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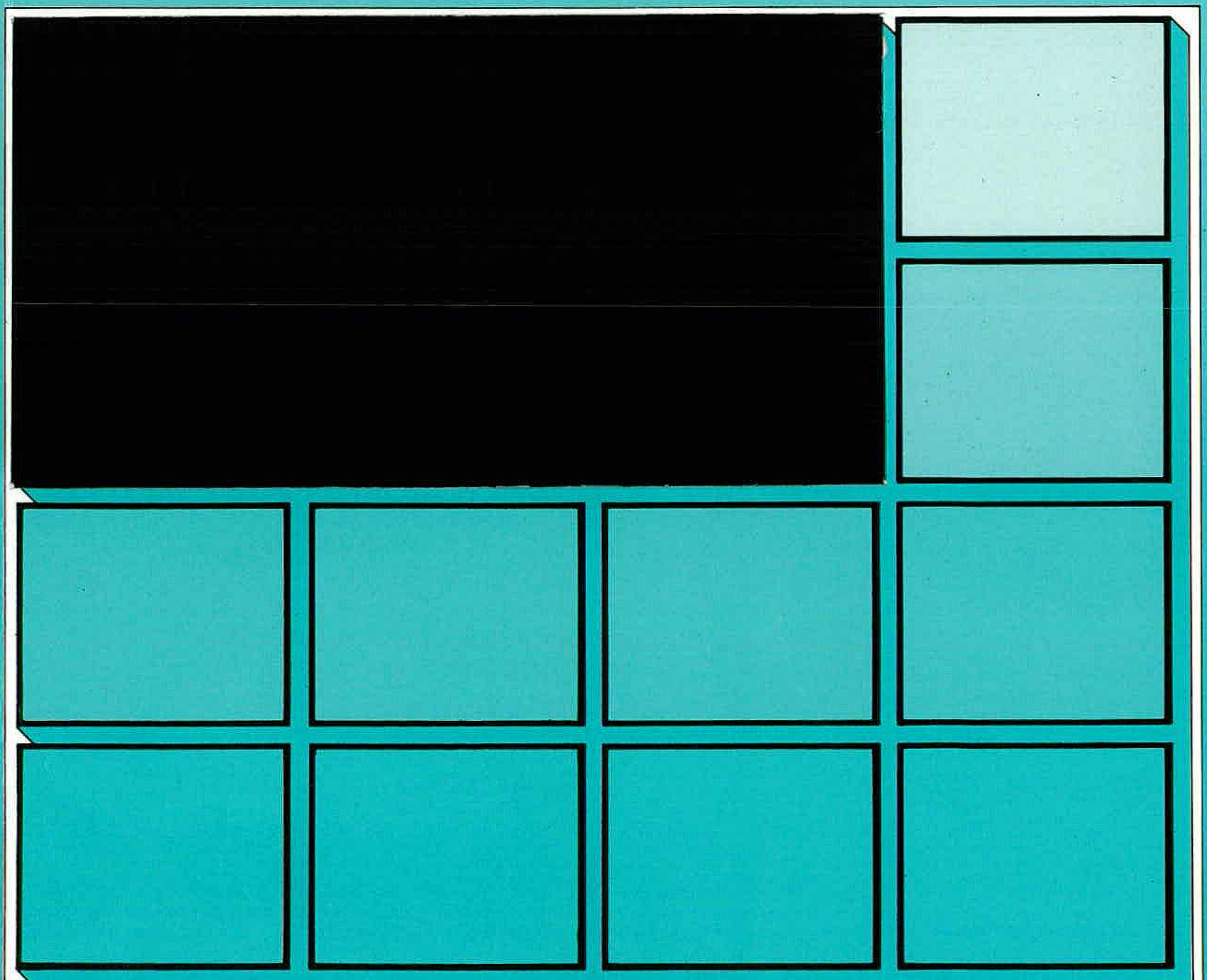

July 9, 1990

Hydrological studies of West Sedgemoor 1989-1990

Report prepared for
Wessex Region of the
National Rivers Authority

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1 INTRODUCTION

The consumptive use study of West Sedgemoor was commissioned by the Wessex Rivers Division of the Wessex Water Authority (now NRA-Wessex). The findings of this study were set out in a report prepared at the end of a three year investigation (Marshall & Gilman 1989[1]): data up to and including the 1988 calendar year were used in the 1989 report.

A 12-month extension to the study has made it possible to improve the results using 1989 data from the instrument network, and from additional raingauges. This report presents refinements of the estimates of evaporation made in the March 1989 report, and extends the original analysis by making use of data from the 1989 calendar year. The two reports are intended to be read in conjunction: the description of the Moor and its water regime, and of the installation of equipment, will be found in the March 1989 report, and will not be repeated here.

The climate over West Sedgemoor during the 1989 calendar year was unusual in some ways and very different from that in 1988. While the annual rainfall at the pumping station approximated well to the long term average of 650 mm, the proportion falling during January (3.6%) was close to the lowest on record, while that for December (20.1%) was close to the highest on record. In addition, the MORECS estimate of 700 mm potential evaporation for square 167 was 27% higher than the long term average, and rainfall in May and June, two months during which the water table falls rapidly, was very low (Figure 1.1). During 1988 the annual rainfall at 598 mm was less than the long term average, but this could be attributed almost entirely to low monthly rainfall totals in November and December (Figure 1.2).

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1 Marshall D C W & Gilman K (1989) Hydrological studies of West Sedgemoor, 1986 - 1989, Report to Wessex Rivers Division of Wessex Water Authority.

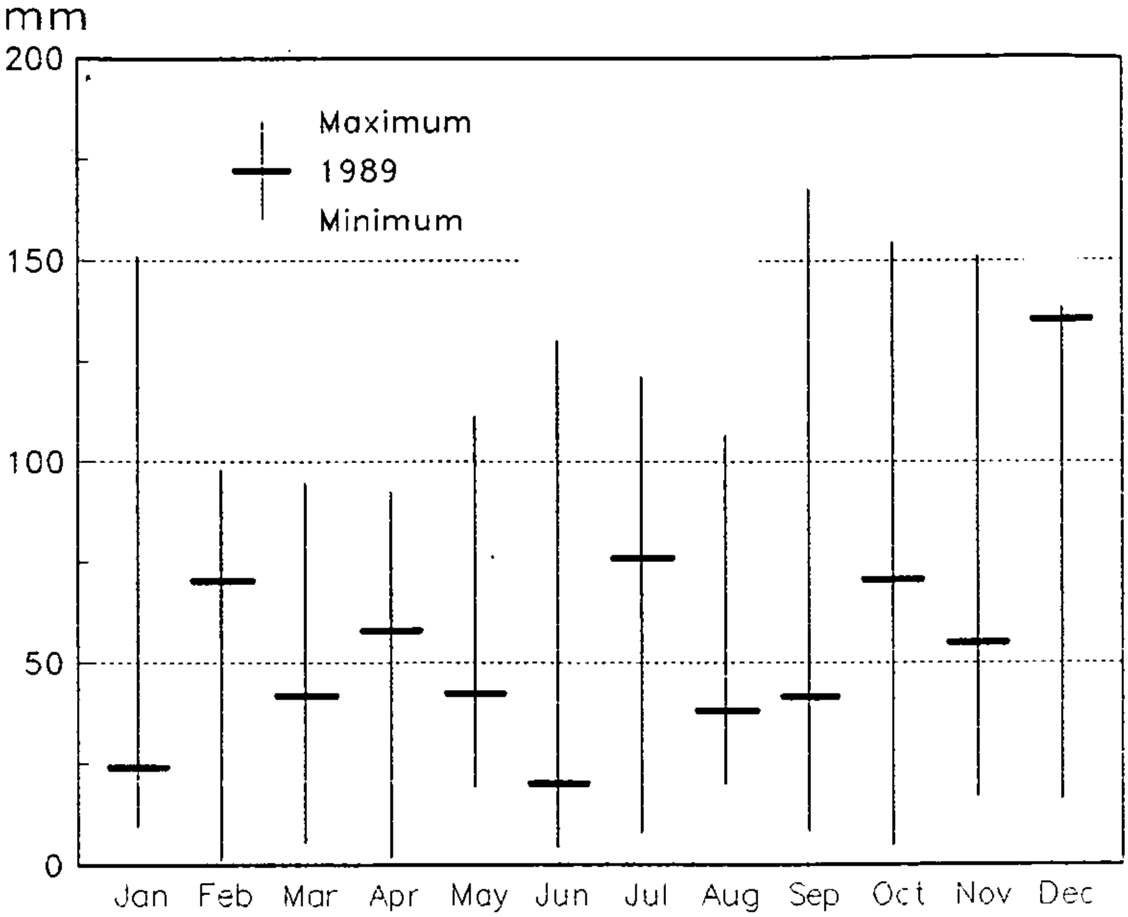

Figure 1.1 Monthly rainfall in 1989 compared with maximum and minimum over the period 1962 to 1989

The eight water level recorders on the rhynes, the IH raingauge and one of the two lysimeters ceased operation at the end of March 1989, and this report on West Sedgemoor will be the last to be primarily concerned with evaporation from the Moor. However, IH is contracted to submit a final report on West Sedgemoor to the Nature Conservancy Council (NCC) and Wessex Rivers during 1991, and other issues, notably ground surface movement and the control of field groundwater levels by water levels in the rhynes will be considered in that report.

As part of the original NCC/Wessex project, a borehole has been drilled through the superficial deposits at the end of Beercrowcombe Drove, to reach the underlying Keuper Marl. This borehole is to carry an aquifer compaction recorder which will give a continuous record of ground surface movement. In Section 5 of this report a stratigraphic interpretation of the borehole is given.

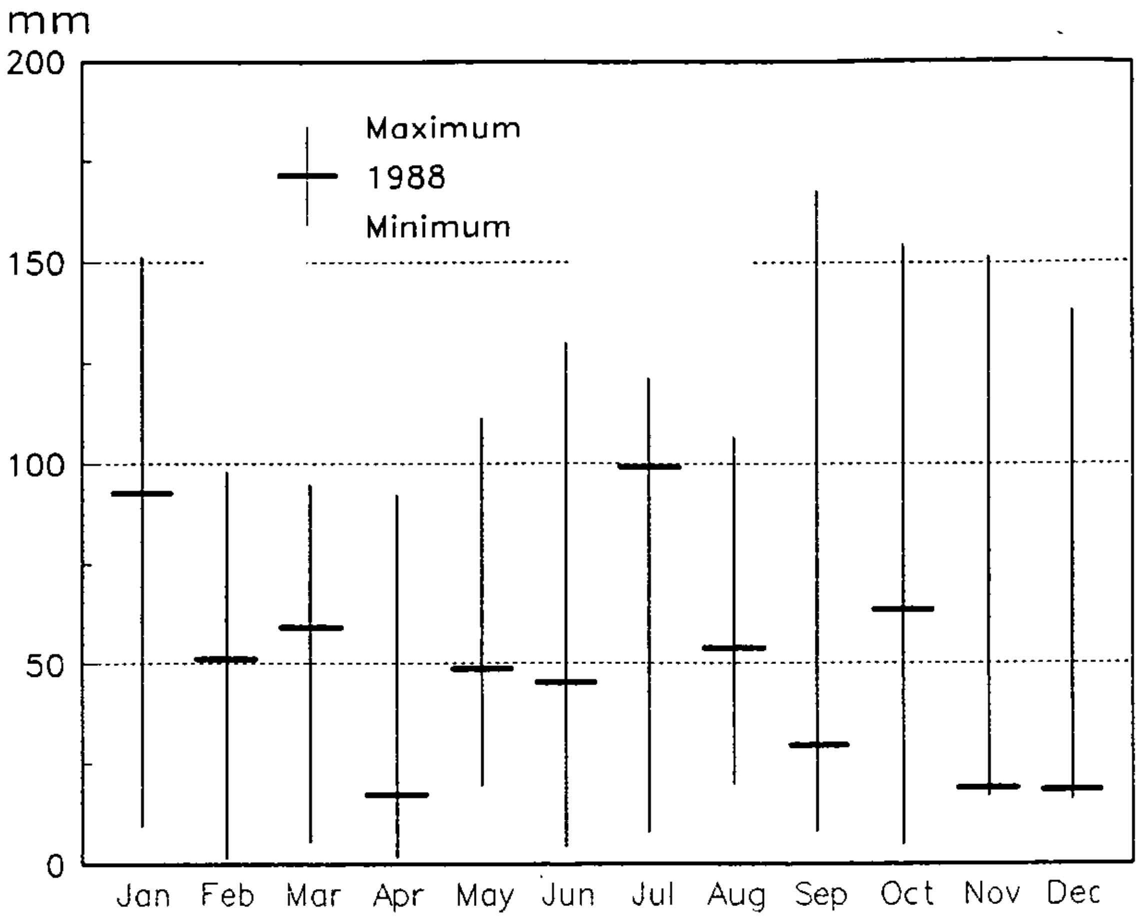

Figure 1.2 Monthly rainfall in 1988 compared with maximum and minimum over the period 1962 to 1989

2 WATER BALANCE STUDIES

In this section, the evaporation from West Sedgemoor is estimated using the water balance technique.

Sections 2.1 to 2.6 relate to the five inflows and one outflow and add to the discussion under these headings in the March 1989 report. However, much of the material in the early part of the corresponding sections of the March 1989 report does not need to be repeated here.

The calendar year 1989 is used for the analysis period, but in addition the analysis of the 1988 data contained in the March 1989 report (Section 2.10 of this report) is examined in the light of additional rainfall data, which lead to revised, more precise estimates of rainfall on the catchment. As in the previous report, the entire catchment to the pumping station is considered in three distinct zones:

(i) the 15.2 km^2 area above the NRA-Wessex streamflow gauging station at Helland

(ii) the 14.0 km^2 area of highland below the Helland gauging station; in the March 1989 report, this area was considered as a single entity but is now considered as two sub-areas.

(iii) the 12.8 km^2 area of flat Moor.

2.1 Rainfall over West Sedgemoor

During 1989, there were problems with the 15 minute recording raingauge operated by the Institute of Hydrology (IH) at grid reference ST 371270, which caused the loss of data over half the year. Although there is little difference between the rainfall at the IH site and that recorded at the West Sedgemoor pumping station, had the IH record been complete, it would have been more appropriate to use it, given that it is closer to the centre of the Moor.

A monthly relationship was developed allowing the prediction of monthly rainfall in mm at the IH site from that occurring at the pumping station:

Rainfall (IH) = 2.3 + Rainfall (WSPS)

This regression equation has been used to generate synthetic data to complete the record at the IH site and these synthetic values are indicated with an asterisk (*) in Table 2.1.

