are also thought to contribute to water quality and ecological problems, particularly in extremely dry events.

6.1.6. Septic Tanks and Diffuse Agricultural Pollution

River Quality Objectives (RQO) are defined for 10 stretches in the By Brook catchment, seven of which are set at RE1 (very good quality) and three stretches at RE2 (good quality). Water Quality samples taken at monthly intervals for the last 5 years have shown a steady improvement in compliance with these objectives, and in 2000 all ten stretches were compliant or exceeded the relevant RQO. The assessment of river quality in terms of biology largely supports the chemical analysis, i.e. most stretches obtaining an 'a' grade (very good quality) with the exception of those near to STWs.

Historic failures were thought to be a combination of septic tanks, agricultural pollution and summer low flows. The absence of elevated ammonia concentrations suggests that the septic tanks of West Kington and Pennsylvania were not causing a significant problem and would not have been the reason for historical failures. However lower water quality could have been caused by farmyard runoff, diffuse pollution from agricultural land and low summer flows.

Most farms in the catchment have been visited by Agency officers and at two farms improvements were made to potential sources of farmyard pollution. The climatic variation identified above could have caused low summer flows in the past, which in turn could have impacted water quality. This is a natural phenomena and it is therefore very difficult to provide protection for this type of extreme event.

It is concluded that diffuse pollution from agriculture remains a significant cause of water quality issues in the catchment, although there are no current RQO failures in the catchment. Diffuse agricultural pollution is not easily solved and North Wessex Area has recently produced 'An Integrated Strategy for Diffuse and Point Source Pollution' in order to facilitate further work on diffuse pollution. RQOs are a key performance indicator for water quality and therefore the strategy has prioritised future resources on work in catchments where RQO failures occur. The need for a full nutrient budget of the Bristol Avon was identified in the strategy, this will be carried out as soon as resources allow. Best management practices need to be applied to agriculture and private waste water disposal in the catchment. This is an area where the residents of the By Brook have the opportunity to contribute to water quality improvements.

6.1.7 Discharges from Sewage Treatment Works

All consented discharges with a maximum daily flow above 5 m^3/d or a DWF above 1.67 m^3/d are monitored for quality on a regular basis by the Environment Agency, there have been no significant issues of consent non-compliance in the By Brook in recent years. However, the impact of Marshfield STW was identified as a LEAP action in the past and as a result capital improvement under AMP3 will be completed by March 2004.

The Agency has also undergone liaison with North Wiltshire DC regarding improvements to two small STWs at Ford and Nettleton. As a consequence, two modern sewage treatment units will be installed in early 2002, which will replace the previous units and provide a much improved level of treatment.

The study considered the impact of Combined Sewage Overflows (CSOs) and found that if properly modelled and designed CSOs have a minimal impact on water quality. There are a number of CSOs within the By Brook catchment two of which are due for improvements during the AMP3 period (2000-2005).

In summary, water quality in the By Brook has been influenced by a combination of pollution sources in the past, namely STW discharges, farmyard pollution and diffuse agricultural pollution. It is likely that these impacts were further exacerbated by low summer flows caused by climatic variation. Many improvements have been negotiated with dischargers in the last few years, the results of which are beginning to be seen in the RQO assessment results.

6.2 Increased Flashiness of the By Brook

Concerns were also raised over the perceived increased flashiness of the By Brook and the potential impact of the M4 motorway which borders the north of the catchment. Since the start of the flow record at Middlehill in 1982, no increase in flashiness could be detected using Base Flow Indicies and Spring Recession curves. Unfortunately it has not been possible to analyse the impacts of the construction of the M4 as there is no historical flow data available. It is noted however, that the degree of flashiness seen on the By Brook is not outside that that would be expected for a catchment with these hydrogeological characteristics. The Environment Agency has a policy of encouraging sustainable urban drainage where possible and any future proposals for works on the M4 would be subject to this policy.

7. Future Actions

7.1 Progress with agreed actions (Halcrow's recommendations)

The review of proposed action (Appendix 1) shows that on most points the Agency has completed the proposed investigations. In many cases more was done than proposed: the spot gauging campaign was extended from 6 to 18 months, BFI analysis of flows was performed as well as recession analysis, the macrophyte survey was repeated in 1999, a macro-invertebrate survey was added, farm pollution was investigated and advice was given. The information presented on water quality is outside the original scope of the investigations, but included because it was a major concern of the FOTBV. Where no further work was done (effective precipitation/water balance) this is due to the absence of sufficiently detailed data close enough to the catchment. This cannot be solved retrospectively.

7.2 Future actions

This study has considered all aspects of concern regarding low flows and water quality within the By Brook catchment. A summary of work which is planned to continue is listed below:

By Brook residents:

- conservation actions for riparian landowners: (see Wiltshire Wildlife Trust brochure – 'River Habitats for Wildlife').
- best practices for land use: advice may be obtained from local FWAG (Farming and Wildlife Advisory Group) officers at the County Council, or from DEFRA (Department Environment, Food and Rural Affairs).
- action on all sewage plant owners to respect schedule of operation & maintenance.
- consider the removal or changed operation of sluices for the benefit of the By Brook ecology (advice available from the Environment Agency)

Environment Agency:

- installation of two new observation boreholes and monitoring of groundwater levels in the Inferior and Great Oolite between the By Brook and Malmesbury. Data to be reviewed in 2003;
- continued monitoring of groundwater levels & review of network in 2003;
- continued surveillance of abstraction licences;
- continued operation of Middlehill and Ford flow measuring stations;
- inclusion of suitable rainfall observer sites in Met Office network;
- continued application of usual water quality procedures (STW sampling, WQ monitoring, response to incidents);
- the need for nutrient budget work (model) on the Upper Bristol Avon has been identified and will be carried out when resources become available;
- *an investigation into the impact of the unsewered population of Pennsylvania has also been identified, however, at the present time resources are being targeted at higher priority catchments in line with the North Wessex Diffuse Pollution Strategy.*

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