Table 2.1 Comparison between rainfall (in mm) at West Sedgemoor Pumping Station (WSPS) and that occurring at the IH site on the Moor

Month	WSPS	IH
Jan 89	24.2	27.0
Feb 89	70.6	72.5
Mar 89	42.1	47.0
Apr 89	58.2	63.0
May 89	42.5	41.0
Jun 89	20.1	22.4 *
Jul 89	76.1	78.4 *
Aug 89	38.1	41.0
Sep 89	41.7	44.0 *
Oct 89	70.8	73.1 *
Nov 89	55.1	57.4 *
Dec 89	135.6	137.9 *
Total	675.1	704.7

2.2 Rainfall on surrounding highland

During April 1989, a new raingauge was installed by NRA-Wessex, on the highland to the north west of the moor at Meare Green Court, near Stoke St Gregory (ST 337270). This gauge provided data for four complete months (May - August 1989), a total rainfall for those four months of 179.6 mm. Predictions of the Meare Green rainfall for the remaining eight months of 1989 were made from a consideration of the rainfall at Fivehead and Weaver's Farm. The Weaver's Farm raingauge was not operational in May 1989, and this month's total, together with those for January to April, was synthesised from the Fivehead data using a regression relationship (see Section 2.7). After the insertion of these synthetic data for Weaver's Farm, the two gauges recorded totals of 168.0 mm and 186.4 mm respectively for the four months May to August, and the 1989 total for Weaver's Farm was 803.1 mm.

Predicted 1989 rainfall at Meare Green Court:

(i) from Fivehead (May - August)

(179.6/168.0) x 738.3 mm = 789.3 mm

(ii) from Weaver's Farm (May - August)

(179.6/186.4) x 803.1 mm = 773.8 mm

The average of these two figures, 781.6 mm, was taken as the probable 1989 rainfall at Meare Green Court.

It is clear that this approach to predicting the rainfall at Meare Green during the remaining eight months of 1989 represents a considerable extrapolation. However, it was felt that this course of action would lead to a far more accurate estimate of rainfall over this area of highland than would be provided by the only alternative assumption: that the rainfall was similar to that occurring at Fivehead. Table 2.2 illustrates the results of adopting this approach for monthly rainfall between January and April, and between September and December, predicted values for Weaver's Farm and Meare Green Court being asterisked.

Table 2.2 Rainfall at Meare Green Court (in mm) predicted from that at Fivehead and Weaver's Farm

Month	Fivehead	Weaver's Farm	Meare Gn Court, predicted from Fivehead	Meare Green Court, predicted from Weaver's Farm
Jan 89	25.5	29.6 *	27.3 *	28.5 *
Feb 89	72.9	78.7 *	77.9 *	75.8 *
Mar 89	56.8	62.0 *	60.7 *	59.7 *
Apr 89	76.4	82.3 *	81.7 *	79.3 *
May 89	36.4	40.9 *	32.6	32.6
Jun 89	25.1	25.9	20.8	20.8
Jul 89	63.0	75.4	78.9	78.9
Aug 89	43.5	44.2	47.3	47.3
Sep 89	40.5	39.4	43.3 *	38.0 *
Oct 89	87.0	95.9	93.0 *	92.4 *
Nov 89	56.0	68.6	59.9 *	66.1 *
Dec 89	155.2	160.2	165.9 *	154.4 *
Total	738.3	803.1 *	789.3 *	773.8 *

2.3 Streamflow gauged at Helland

During 1989, 22 days (6% of the year) were affected by loss of data due to chart failure. Fortunately, over half of this missing data occurred on days when the flow was very low (less than 0.01 cumec) and not difficult to estimate. The missing days were infilled using a regression equation which made use of data from gauging station 52011 Cary at Somerton. These data are represented as a hydrograph in Figure 2.1.

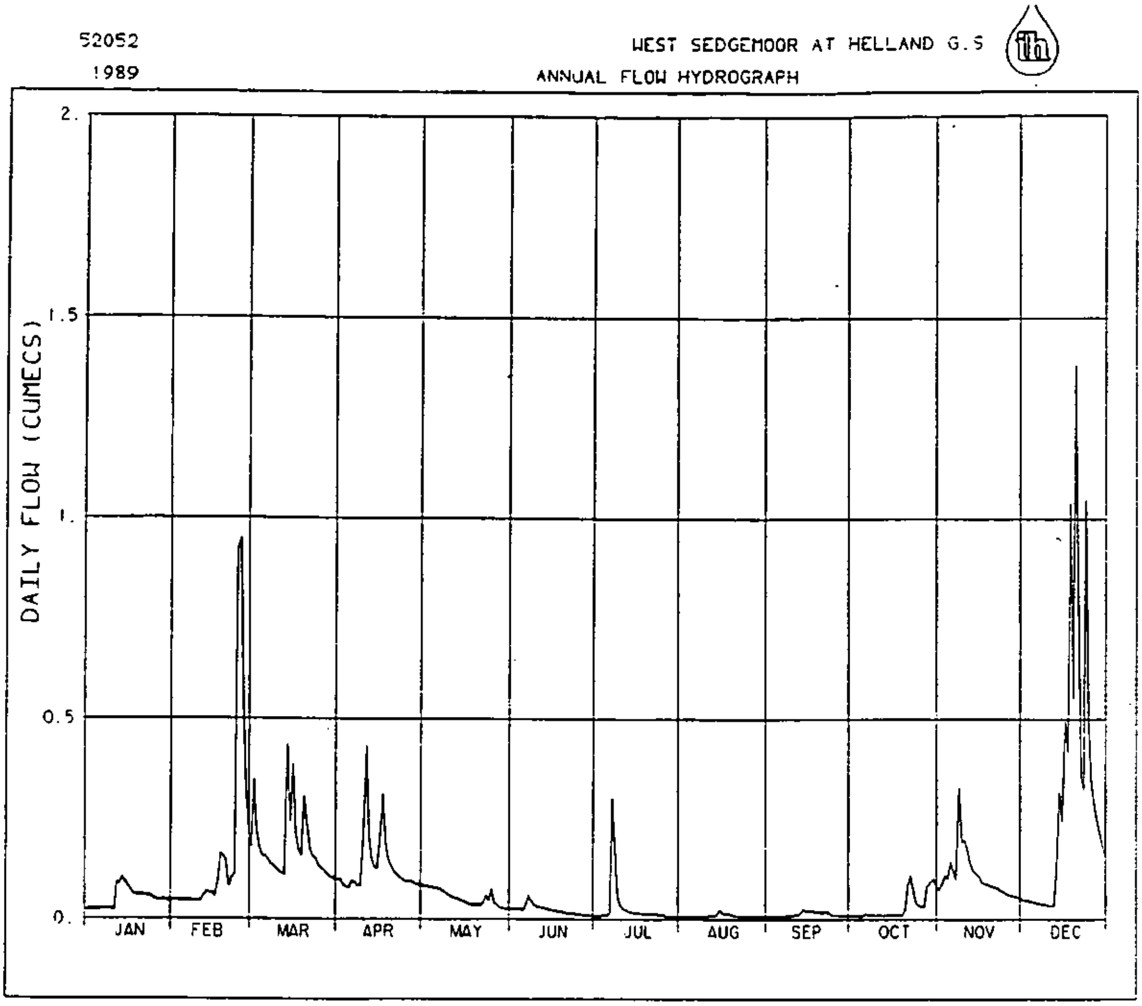

Figure 2.1 Discharge at Helland ST 331243

2.4 Wick Moor Rhyne streamflow

The central sluice was reported as having been closed between 6 April 89 and 5 December 89. The rhyne level did not reach the crest level of the side weir until the last day of April. The rhyne level recorder suffered a malfunction during November, which resulted in the loss of data for almost the entire month. The inflow during that month has been estimated assuming a linear variation in flow between the start and end of the month. The data are presented in Table 2.3.

2.5 Oath Hill streamflow

During 1989, current meterings were taken at this point during the period 4 May to 29 November. A total of 27 meterings were taken at approximately weekly intervals. On days when a metering was not taken, the flow was assumed to be that of the nearest metering. Monthly streamflows were calculated on this basis and are presented in Table 2.3 and Figure 2.2.

Table 2.3 Surface water inflows (cumec-days)

Month	Oath Hill	Wick Moor
Jan 89	nil	nil
Feb 89	nil	nil
Mar 89	nil	nil
Apr 89	nil	0.00 from 6 April
May 89	2.94	0.45
Jun 89	5.63	0.27
Jul 89	4.32	0.26
Aug 89	4.02	0.49
Sep 89	2.61	0.96
Oct 89	2.45	1.20
Nov 89	3.04	0.95 (estimated)
Dec 89	nil	0.08 until 5 December
Total	25.01	4.66

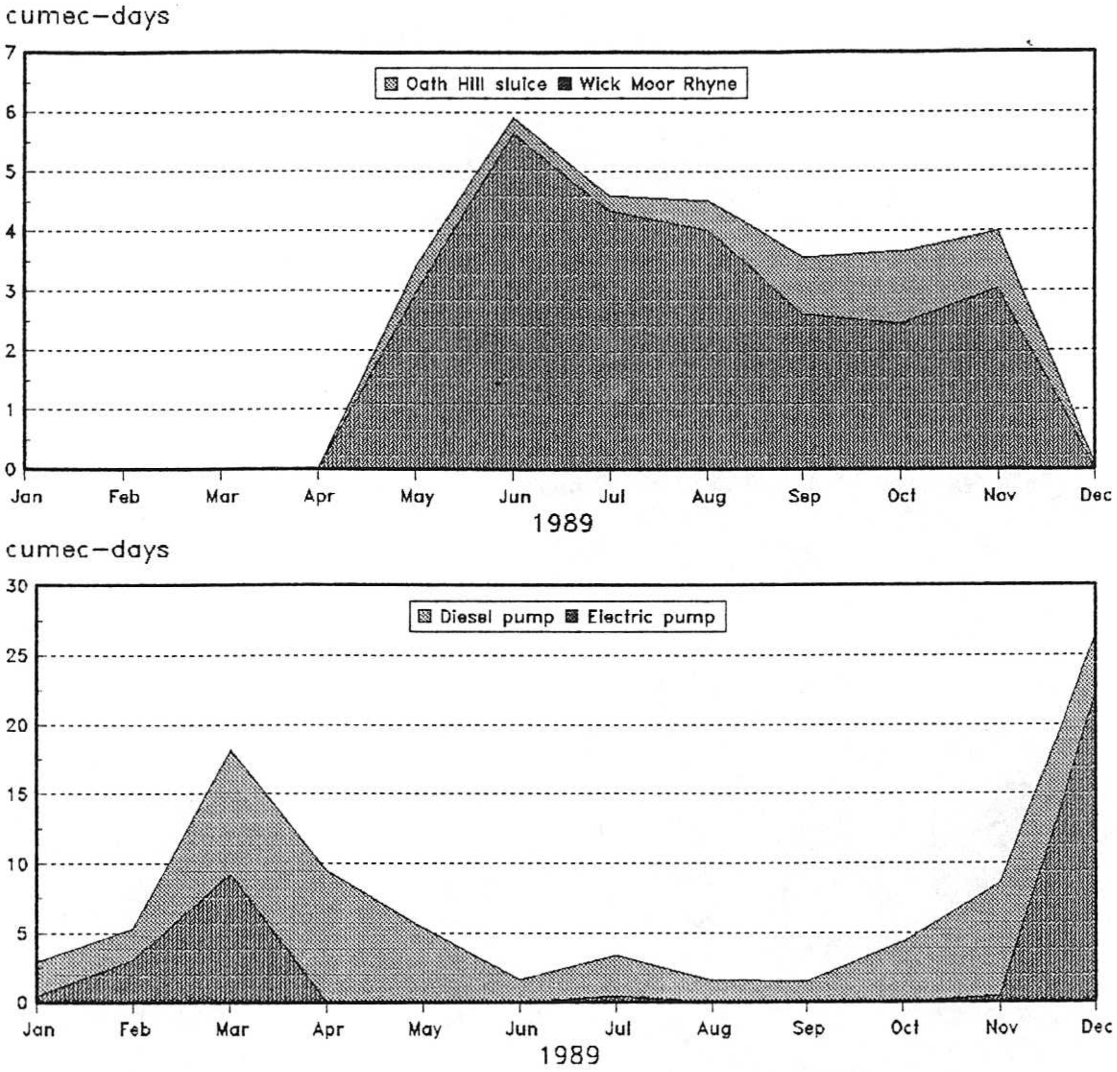

Figure 2.2 Inflows to West Sedgemoor and pumping from the Moor, 1989

2.6 Pumping stations

Figure 2.2 gives a clear picture of the operation of the pumps at the West Sedgemoor pumping station during 1989.

2.6.1 Diesel pumping station

With the electric pump acting as the duty pump, the diesel pumps are only used when there is a need to clear large volumes of water from the Moor over a sustained period. The diesel pumps were used on 26 days during 1989, mainly during March and December. The operator's pumping log shows that "gravitating" was used on three days during May although there is unfortunately no way to compute the volume released in this fashion.

2.6.2 Electric pumping station

During June to July 1989 there were comments in the operator's pumping log to the effect that the cumulative flow meter was giving a false reading. A check against the "hours run" meter proved that this was the case: the hours run meter showed the pump to be inactive at the same time that the cumulative flow meter indicated pumping taking place. Because there is not a well defined relationship between the hours run and the volume pumped it is not easy to detect inaccuracy in the cumulative flow meter when pumping is taking place. The entire record for 1989 was examined in the hope of identifying related problems. Corrections were made to eight days in June and two days in July when it was known that the pump was inactive; there was no alternative to assuming that the remainder of the data was valid.

Table 2.4 Pumped outflows (cumec-days)

Month	Diesel	Electric	Total	Total
	(cumec-days)			(mm over catchment)
Jan 89	0.41	2.51	2.92	6.0
Feb 89	2.99	2.30	5.29	10.9
Mar 89	9.24	8.99	18.23	37.5
Apr 89	0.00	9.45	9.45	19.5
May 89	0.00	5.33	5.33	11.0
Jun 89	0.00	1.58	1.58	3.3
Jul 89	0.40	2.92	3.32	6.8
Aug 89	0.00	1.52	1.52	3.1
Sep 89	0.00	1.46	1.46	3.0
Oct 89	0.00	4.34	4.34	8.9
Nov 89	0.38	8.20	8.58	17.6
Dec 89	22.28	4.23	26.51	54.5
Total	35.70	52.83	88.53	182.1

2.7 Water balance of Helland catchment for 1989

During April 1989, a new raingauge was installed by NRA-Wessex near the centre of the Helland catchment at Weaver's Farm, near Wrantage (ST 308227). This obviated the need to use data from the Fivehead raingauge (ST 349235), sited 4 km further east and at a higher altitude, to represent this part of the catchment. The altitude of the Weaver's Farm raingauge, 17 mOD, is somewhat lower than the extreme south west part of the Helland catchment, which rises to 110 mOD in the vicinity of Broadlands Farm. However, confidence in the data is increased by the knowledge that the rainfall at the Hatch Beauchamp gauge (ST 298199, 55 mOD) during 1989 was practically identical to that at Weaver's Farm.

Data were available from the raingauge at Weaver's Farm during June to December 1989 inclusive. It has been established that a very good relationship exists between the monthly rainfall at Weaver's Farm and that at Fivehead.

Rainfall (Weaver's Fm) = 3.2 + 1.03 x Rainfall (Fivehead)

$(r^2 = 0.9925)$

This regression equation has been used to generate synthetic Weaver's Farm data for the period January to May, and these months are indicated by an asterisk in Table 2.5. The data in the Table are presented in graphical form in Figure 2.3.

Table 2.5 Monthly rainfall (P), streamflow (Q) and losses (P-Q) in mm for the 15.2 km² Helland catchment during 1989.

Month	Rainfall at Weaver's Fm	Streamflow	Losses
Jan 89	29.6 *	8.6	21.0
Feb 89	78.7 *	26.2	52.5
Mar 89	62.0 *	31.5	30.5
Apr 89	82.3 *	22.7	59.6
May 89	40.9 *	9.1	31.8
Jun 89	25.9	3.7	22.2
Jul 89	75.4	5.0	70.4
Aug 89	44.2	1.4	42.8
Sep 89	39.4	2.1	37.3
Oct 89	95.9	5.5	90.4
Nov 89	68.6	18.1	50.5
Dec 89	160.2	54.0	106.2
Total	803.1	187.9	615.2

The Meteorological Office publishes estimates of potential and actual evaporation, and soil moisture deficit, for the United Kingdom on a 40 km square basis. These estimates, based on the MORECS model, take account of regional variations in rainfall and climatic variables, and the actual evaporation figure is based on an assessment of land use within the 40 km square. West Sedgemoor lies in square number 167, but it is near a corner of the square. Square 167 is also likely to be influenced strongly by coastal effects, so where comparisons of monthly or annual totals are made in this report the mean of MORECS squares 167, 168, 179 and 180 is used.

Bearing in mind the deficiencies of the regional estimate, it is instructive to compare the losses figure of 615.2 mm with the actual evaporation (AE) data resulting from the MORECS model for square 167 during 1989. The actual evaporation estimate allows for control of evaporation rates by the soil moisture deficit, and is an appropriate estimate to use in the catchment of the Moor. In Table 2.6 and Figure 2.4, it is evident that in some months a large proportion of the losses recorded cannot be due to actual evaporation alone, but must be the result of catchment storage. Despite the underlying geology's being Keuper Marl and fairly impermeable, the catchment returns a base flow index of 0.44, indicating that there is significant sub-surface storage within it, probably within the unsaturated zone of the soil.

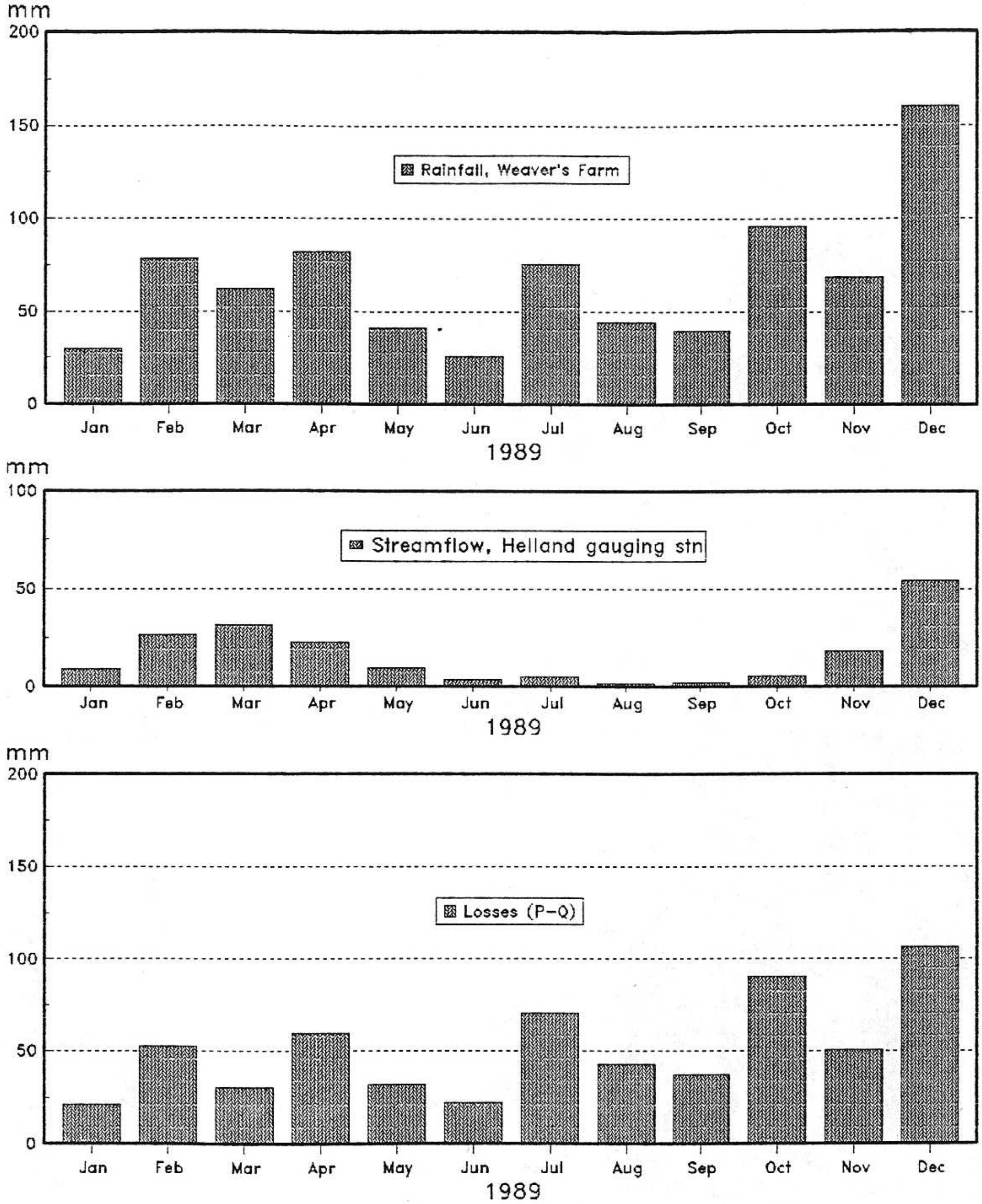

Figure 2.3 Water balance of Helland catchment, 1989

Table 2.6 Comparison between monthly losses and AE in mm from the MORECS model (square 167) during 1989.

Month	Losses	AE
Jan 89	21.0	16.2
Feb 89	52.5	22.7
Mar 89	30.5	39.2
Apr 89	59.6	53.9
May 89	31.8	94.2
Jun 89	22.2	60.0
Jul 89	70.4	59.1
Aug 89	42.8	51.5
Sep 89	37.3	35.7
Oct 89	90.4	38.1
Nov 89	50.5	20.7
Dec 89	106.2	16.7
Total	615.2	508.0

The immediate objective is to determine what fraction of the catchment losses is due to actual evaporation, the remainder being assumed to enter or leave storage. While the MORECS data are average values taken to apply to a 1600 km^2 area, and are related to the average land use and climate of that very large area, they can be taken as an initial estimate of the true situation. The MORECS estimates of soil moisture deficit (SMD) for square 167 during 1989 indicate that a zero SMD existed at the end of February, and to a very good approximation again at the end of December.

Clearly, when catchment storage enters into the water balance, it cannot be assumed that streamflow at the Helland gauging station occurring in a given month fell as rainfall during the same month. However, over any given period, the loss should equate to actual evaporation plus the change in storage (considered positive for an increase in the volume of stored water). Between two points when the SMD is zero, the volumes of water entering and leaving storage must sum to zero. Therefore between these same two points, the sum of the monthly losses must equate to actual evaporation alone.

The sum of catchment losses over the period 1 March 1989 to 31 December 1989 was 541.7 mm, which exceeds the total MORECS actual evaporation estimate for the same period (469.1 mm) by a factor of 1.155. This multiplying factor of 1.155 is applied to the monthly MORECS AE in Table 2.7, and presented graphically in Figure 2.5 as an illustration of the development and subsequent decay of the SMD during summer 1989.

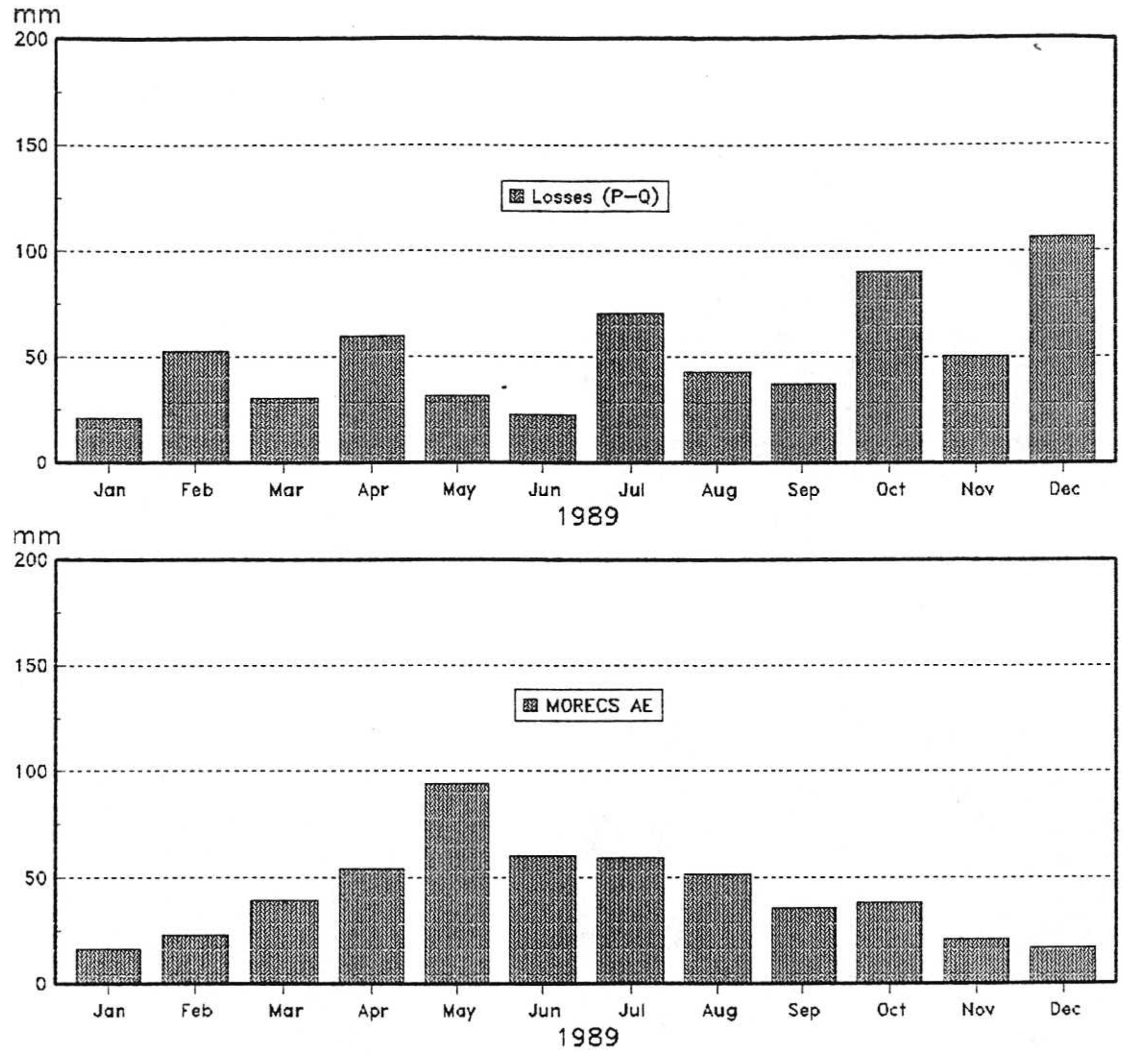

Figure 2.4 Comparison of losses from Helland catchment with MORECS AE, 1989

Table 2.7 Monthly losses, AE and computed SMD (in mm) between March and December 1989

Month	Losses	AE MORECS (square 167)	Computed SMD at end of month: $\sum$(AE MORECS x 1.155 - Losses)
Mar 89	30.5	39.2	15.0
Apr 89	59.6	53.9	17.4
May 89	31.8	94.2	94.4
Jun 89	22.2	60.0	141.5
Jul 89	70.4	59.1	139.4
Aug 89	42.8	51.5	156.1
Sep 89	37.3	35.7	160.0
Oct 89	90.4	38.1	113.6
Nov 89	50.5	20.7	87.0
Dec 89	106.2	16.7	0.1
Total (March - October)	541.7	469.1	

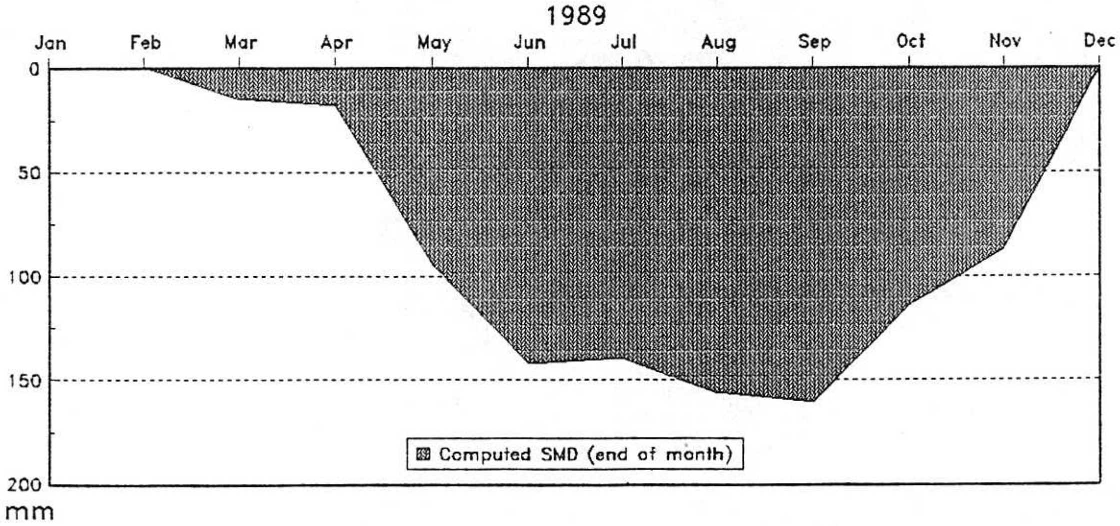

Figure 2.5 Development of SMD in Helland catchment during 1989

The constant of 1.155 was then applied to the AE MORECS figures for the complete 1989 calender year resulting in a value of:

508.0 x 1.155 = 586.7 mm

which was accepted as the true value of AE for the Helland catchment during 1989.

2.8 Water balance over West Sedgemoor

2.8.1 Inflows

Rainfall over West Sedgemoor

The 1989 annual rainfall of 704.7 mm recorded at or synthesised for the IH site was assumed to be representative of that occurring on the entire 12.8 km^2 area of Moor, and its application to this area results in a volume of 9,020,000 m^3.

Rainfall over highland below the Helland gauging station, excluding the Moor

The two areas of highland were considered separately. In each case, the average of the rainfall occurring on the 5 mOD Moor and that occurring on the 60 mOD highland has been calculated, as being representative of the sloping hillsides bordering the moor.

The Fivehead data is assumed to be representative of the rainfall on the crest of the 7.8 km^2 south east highland. For the slopes between the ridge and the Moor, the rainfall of 721.5 mm (average of 704.7 mm and 738.3 mm) results in a volume of 5,628,000 m^3.

The Meare Green Court data is assumed to be representative of the rainfall on crest of the 6.2 km^2 north west highland. The average of the two Meare Green Court estimates (Table 2.2) is calculated as 781.0 mm. For the slopes down to the Moor, the rainfall of 742.9 mm (average of 704.7 mm and 781.0 mm) results in a volume of 4,606,000 m^3.

Streamflow recorded at the Helland gauging station

The total streamflow for 1989 was 33.06 cumec-days, or 2,856,000 m^3.

Streamflow recorded at Wick Moor Rhyne sluice

The streamflow recorded between 6 April 1989 and 5 December 1989 was 4.66 cumec-days, equivalent to 402,600 m^3.

Streamflow recorded at Oath Hill sluice

The total of 25.01 cumec-days represents 2,161,000 m^3.

2.8.2 Outflows

The outflows from the diesel and electric pumping stations, shown in Table 2.4, total 88.53 cumecs-days, equivalent to 7,649,000 m^3.

2.8.3 Water balance

The sum of the inflows is computed to be:

Rainfall on West Sedgemoor	9,020,000 m^3
Rainfall on south east slopes	5,628,000 m^3
Rainfall on north west slopes	4,606,000 m^3
Helland streamflow	2,856,000 m^3
Wick Moor Rhyne streamflow	402,600 m^3
Oath Hill streamflow	2,161,000 m^3
Total inflow	24,673,600 m^3
The pumped outflow is	7,649,000 m^3
Net inflow	17,024,600 m^3

The evaporation from the two areas of highland below the Helland gauging station (E_H) is likely to resemble that of the area above the Helland gauging station rather than that of the Moor itself. The evaporation calculated for the area above the Helland gauging station is 586.7 mm and this is the value assigned to E_H. The evaporation on the Moor is then the only unknown in the following equation for the water balance of the Moor and the highland below the Helland gauging station, and is termed E_M.

(Area of NW and SE slopes below Helland gauging station)	x E_H		(Area of Moor)	x E_M		Net inflow
(14.0×10^6)	x 0.5867	+	(12.8×10^6)	x E_M	-	17,024,600 m^3

Therefore the evaporation over the Moor (E_M) = 688 mm, which is 102.9% of the MORECS potential evaporation, averaged over squares 167, 168, 179 and 180.

2.9 Sensitivity analysis - 1989 data

The content of this section is intended to build on Section 2.9 of the March 1989 report and should be read in conjunction with that earlier material.

2.9.1 Catchment above the Helland gauging station

Rainfall at Weavers Farm

While there is a range in catchment altitude of 110 mOD at the head of the catchment down to 17 mOD at the Helland gauging station, the Weavers Farm raingauge is located close to the centroid of the Helland catchment. As mentioned in Section 2.7, a raingauge at Hatch Beauchamp sited 3 km to the south west of that at Weaver's Farm and at a higher altitude (55 mOD) returned almost exactly the same annual rainfall (803.9 mm) during 1989. Despite the fact that the Hatch Beauchamp raingauge does not quite fall within the Helland catchment, this fact reinforces the belief that the Weavers Farm rainfall is representative of the Helland catchment. The errors resulting from gauge operation and taking the Weaver's Farm rainfall to apply to the entire Helland catchment are considered to be less than ±5%.

At the time of the March 1989 report, the Weavers Farm raingauge had not been deployed, and it was not realised that the Hatch Beauchamp data was available. The error in the enforced substitution of the Fivehead data for the Helland catchment was estimated at a maximum of 5%. This is now known to be incorrect: in Table 2.11 (Section 2.10) the Weavers Farm rainfall for 1988 is predicted using a regression relationship as 668.6 mm, 9% higher than that at Fivehead.

Streamflow at Helland gauging station

As in the 1989 report, streamflow data from the Helland gauging station were calculated by NRA-Wessex and have been accepted and used as supplied.

Since the March 1989 report, further current meter gaugings have been carried out by both NRA-Wessex and IH: results for a total of 43 gaugings have been supplied to IH by NRA-Wessex. The 21 gaugings taken during 1989 and 1990 were used in the derivation of equations (i) and (ii) below, which were used to generate daily flow data for 1989.

$$Q = 1369.h^{4.5798} \qquad \text{for } 0\text{ m} < h < 0.117\text{ m} \qquad \text{(i)}$$

(derived from 14 gaugings)

$$Q = 1.315h^{1.333} \qquad \text{for } 0.117\text{ m} < h < 2.000\text{ m} \quad \text{(ii)}$$

(derived from 7 gaugings)

The gaugings used in the generation of the above two rating curves were applied to a program which computes the 'best fit' rating curve of the type:

$$Q = C(h + \alpha_0)^b$$

and calculates 95% confidence limits on the resulting flow estimates. Although the structure of this equation is not identical to that used by NRA-Wessex in computing the daily flow data, the curves resulting from use of this equation were found to be very similar to those generated by (i) and (ii) above.

The results are shown in Tables 2.8 and 2.9. In Table 2.8, current meter gaugings of flows between 0.005 m^3/s and 0.027 m^3/s have been used in the derivation of the rating curve, while Table 2.9 refers to gaugings between 0.066 m^3/s and 0.568 m^3/s.

Table 2.8 95% confidence limits on low flow Helland rating curve (i).

Flow (cumec)	95% limits		Number of days during 1989 when flow is between these values
	upper	lower	
			12
0.005	+34	-25	
			24
0.007	+25	-20	
			14
0.008	+22	-18	
			24
0.010	+18	-15	
			14
0.012	+17	-15	
			16
0.016	+20	-16	
			4
0.017	+21	-17	
			10
0.021	+26	-21	
			6
0.022	+28	-22	
			8
0.024	+30	-23	
			13
0.027	+33	-25	
			79

Table 2.9 95% confidence limits on high flow Helland rating curve (ii).

Flow (cumec)	95% limits		Number of days during 1989 when flow is between these values
	upper	lower	
0.066	+39	-28	
			19
0.081	+33	-25	
			26
0.094	+29	-23	
			20
0.113	+26	-21	
			12
0.132	+26	-20	
			16
0.158	+27	-21	
			42
0.568	+75	-43	
			6

Because two rating curves have been used, two points of minimum error appear to exist at Q = 0.012 cumecs and Q = 0.132 cumecs. A more realistic view would be to assume that the flow prediction error at flows between these two values was at least comparable, or even less. The estimation of maximum error on the streamflow data has to be subjective; values of +22% and -18%, the average of the minimum values from both rating curves, seem reasonable and have been adopted.

Water balance

Following the procedure outlined in 2.7, and having regard to Tables 2.5, 2.6 and 2.7, the following worst case outcomes are detailed below:

a) If rainfall in error by +5% and streamflow in error by -18%

True (March - Dec) rainfall = 0.95 x 694.8 = 660.1 mm

True (March - Dec) streamflow = 1.18 x 153.1 = 180.7 mm

The revised (March - Dec) losses figure would then be

660.1 - 180.7 = 479.4 mm

and the new AE MORECS multiplying factor would have to be 1.022, so that the resulting figure of 1.022 x 469.1 would equate with the revised losses figure.

The new AE value would be 508 x 1.022 = 519.2 mm.

b) If rainfall in error by -5% and streamflow in error by +22%

True (March - Dec) rainfall = 1.05 x 694.8 = 729.5 mm

True (March - Dec) streamflow = 0.78 x 153.1 = 119.4 mm

The revised (March - Dec) losses figure would then be

729.5 - 119.4 = 610.1 mm

and the new AE MORECS multiplying factor would have to be 1.301, so that the resulting figure of 1.301 x 469.1 would equate with the revised losses figure.

The new AE value would be 508 x 1.301 = 660.9 mm.

Therefore the 1989 estimate of AE for the Helland catchment of 586.7 mm lies between limits of 519.2 and 660.9 mm. This is equivalent to approximately ±71 mm or ±12%.

2.9.2 West Sedgemoor

Each of the five inflows and two outflows is subject to uncertainty. The significance of the uncertainty in each to the final result depends upon the proportion of the total input or output that each constitutes. The fractions of the inflow and outflow that are derived from each source are shown in Table 2.10 and expressed as a percentage of the total, on the assumption that the estimates are accurate.

Table 2.10 Inflows and outflows expressed as m^3 and as a percentage.

	m^3	%
Inflows		
Rainfall on West Sedgemoor	9,020,000	36.5
Rainfall on S.E slopes	5,628,000	22.8
Rainfall on N.W slopes	4,606,000	18.7
Helland streamflow	2,856,000	11.6
Wick Moor Rhyne streamflow	402,600	1.6
Oath Hill streamflow	2,161,000	8.8
Total	24,673,600	100.0
Outflows		
Diesel pumping	3,084,000	40.3
Electric pumping	4,565,000	59.7
Total	7,649,000	100.0

In Section 2.8.3, the end product of the calculations was an equation which sought to distribute the net inflow volume between the area of surrounding highland and flat moor:

$$(14.0 \times 10^6) \times 0.5867 + (12.8 \times 10^6) \times E_M = 17{,}024{,}600 \text{ m}^3$$

The probable extent of uncertainty in E_H has been outlined in Section 2.9.1. It is also necessary to estimate uncertainty in the net inflow volume 17,024,600 m^3 in the above equation.

Inflow uncertainty

In Table 2.10, the maximum error on all three rainfall estimates is assessed at 5%. The total proportion of inflow due to rainfall is 78.1%.

The uncertainty in the Helland streamflow, here considered as an inflow, was assessed in Section 2.9.1 to have maximum values of +22% and −18%. The proportion of inflow due to the Helland streamflow is 11.6%.

The reader is referred to page 13 of the March 1989 report for discussion on the Wick Moor Rhyne and Oath Hill sluices. Both the Wick Moor Rhyne sluice data and that from Oath Hill were assessed to have a maximum uncertainty of 10%.

Outflow uncertainty

The reader is referred to pages 13 & 14 of the March 1989 report for discussion on uncertainty in the pumped outflows.

The operator log sheets for the diesel pumps show the start and stop times of the periods of operation of the pumps correct to the nearest 5 minutes. The maximum error in a start or stop time is therefore 2.5 minutes, and in a pumping run (2.5 + 2.5) = 5 minutes. The significance of this uncertainty depends upon the duration of the pumping. When the pumps are running continuously over a 24 hour period as they would do in a flood situation, the resulting uncertainty is

$$(5/60)/24 \times 100 = 0.35\%$$

This uncertainty increases with a reduction in pumping duration, for example a one hour pump run would generate an uncertainty of

$$(5/60)/1 \times 100 = 8.3\%$$

The operator log sheets for 1989 show that the average pump run time was 7.6 hours. Therefore the associated uncertainty is assessed as

$$(5/60)/7.6 \times 100 = 1.1\%$$

This figure has been used in the following calculations.

The volumes pumped by the electric pumping station have been taken as those indicated by the cumulative flow meter. NRA-Wessex staff assess the accuracy of this meter as 0.25%, but see Section 2.6.2. A gross malfunction of some sort clearly occurred during 1989 and it is not practical to try and assess error resulting from such a "one-off" event.

Worst case estimates of uncertainty

It is possible to calculate a weighted estimate of uncertainty by applying the estimated uncertainty for each component of inflow and outflow to the percentage of the total that each comprises.

Inflow

Maximum positive uncertainty

$$\frac{\overset{\text{Rainfall}}{(1.05 \times 78.0)} + \overset{\text{Helland}}{(1.22 \times 11.6)} + \overset{\text{Wick Moor}}{(1.1 \times 1.6)} + \overset{\text{Oath Hill}}{(1.1 \times 8.8)}}{100.0}$$

= 1.075, equivalent to +7.5%

Maximum negative uncertainty

$$\frac{\overset{\text{Rainfall}}{(0.95 \times 78.0)} + \overset{\text{Helland}}{(0.82 \times 11.6)} + \overset{\text{Wick Moor}}{(0.9 \times 1.6)} + \overset{\text{Oath Hill}}{(0.9 \times 8.8)}}{100.0}$$

= 0.930, equivalent to -7.0%

Outflow

Estimated maximum positive error

$$\frac{\overset{\text{Diesel}}{(1.011 \times 40.3)} + \overset{\text{Electric}}{(1.0025 \times 59.7)}}{100.0}$$

= 1.006, equivalent to +0.6%

Estimated maximum negative error

$$\frac{\overset{\text{Diesel}}{(0.989 \times 40.3)} + \overset{\text{Electric}}{(0.9975 \times 59.7)}}{100.0}$$

= 0.994, equivalent to −0.6%

Water balance over West Sedgemoor and surrounding highland 1989

1. Inflow subject to maximum positive error (7.5%) and outflow subject to maximum negative error (0.6%).

Net inflow volume = (0.925 x 24,673,600) - (1.006 x 7,649,000)

= 15,128,000 m^3

2. Inflow subject to maximum negative error (7.0%) and outflow subject to maximum positive error (0.6%).

Net inflow volume = (1.070 x 24,673,600) - (0.994 x 7,649,000)

= 18,798,000 m^3

(see also Section 2.9.2).

The calculations of Section 2.8.3 are now repeated to determine the possible uncertainty in the figure of 688 mm evaporation for West Sedgemoor. The original equation:

$$(14 \times 10^6) \times 0.5867 \quad + \quad (12.8 \times 10^6) \times E_M \quad = \quad 17{,}024{,}600$$

is solved again using the new values of net inflow volume in place of 17,024,600 m^3 and having regard to possible uncertainty in the figure of 586.7 mm for E_H.

The Helland streamflow is an outflow in the calculation of E_H and an inflow in the calculation of E_M. If the streamflow were higher than estimated, a reduction in the estimated value of E_H would result, together with an increase in the net inflow volume to West Sedgemoor. Similarly, a lower streamflow is associated with a higher value of E_H and a lower net inflow volume to West Sedgemoor.

E_H (mm)	Net inflow volume (m^3)	E_M (mm)
519.2	18,798,000	901
586.7	17,024,600	688
660.9	15,128,000	459

2.10 Revised water balance of Helland catchment for 1988

The March 1989 report contained water balance calculations using data from the 1988 calendar year. The procedures outlined in Sections 2.1, 2.2 and 2.7 of this report can be used to improve the estimates of the rainfall over the Moor and over both areas of highland below the Helland gauging station. It is thus possible to repeat the 1988 water balance calculations contained in the March 1989 report in the light of this more accurate data. Other elements involved in the water balance calculations are still considered valid.

Table 2.11 Predicted 1988 rainfall for Meare Green Court and Weavers Farm using real Fivehead rainfall.

Month	Fivehead	Meare Gn Court	Weaver's Farm
Jan 88	112.1	Rainfall estimated from Fivehead by method outlined in Section 2.2	118.7
Feb 88	56.0		60.9
Mar 88	62.1		67.2
Apr 88	21.7		25.6
May 88	42.4		46.9
Jun 88	42.8		47.3
Jul 88	83.5		89.2
Aug 88	65.1		70.3
Sep 88	31.1		35.3
Oct 88	61.2		66.3
Nov 88	17.0		20.7
Dec 88	16.5		20.2
Total	611.5	653.7	668.6

Table 2.12 Predicted monthly rainfall, streamflow and losses (in mm) for the 15.2 km² Helland catchment during 1988.

Month	Predicted rainfall at Weaver's Farm	Streamflow	Losses
Jan 88	118.7	73.0	45.7
Feb 88	60.9	64.9	-4.0
Mar 88	67.2	30.0	37.2
Apr 88	25.6	10.9	14.7
May 88	46.9	5.6	41.3
Jun 88	47.3	3.6	43.7
Jul 88	89.2	4.4	84.8
Aug 88	70.3	3.5	66.8
Sep 88	35.3	3.8	31.5
Oct 88	66.3	5.6	60.7
Nov 88	20.7	3.4	17.3
Dec 88	20.2	6.3	13.9
Total	668.6	215.0	453.6

Using the same approach as is outlined in Section 2.7 the losses are compared with the MORECS actual evaporation (AE) values between two points (end January and end November) when the SMD is zero. The sum of the AE MORECS values between these two points needed to be multiplied by 0.735 in order that it would equate to the sum of the losses.

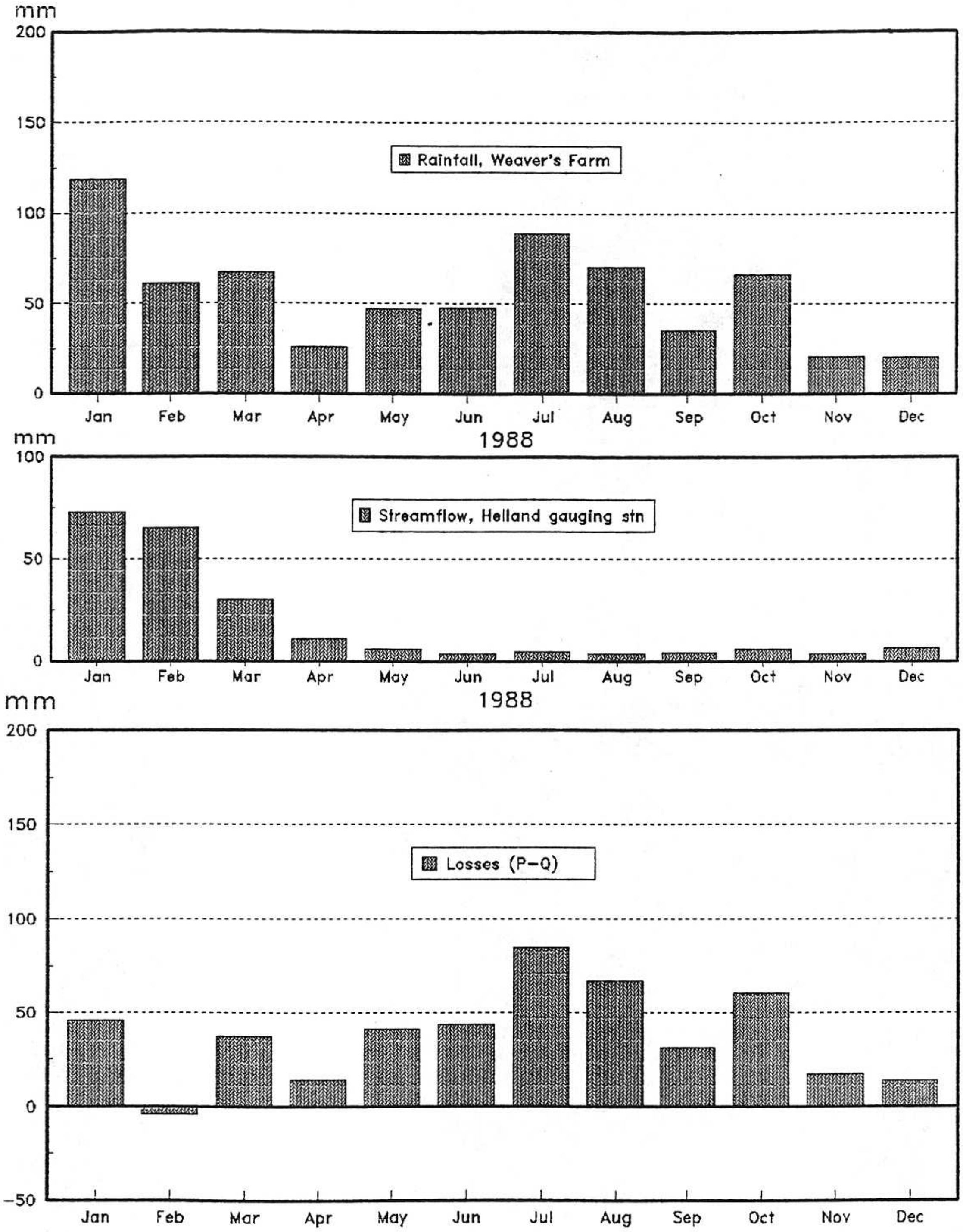

Figure 2.6 Water balance of Helland catchment, 1988

Table 2.13 Monthly losses, MORECS AE and computed SMD (in mm) between February and November 1988

Month	Losses	AE MORECS (square 167)	Computed SMD at end of month: $\sum$(AE MORECS x 0.735 - Losses)
Feb 88	-4.0	23.8	21.5
Mar 88	37.2	39.9	13.6
Apr 88	14.7	54.8	39.2
May 88	41.3	83.5	59.3
Jun 88	43.7	67.4	65.1
Jul 88	84.8	84.5	42.4
Aug 88	66.8	76.0	31.5
Sep 88	31.5	55.8	41.0
Oct 88	60.7	35.8	6.6
Nov 88	17.3	14.3	-0.2
Total	394.0	535.8	

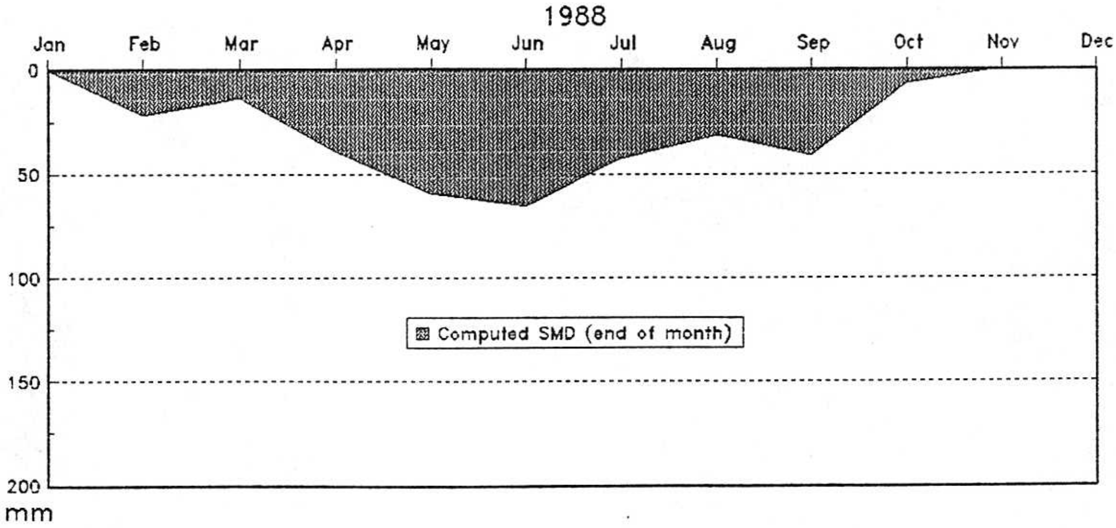

Figure 2.7 Development of SMD in Helland catchment during 1988

When the constant of 0.735 is applied to the 1988 annual AE MORECS value of 569.6 mm, the resulting value of estimated actual evaporation from the catchment:

0.735 x 569.6 = 418.7 mm

This should be compared with the figure of 397 mm from the March 1989 report.

2.11 Revised water balance over West Sedgemoor for 1988

2.11.1 Inflows

Rainfall over West Sedgemoor

The annual rainfall over West Sedgemoor at the IH raingauge was estimated using the relationship described in Section 2.1 as:

(12 x 2.3 mm) + 597.9 mm = 625.5 mm

(see also Table 2.2, page 7, March 1989 report).

The area of flat moor being 12.8 km^2, this leads to a revised inflow volume of

$(12.8 \times 10^6) \times (0.6255) = 8{,}006{,}000\ \text{m}^3$

Rainfall over north west slopes

The annual rainfall predicted for Meare Green Court was 653.7 mm. The annual rainfall predicted for the Moor was 625.5 mm.

The average of these two is 639.6 mm and has been taken as representative of the 1988 annual rainfall over this 6.2 km^2 area.

The inflow from this zone was therefore revised to:

$(6.2 \times 10^6) \times (0.6396) = 3{,}966{,}000\ \text{m}^3$

Rainfall over south east slopes

The annual rainfall at Fivehead was 611.5 mm. The annual rainfall predicted for the flat moor was 625.5 mm.

The average of these two is 618.5 mm and has been taken as representative of the 1988 annual rainfall over this 7.8 km^2 area.

The inflow from this zone was therefore revised to:

$(7.8 \times 10^6) \times (0.6185) = 4{,}824{,}000\ \text{m}^3$

Additional inflows

The 1988 inflows calculated for the Helland streamflow gauging station, Oath Hill sluice and Wick Moor Rhyne sluice are still considered valid and are summarised below.

Site	Inflow volume
Helland gauging station	3,275,000
Wick Moor Rhyne	743,000
Oath Hill sluice	1,668,000
Total	5,686,000 m^3

2.11.2 Outflows

The estimate of 10,910,000 m^3 for the 1988 pumped outflow has not been altered from the March 1989 report.

2.11.3 Water balance

The sum of the inflows is computed to be:

Rainfall on West Sedgemoor	8,006,000
Rainfall on north west slopes	3,966,000
Rainfall on south east slopes	4,824,000
Helland streamflow	3,275,000
Wick Moor Rhyne streamflow	743,000
Oath Hill streamflow	1,668,000
Total	22,482,000 m^3
The pumped outflow is	10,910,000 m^3
Net inflow volume	11,572,000 m^3

Using again the argument that the evaporation from the north west and south east slopes surrounding the Moor will approximate better to the area above the Helland gauging station (E_H = 418.7 mm) than to the Moor, the following equation results where E_M represents the evaporation from the Moor:

(Area of NW and SE slopes below Helland gauging station)	x E_H	(Area of Moor)	x E_M	=	Net inflow
(6.2 + 7.8) x 10^6	x 0.4187	(12.8 x 10^6)	x E_M	=	11,572,000 m^3

The actual evaporation for 1988, E_M = 446 mm (77.3% of MORECS PE averaged over squares 167, 168, 179 and 180).

This should be compared with the figure of 417 mm from the March 1989 report.

3 LYSIMETER STUDIES

The design and installation of the lysimeter and the background to the approach were described in detail in the March 1989 report. During 1989 no alterations were made to the lysimeter, which is essentially a cylindrical tank containing a block of reconstituted soil, dimensions 0.92 m diameter by 0.80 m in height. A dipwell in the centre was used for readings of the water table elevation in the lysimeter, which was matched approximately to the water table in dipwell T4-5 by addition or removal of measured quantities of water at weekly intervals.

3.1 The 1988 season

The analysis of the lysimeter records presented in Section 3 of the March 1989 report used a value of 16% for the specific yield of the peat at transect T4. The choice of specific yield does not have a large effect on the computed evaporation over the summer, as the accounting period has only a small overall change in groundwater level. However, with a new value of specific yield of 11.1% computed from the dipwell records for the years 1986 to 1989 (Section 4.2), it is necessary to recalculate the evaporation estimate presented in the March 1989 report. Table 3.1 shows the evaporation totals computed using a range of specific yields, including the optimal value of 11.1%. This table is an updated version of Table 3.2 in the March 1989 report.

Table 3.1 Actual evaporation figures computed from lysimeter data, 1988

Date	Total actual evaporation between visits, based on a specific yield of					Average evaporation rate (mm/day)	
	S=10%	S=11%	S=11.1%	S=12%	S=13%	S=11.1%	MORECS PE
07/04/88							
13/04/88	10.0	10.8	10.9	11.6	12.4		
20/04/88	3.4	3.0	2.9	2.5	2.0		
27/04/88	20.5	22.3	22.4	24.0	25.8	1.8	1.8
05/05/88	3.9	2.5	2.4	1.1	-0.2		
11/05/88	22.5	24.5	24.7	26.5	28.4		
18/05/88	13.3	14.5	14.6	15.6	16.7		
25/05/88	3.4	3.5	3.5	3.6	3.7	1.6	2.8
07/06/88	43.1	43.1	43.1	43.2	43.2		
15/06/88	20.1	19.4	19.4	18.8	18.1		
22/06/88	7.3	7.9	8.0	8.5	9.1	2.5	2.8
06/07/88	45.9	42.3	41.9	38.7	35.0		
13/07/88	11.7	11.8	11.8	11.8	11.9		
20/07/88	35.1	37.1	37.3	39.1	41.0		
27/07/88	14.7	13.5	13.4	12.4	11.3	3.0	2.6
03/08/88	26.0	27.2	27.4	28.5	29.7		
10/08/88	16.4	17.7	17.8	19.0	20.3		
18/08/88	26.8	28.8	29.0	30.8	32.8	3.4	2.4
01/09/88	17.7	14.5	14.1	11.3	8.1		
07/09/88	12.9	13.6	13.7	14.2	14.9	1.4	1.8
Total 07/04/88 to 07/09/88	354.7	357.9	358.2	361.1	364.3		

The actual evaporation from the lysimeter is calculated as the residual term in the lysimeter water balance:

Rainfall + water added = Change in soil water storage + evaporation

For example, referring to Table 3.1 of the March 1989 report, for the interval 20 July to 27 July 1988, the total of rainfall and water added is

(25.3 x 0.6576) + 1.000 = 17.637 litres

or (17.637/0.6449) = 27.35 mm over the grassed area of the lysimeter.

The rainfall figure used is the total rainfall over the days 20 July to 26 July inclusive, and the irrigation water was added on the 20 July visit.

The change in soil water storage, using a specific yield of 11.1%, is

113 x (0.6449 x 11.1/100 + 0.00785) = 8.976 litres

or (8.976/0.6449) = 13.92 mm over the grassed area of the lysimeter.

The actual evaporation is

(27.35 - 13.92) = 13.4 mm.

The average evaporation rate is computed by summing the actual evaporation figures and dividing by the number of days between the last visit of the previous month and the last visit of the current month, for example in July 1988, assuming S = 11.1%

Total evaporation = (41.9 + 11.8 + 37.3 + 13.4) = 104.4 mm

Number of days between visits on 22 June and 27 July is 35

Average evaporation rate = 104.4/35 = 3.0 mm

3.1.1 Annual total, 1988

Over the accounting period 7 April to 7 September 1988, the MORECS model predicts that 66.4% of the 1988 annual total potential evaporation would occur. The lysimeter figure can be scaled up to give an annual total of

(358.2/0.664) = 540 mm (93.6% MORECS PE averaged over squares 167, 168, 179 and 180)

3.2 The 1989 season

During 1989 the frequency of monitoring the lysimeter was intended to be the same as that for 1988, weekly during April to October and fortnightly during the remainder of the year. This pattern was adhered to in general, but on nine occasions, mainly during the last three months of 1989, access to the site was prevented for a variety of reasons. These included the rebuilding of an access bridge across the West Sedgemoor Main Drain, vehicle problems, flooding and obstruction by livestock. As a result, there were a total of 33 visits during the year. On 15 of these water was added, on 5 water was removed and on the remaining 13 no water was added or removed.

Due to the very hot summer in 1989 the groundwater level in the immediate vicinity of the lysimeter dropped to a level lower than had been experienced in 1988. As a result, the external groundwater level fell below the base of the lysimeter and it was not possible to keep the internal water level "in balance" with that in the surrounding field for the entire year. For a three month period between late July and late October the lysimeter was reported by the field worker as being dry. During this three month period the grass on the lysimeter surface remained green: indeed it appeared from its colour to have a higher moisture content than the surrounding field surface. However, the loss of the saturated zone at the base of the lysimeter does appear to have exerted a control on the evaporation rate from the lysimeter during the summer of 1989.

The results obtained from the lysimeter between 5 January and 29 November 1989 are presented in Table 3.2

The observations about excess winter rainfall in the March 1989 report also apply here: when the lysimeter water level is high, it is probable that surface runoff occurs. Hence, the lysimeter method can only be used over the summer months, when surface runoff is unlikely. Even so, there is some doubt over the lysimeter's response to high rainfall recorded on 22 May 1989, when 11.5 mm fell over a quarter-hour interval. In this case the rise in water table in the lysimeter, taking into account the specific yield and the likely evaporation over the week between readings, was suspiciously large, and this suggests that runoff may have occurred from

Table 3.2 Lysimeter water levels, additions of water and rainfall, 1989

Date	Water level in dipwell (mOD)	Change in water level (m)	Quantity of water added (l)	WSPS rainfall (mm)
05/01/89	4.751			
18/01/89	4.857	0.106	0.100	15.5
01/02/89	4.868	0.011	-0.510	6.9
15/02/89	4.829	-0.039	-0.490	6.8
01/03/89	4.880	0.051	-1.500	63.8
15/03/89	4.805	-0.075	-0.420	18.5
29/03/89	4.748	-0.057	0.410	23.0
05/04/89	4.641	-0.107	1.000	4.5
12/04/89	4.903	0.262	0.000	30.3
19/04/89	4.807	-0.096	0.000	11.7
26/04/89	4.768	-0.039	0.500	1.7
04/05/89	4.765	-0.003	0.300	10.0
10/05/89	4.577	-0.188	0.000	0.0
17/05/89	4.457	-0.120	0.700	2.7
24/05/89	4.832	0.375	-0.500	37.0
07/06/89	4.500	-0.332	0.200	14.3
14/06/89	4.362	-0.138	0.700	5.0
21/06/89	4.291	-0.071	0.600	0.0
28/06/89	4.287	-0.004	1.000	1.1
13/07/89	4.352	0.065	0.940	78.6
19/07/89	4.291	-0.061	0.750	0.0
26/07/89	4.292	0.001	0.460	0.0
02/08/89	4.294	0.002	0.000	0.0
09/08/89	4.278	-0.016	1.000	0.0
16/08/89	4.267	-0.011	0.000	32.1
30/08/89	4.285	0.018	0.000	6.0
06/09/89	4.284	-0.001	0.000	0.0
12/09/89	4.126	-0.158	0.000	4.0
20/09/89	4.290	0.164	0.000	25.5
27/09/89	4.294	0.004	0.000	12.2
18/10/89	4.283	-0.011	0.000	9.1
25/10/89	4.281	-0.002	1.000	34.0
20/11/89	4.422	0.141	0.000	81.6
29/11/89	4.387	-0.035	0.000	1.2
Total 07/06/89 to 29/11/89			6.450	290.4

the field around the lysimeter into the lysimeter itself, recharging the saturated zone within the lysimeter by vertical movement down the inside of the lysimeter walls. Because of the uncertainty surrounding this event, the accounting period for 1989 was taken from 24 May to 29 November.

The monthly and seasonal evaporation totals were calculated in the same way as for the March 1989 report. Table 3.3 shows the results obtained.

Table 3.3 Actual evaporation figures computed from lysimeter data, 1989

Date	Total actual evaporation between visits, based on a specific yield of					Average evaporation rate (mm/day)	
	S=10%	S=11%	S=11.1%	S=12%	S=13%	S=11.1%	MORECS PE
24/05/89							
07/06/89	51.0	54.4	54.7	57.7	61.0		
14/06/89	20.9	22.3	22.4	23.6	25.0		
21/06/89	9.0	9.8	9.8	10.5	11.2		
28/06/89	2.5	2.5	2.5	2.6	2.6	2.6	3.3
13/07/89	74.4	73.8	73.7	73.1	72.5		
19/07/89	8.3	8.9	9.0	9.5	10.1		
26/07/89	1.1	1.0	1.0	1.0	1.0	3.0	3.8
02/08/89	0.5	0.5	0.5	0.4	0.4		
09/08/89	1.8	2.0	2.0	2.1	2.3		
16/08/89	35.5	35.6	35.6	35.7	35.8		
30/08/89	4.1	3.9	3.9	3.7	3.6	1.2	3.0
06/09/89	0.1	0.1	0.1	0.1	0.1		
12/09/89	21.8	23.4	23.5	25.0	26.5		
20/09/89	7.6	6.0	5.8	4.3	2.7		
27/09/89	12.0	12.0	11.9	11.9	11.9	1.5	1.8
18/10/89	10.5	10.6	10.6	10.7	10.8		
25/10/89	34.9	34.9	34.9	34.9	35.0	1.6	1.3
20/11/89	68.9	67.5	67.4	66.1	64.7		
29/11/89	5.1	5.5	5.5	5.8	6.2	2.1	0.7
Total 01/06/89 to 29/11/89	370.2	374.6	375.0	379.1	383.5		

3.2.1 Annual total, 1989

The total actual evaporation, as estimated by the lysimeter over the 1989 accounting period, is 375.0 mm. During the accounting period, the MORECS PE estimate accounted for 63.6% of the annual total. Thus the lysimeter figure may be scaled up to give an annual total of

(375.0/0.636) = 589.6 mm (88.0% of MORECS PE)

The fact that this is lower than other estimates prepared from the catchment water balance (Section 2) and dipwell levels (Section 4) suggests that the reduced soil moisture levels in the lysimeter over the summer of 1989 may have exerted some control over evaporation from the lysimeter.

3.3 Seasonal distribution of evaporation

The final two columns in Table 2.3 compare the seasonal distribution of the actual evaporation figure computed from the lysimeter results with the MORECS PE estimate averaged over squares 167, 168, 179 and 180.

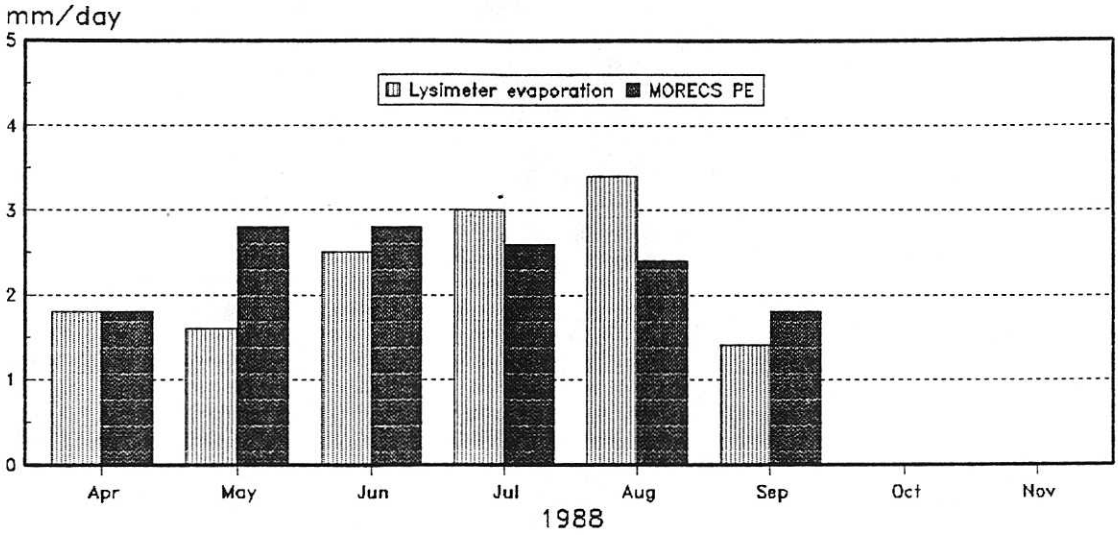

Figure 3.1 Monthly average evaporation rates, comparison between lysimeter results and MORECS PE, 1988

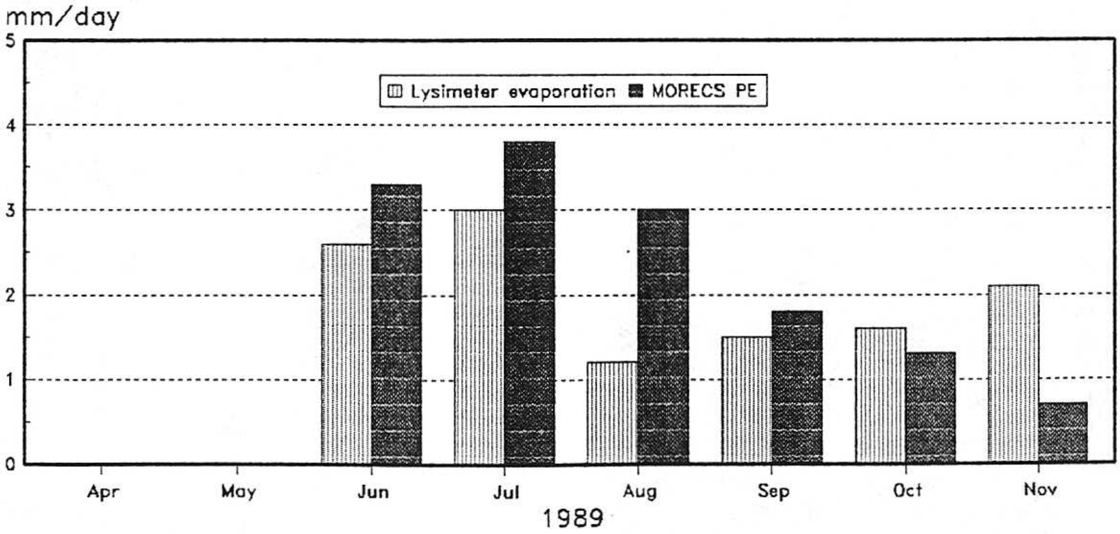

Figure 3.2 Monthly average evaporation rates, comparison between lysimeter results and MORECS PE, 1989

A comparison between Tables 3.2 and 3.3 is instructive: in 1988 the actual evaporation estimate was generally slightly less than the MORECS PE, becoming greater than MORECS in July and August, while in 1989 the lysimeter estimate is much smaller than MORECS in July and August, and greater than MORECS in October and November (Figures 3.1 and 3.2). Two reasons may be advanced for this behaviour:

(i) the groundwater store does not represent in full the changes in stored water in the lysimeter, as there are also changes in the unsaturated zone above the water table. In 1988 these changes in the unsaturated zone were reduced by the availability of groundwater for upward transfer, but in 1989 the unsaturated zone was without this protection, and was depleted by evaporation. This depletion of the stored water would not have shown up in the lysimeter records, and would have caused an underestimate of actual evaporation during the months of July and August. At the end of the summer, the restoration of the soil moisture stored in the unsaturated zone to its winter levels would reduce the water supply available to the saturated zone. The consequent subdued response of the water table would lead to an overestimate of actual evaporation in October and November.

(ii) the build-up of a soil moisture deficit in the unsaturated zone in the lysimeter during the summer of 1989 would impose a control on the actual evaporation rate, so that true evaporation from the lysimeter would be at well below the potential rate, and the magnitude of the lysimeter's under-estimation of actual evaporation rates in June and July would not be so great as is suggested by (i).

Over the whole season, the groundwater levels fall and rise again almost to their winter levels, so the under- and over-estimation of monthly evaporation rates, which is also present in the estimates from dipwell levels, when they are considered over short time intervals, does not have a significant effect on the seasonal total. However, without measurements of soil moisture in the unsaturated zone, some doubt still remains regarding the change in soil water storage over the 1989 accounting period.

4 WATER TABLE PROFILES WITHIN THE FIELDS

Groundwater levels within the fields of West Sedgemoor have been measured at intervals of one or two weeks in shallow dipwells, which are arranged in four transects, chosen to give a good spatial coverage of the Moor.

Each transect consists of five dipwells located at 10 m intervals along a line perpendicular to a major rhyne (Figure 4.1):

T1 at Beercrowcombe Drove near Burton's Dairy Farm, north of the New Cut, ST 369257. This transect is in a part of the Moor now isolated from the main rhyne network and irrigated by RSPB.

T2 near Eastwood Farm, south of the Middle Drain, ST 350250

T3 at the end of Pincombe Drove, south of North Drove Rhyne, ST 359265

T4 towards the eastern end of the Moor, north of Middle Drain, ST 371270, in the same field as the lysimeter.

Figure 4.1 Locations of dipwell transects

The installation of the dipwells is described in the March 1989 report. It was intended that each transect should start with a well as near as possible to the rhyne, and extend into the field as far as the distance between the transect and the nearest lateral drain. If all lateral drains were well-maintained and in good hydraulic connection with the rhynes, the last well would represent the point in the field most distant from the influence of open water. Three transects consist of wells in a straight line at distances of 2, 12, 22, 32 and 42 m from the water's edge. In the other transect (T1) the final well is 52 m from the water. Water level measurements began in July 1986 and continued until the start of April 1990. Readings up to the end of 1989 are considered in this report.

4.1 Seasonal variations in groundwater levels

The seasonal pattern of variation in groundwater level, established in the summers of 1987 and 1988, continued through the summer of 1989. The influence of the 1989 summer drought resulted in a slightly lower minimum level than in 1987. In 1989 groundwater levels dropped more rapidly than in 1987, following the dry months of May and June, but a high rainfall in July brought about a partial restoration. It is notable that the changes in water level within the field, as shown by Figures 4.2 and 4.3, are a response to climatic fluctuations and not to variations in rhyne level: seasonal changes in the penning level are in the opposite sense to those of groundwater level.

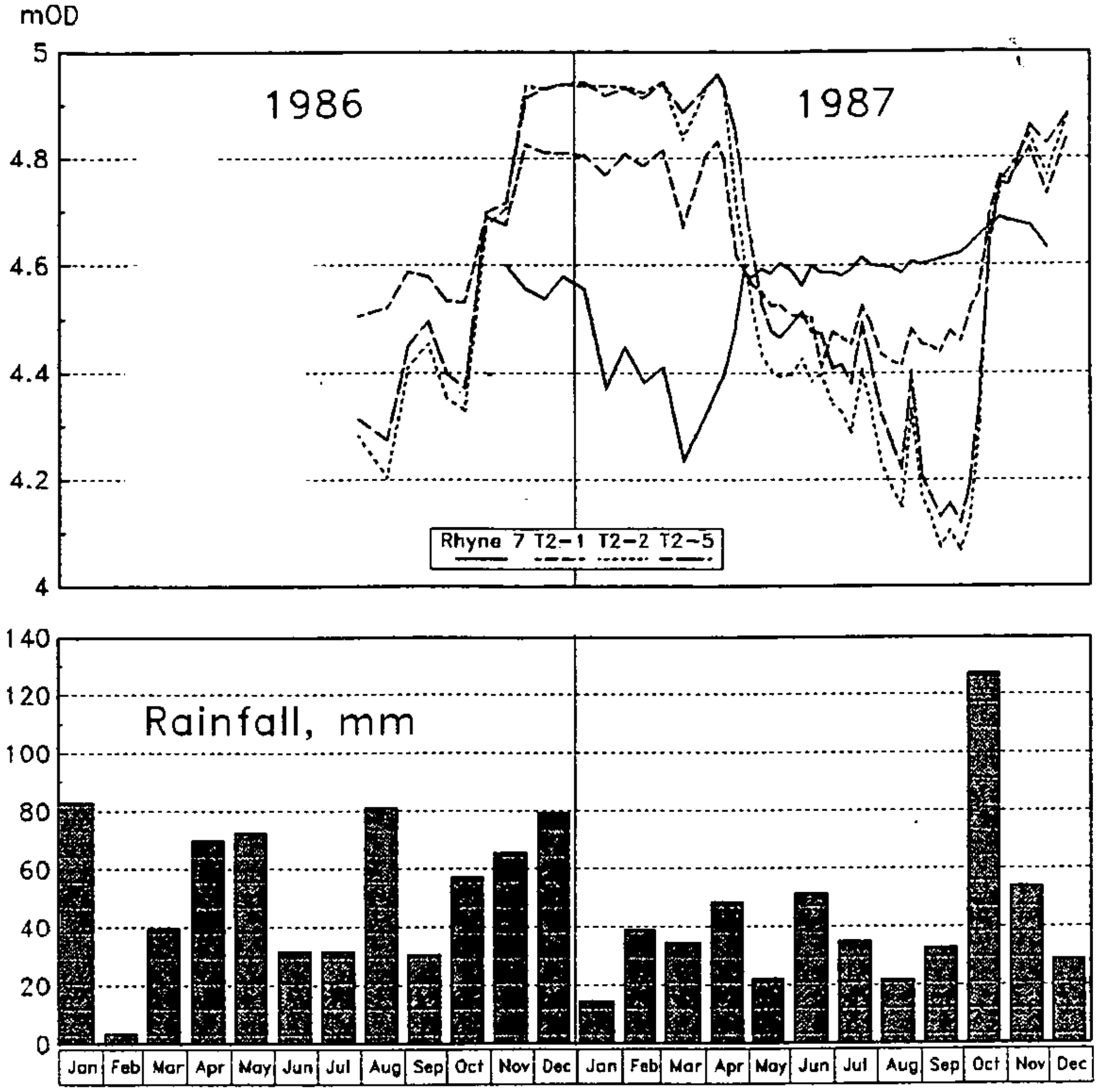

Figure 4.2 Groundwater levels in dipwells of transect 2, 1986-87. Transect 2 is adjacent to rhyne water level recorder 7, and the rhyne levels are also shown in the figure.

The relationship between groundwater levels, as measured in the dipwells, and climate factors is the basis of a third method for estimating evaporation from the Moor over the summer period, when runoff can be eliminated from the water balance. The change in soil water and groundwater storage, a function of the water table elevation, is a component in the water balance of the Moor, which must be taken into account during the summer. For any elemental area of the Moor:

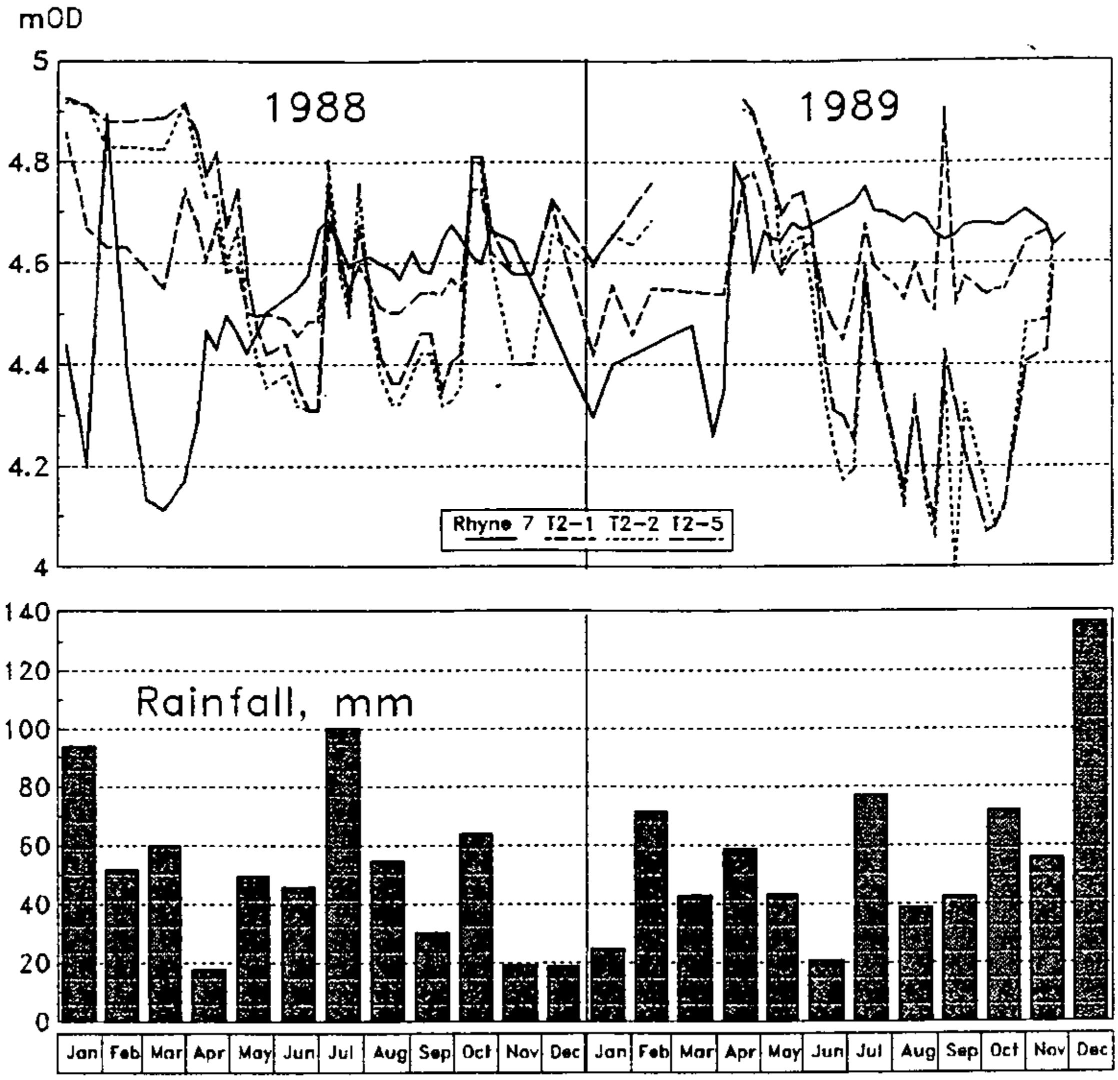

Figure 4.3 Groundwater levels in dipwells of transect 2, 1988–89

$$P + G_{in} = Q + E + G_{out} + \Delta s\ ,$$

where P is precipitation
G_{in} is the lateral groundwater inflow
Q is surface runoff
E is evaporation
G_{out} is the lateral groundwater outflow
Δs is the change in storage of soil water and groundwater.

During the summer, except at times of very high rainfall, the surface runoff Q will be zero, and the hydraulic gradient from the rhyne into the field ensures that the groundwater outflow G_{out} is also zero. The water balance thus simplifies to:

$$P + G_{in} = E + \Delta s$$

If reasonable estimates can be made of the unknowns in this equation, and if the assumptions are valid, it can be used for the estimation of the evaporation rate over an arbitrary time interval, as the method does not rely on the choice of endpoints with equal soil water and groundwater storage, for instance when the soil is at "field capacity". However, it is not possible to take account of surface runoff in the groundwater level method, so the method can only be used for periods when there is a significant soil moisture deficit: hence soil water storage must always be considered.

4.2 Specific yield estimation

It is assumed that the change in soil water and groundwater storage over a period is proportional to the change in groundwater level, i.e. that the most important component of subsurface water storage is the groundwater body. The constant of proportionality, which may vary with depth in the soil profile according to the degree of compaction of the peat, is termed the specific yield, and denoted by *S*. For an estimate of actual evaporation over a period which does not begin and end with zero SMD, it is essential that the specific yield be known.

4.2.1 A method of estimating specific yield

The specific yield may be estimated by examining the change in water level over a period when the precipitation input significantly exceeds evaporation, without generating surface runoff, i.e. for summer rainstorms. For a location towards the centre of a field, the lateral groundwater inflow over a short period is likely to be relatively small, compared with rainfall and evaporation, as both the permeability and the hydraulic gradient are known to be low.

For a time interval Δt between two water level readings, the change in groundwater storage

$$\Delta s = \sum (P - E) = S \Delta h$$

The rainfall record for the West Sedgemoor pumping station was used for *P*. The evaporation term was approximated by the MORECS monthly potential evaporation estimate, the average of estimates for squares 167, 168, 179 and 180, applied as a mean daily rate over the time interval Δt. The change in water level Δh was computed as the mean of changes in the three dipwells at the "field" end of each transect, i.e. dipwells 3, 4 and 5. Realistic values of *S* have been obtained for $\sum (P - E)$ greater than 5 mm, provided that the groundwater level was below 4.695 mOD. Above this level, there is a chance that surface runoff or shallow lateral groundwater flow may have occurred, giving rise to an over-estimate of the amount of water supplied to the groundwater body, and hence to a very high estimate of *S*. Estimates of *S* made by this method are presented in Table 4.1.

Transect T4 is in the same field as the lysimeter, so the specific capacity of 11.1% has been used in the lysimeter calculations of Section 3 of this report. Although there is some spread in the individual values of *S*, the averages for the four transects, for the years 1986 to 1989, range from 10.4% to 14.3%, and there is evidence to suggest that an extension of the data collection programme into the summer of 1990

Table 4.1 Specific yield estimates from water level changes

Date	Specific yield *S*, expressed as %			
	T1	T2	T3	T4
03/09/86	27.0	10.4	10.9	15.6
29/10/86	13.3	9.4	12.0	9.1
22/07/87	9.4	6.8		14.9
07/10/87	13.0	23.7	13.8	13.7
14/10/87	25.6	13.3	22.2	18.6
21/10/87	18.0	10.2	13.7	11.7
28/10/87	20.5	9.1	11.4	19.6
Mean 86-87	18.1	11.8	14.0	14.7
06/07/88	5.8	4.5	4.8	4.2
27/07/88	10.8	4.6	10.0	4.2
01/09/88			12.0	5.5
28/09/88	7.9	11.0	6.3	
Mean 86-88	15.1	10.3	11.7	11.7
13/07/89	21.2	13.1	24.4	11.2
16/08/89	9.1	5.5	12.6	7.9
20/09/89	12.1		11.7	6.4
25/10/89				4.4
01/11/89	7.0	13.8		19.8
Mean 86-89	14.3	10.4	12.7	11.1

would not have led to a substantial improvement in the estimates. Table 4.2 shows the improvement in the estimates obtained by using each successive year's figures, together with 95% confidence limits on *S*.

Table 4.2 Specific yield estimates and confidence limits for 1986 to 1989, %

Years	T1	T2	T3	T4
1986	20.1 ± 13.7	9.9 ± 1.0	11.5 ± 1.1	12.3 ± 6.5
1986-87	18.1 ± 5.0	11.8 ± 4.2	14.0 ± 3.4	14.7 ± 2.8
1986-88	15.1 ± 4.6	10.3 ± 3.5	11.7 ± 3.0	11.7 ± 3.6
1986-89	14.3 ± 3.7	10.4 ± 2.8	12.7 ± 3.0	11.1 ± 2.9

The March 1989 report quoted values of 18%, 12%, 17% and 16% respectively for the specific yields of the peat at the four transects. These higher estimates were affected by the inclusion of values obtained at the beginning and end of the summer, when surface runoff may have occurred.

4.3 Lateral inflow from the rhynes into the fields

The water balance equation may be rearranged:

$$E = P - S\Delta h + G_{in}$$

where P is the total precipitation over the time interval

S is the specific yield

Δh is the change in water level over the time interval

and G_{in} is the lateral inflow

The remaining unknown is the lateral inflow G_{in} which may be expected to be proportional to the difference between the water level in the centre of the field and that in the rhyne system. As rhyne levels vary on a short timescale, and are not available for all four transects, an approximation to the rhyne level in summer is taken as the mean level in the dipwell nearest the rhyne, $\bar{h}_1$

$\bar{h}_1$ = 4.624 mOD for T1

4.598 mOD for T2

4.534 mOD for T3

and 4.621 mOD for T4.

$$G_{in} = K(\bar{h}_1 - h_5)\Delta t$$

where h_5 is the water level in dipwell 5, the "field" dipwell

and Δt is the time interval over which the balance is taken.

There is a very limited data set from which to estimate the constant K: for this purpose reference is made to the results from the lysimeter in 1988 (see March 1989 report section 4). An equivalent of 48.4 mm of water was added to the lysimeter over the summer of 1988, to compensate for lateral inflow that was excluded by the lysimeter walls. The lysimeter was operated in such a way as to match the behaviour of dipwell T4–5, 42 m from the nearest rhyne. The value of the constant K is chosen so as to force the mean lateral inflow over the four transects in summer 1988, during the period 20 April to 12 October, to match this 48.4 mm. The hydraulic gradient away from the rhynes was much larger in both 1987 and 1989, and the formula above predicts average lateral inflows of 121.8 mm in 1987 and 129.6 mm in 1989.

The lateral inflow to any given square metre of a field will depend on the distance from a rhyne: very close to the rhyne the summer decline of the water table is much reduced, presumably by an increased lateral inflow, but the dipwell transect data indicate that the zone dominated by rhyne levels is relatively narrow, and in the absence of more detailed information it is assumed that the lateral inflow at the "field end" of the transect is representative of the average over the Moor as a whole.

4.3.1 Seasonal distribution of lateral inflow

The seasonal distribution of lateral inflow varies according to both rainfall and evaporative demand: in 1988 high July rainfall raised water levels and caused a temporary reversal in the hydraulic gradient, while during the latter part of the summers of 1987 and 1989 a steep and increasing hydraulic gradient into the fields would have led to an increasing lateral inflow, reaching a maximum rate of just over 1 mm/day. The lateral inflows, calculated as monthly means over the four dipwell transects, are presented in Table 4.3.

Table 4.3 Seasonal distribution of lateral inflow, in mm/day

	Year		
Month	1987	1988	1989
January			
February			
March			
April	0.0		
May	0.3	0.2	0.0
June	0.4	0.5	0.5
July	0.7	0.0	0.6
August	1.0	0.4	1.0
September	1.2	0.3	1.1
October	0.4	0.1	1.1
November			
December			

A similar table, derived from large-scale catchment water balances for an unspecified period, is presented by Twort *et alia* (1985)[2]. Values of subsurface irrigation for the South level fens of Cambridgeshire rose from 0.3 mm/day in April to 1.3 mm/day and 1.2 mm/day in June and July: a similar exercise for the Somerset Moors gave values averaging 0.3 mm/day:

	South level fens (Cambridgeshire)	Somerset Moors
March		
April	0.3	
May	0.8	0.3
June	1.3	0.2
July	1.2	0.4
August	0.6	0.4
September		0.1

4.3.2 Role of lateral inflow in the Moor water balance

The lateral inflow may also be regarded as a term in the summer water balance of the rhyne network, which may be itemised as follows:

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[2] Twort A C, Law F M & Crowley F W (1985) *Water supply* (3rd ed.), Federal (Hong Kong) & Edward Arnold (London), first published by Edward Arnold 1963.

Sub-irrigation data are presented as Table 3.2 on page 57 of 3rd edition.

Inflows

- Direct rainfall into rhynes
- Helland streamflow
- Oath Hill streamflow
- Wick Moor Rhyne flow
- Unspecified inflows

Outflows

- Evaporation from rhynes
- Pumping station
- Lateral flow into fields
- Change in volume of water contained in rhynes

Evaporation from the rhynes is a rather uncertain quantity, as the conditions of vegetation growth and exposure have an unknown effect. The rhynes make up about 1.8% of the total area of the Moor (see section 5.5 of the March 1989 report), and rhyne levels are relatively constant over the summer, so it can be assumed as a first estimate that there is a balance between direct rainfall, direct evaporation and change in storage. This leaves an approximate equality between the net surface water inflow and the lateral flow into the fields for the summer months.

Over the months of May to September 1988, the measured net surface water inflow to the rhynes was 374,000 m^3, indicating a lateral flow into the fields of 29 mm, or an average of 0.2 mm/day: in summer 1989, the net surface water inflow for the months of June to October was 1,132,000 m^3, equivalent to a lateral flow of 88 mm, or an average of 0.6 mm/day. These figures are 60% and 68% respectively of the estimates obtained from the dipwell and lysimeter results: this large but consistent discrepancy points to an additional source of water for the rhyne network in summer.

It is suggested that the unquantified contribution to the summer water balance of the Moor is groundwater flow from the slowly permeable Keuper Marl highland: the flow required would be a small proportion of the annual input of more than 20,000,000 m^3 to the highland catchment area. It has been noted (Section 2.7) that the base flow index of the Helland catchment is 0.44. If this base flow index also applies for the high ground flanking the Moor, the total available groundwater flow from these two ridges, not counting any flow from the Helland catchment, would be 1,288,400 m^3 in 1988 and 888,900 m^3 in 1989. Even allowing for the reduction of the groundwater component in summer, these figures are high enough to provide a significant supplement to the rhyne water balance.

4.4 Evaporation estimates from water level variations

The water balance equation as set out above assumes that the quantity of water stored in the soil is a simple function of the groundwater level. If the equation is applied to short time intervals, over which there is a significant change in groundwater level, the storage change is a significant term in the equation, and inaccuracies in this assumption, due for example to a significant unsaturated soil moisture component, become obvious. For this reason, the method is used to compute evaporation over as long a period as possible. The endpoints of the accounting periods were established by considering the dates of the early summer decline and of the return to winter levels. In 1987 and 1988 it was possible to choose the same endpoints for all four transects, but water levels were kept high at transect T1 in early 1989, and the accounting period for this transect begins later than at T2, T3 and T4. Missing readings for T3 for 1 November led to a slightly earlier end to the accounting period for this transect.

With the values of specific yield derived above, and taking into account the calculated lateral inflow, evaporation totals in mm were computed for the summers of 1987 to 1989, and are presented in Table 4.4.

Table 4.4 Evaporation totals for 1987, 1988 and 1989 summer periods

	T1	T2	T3	T4	Mean
10 April 1987 to 16 December 1987	501.8	479.9	495.9	502.1	494.9
20 April 1988 to 12 October 1988	380.6	400.3	390.1	380.3	387.8
7 June 1989 to 1 November 1989	350.4				
10 May 1989 to 1 November 1989		459.8		460.1	
10 May 1989 to 25 October 1989			457.6		

Assuming that, as is the case with the MORECS potential evaporation estimate, the summer periods in 1987 and 1988 account for 85.0% and 71.9%, and the three summer periods in 1989 for 57.4%, 71.0% and 69.6% respectively, of the annual total, the estimates in Table 4.4 can be scaled up to provide estimates of the annual totals for each transect. These are presented in Table 4.5.

Table 4.5 Annual evaporation totals computed from water levels

	T1	T2	T3	T4	Mean
1987	590	565	583	591	582 (103.4% MORECS)
1988	529	557	543	529	539 (93.4% MORECS)
1989	610	648	658	648	641 (95.4% MORECS)

5 THE WEST SEDGEMOOR BOREHOLE

5.1 Location

The borehole was sited at the end of Beercrowcombe Drove adjacent to the Middle Drain (ST 365263) in a central part of West Sedgemoor which was considered a representative site. Kidson and Heyworth (1976[3], Figure 9) estimated that the Holocene sequence attains a maximum of 15 m at the north east end of West Sedgemoor, and thins to the south west, giving an estimated thickness at the selected site of about 8 m. However a borehole drilled at ST 374279, about 2 km north east of the selected site (pers. comm. W G Grant, British Rail) proved a Holocene sequence of peat (4.9 m) over mud (8.4 m), resting on stiff brown silty clay interpreted as Mercia Mudstone (Keuper Marl). It was therefore anticipated that bedrock would be proved between 8 m and 13 m.

5.2 Method of drilling

A light cable percussion rig was used to obtain cores of the Holocene sequence and prove bedrock. Drilling was undertaken in accordance with BS5930 (1981) between 7 to 9 August 1989 using a lined 100 mm diameter open-tube sampler with a valvator core catcher (Vallally 1984[4]; Dixon 1989[5]) with 150 mm casing. It was not possible to core between 3.00 m and 6.55 m because of the fluid nature of peat at this depth.

5.3 Drilling results

The borehole proved 5.9 m of spongy peat over 3.8 m of very soft mud[6]. This was underlain by 0.6 m of a firm peat, over 0.7 m of soft Silt, over 0.45 m of muddy sandy gravel which was found to rest on silty Clay interpreted as Mercia Mudstone (Keuper Marl). Total drift sequence was therefore 11.45 m, proving the bedrock surface to lie at -6.34 mOD (lower than the -3.0 mOD estimate of Kidson and Heyworth, 1976). Drilling was terminated at 12.46 m. Details are presented in the borehole log (Figure 5.1).

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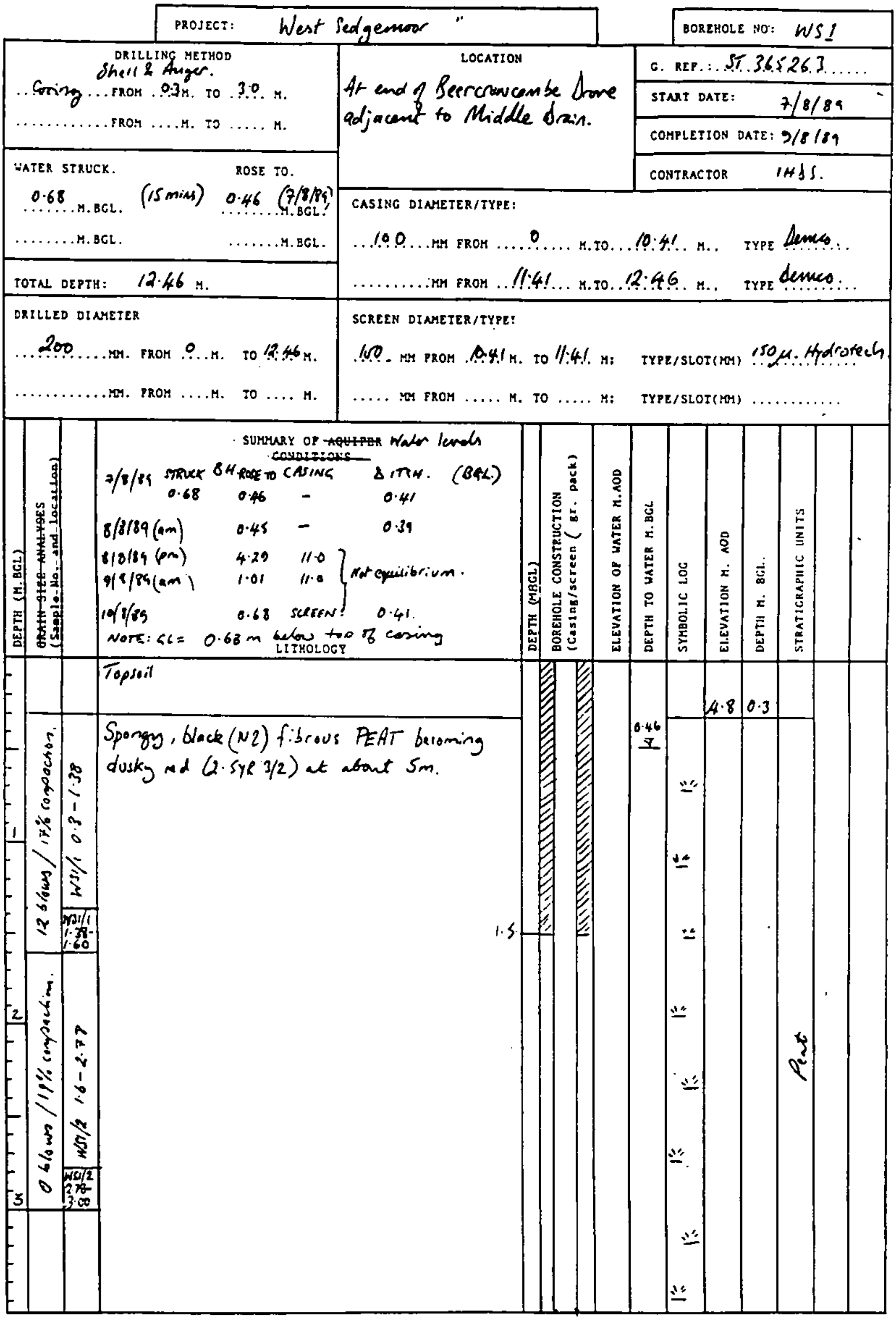
3 Kidson C & Heyworth A (1976) The Quaternary deposits of the Somerset Levels. *Q. J. Engng. Geol., Vol 9,* pp 217-235.

4 Vallally C O (1984) The 'Valvate' system related to percussive boring and sampling techniques, in "Site investigation practice: assessing BS5930", 20th Regional Meeting Eng Group, Geol. Soc., at Univ. Surrey, pp 474-482.

5 Dixon A J (1989) An open drive method for borehole sampling sand and gravel deposits, *Ground Engineering, 22(1),* pp 32-35.

6 precise thicknesses of deposits will be uncertain until the core is cut.



PROJECT: West Sedgemoor "

BOREHOLE NO: WS1

DRILLING METHOD
Shell & Auger.
Coring FROM 0.3 M. TO 3.0 M.
FROM M. TO M.

LOCATION
At end of Beercrowcombe Drove adjacent to Middle Drain.

G. REF.: ST 365263

START DATE: 7/8/89

COMPLETION DATE: 9/8/89

CONTRACTOR IH&S.

WATER STRUCK. 0.68 M.BGL. (15 mins)
ROSE TO. 0.46 (7/8/89) M.BGL.
M.BGL.
M.BGL.

TOTAL DEPTH: 12.46 M.

CASING DIAMETER/TYPE:
100 MM FROM 0 M. TO 10.41 M. TYPE Demco.
MM FROM 11.41 M. TO 12.46 M. TYPE demco.

DRILLED DIAMETER
200 MM. FROM 0 M. TO 12.46 M.
MM. FROM M. TO M.

SCREEN DIAMETER/TYPE:
100 MM FROM 10.41 M. TO 11.41 M: TYPE/SLOT(MM) 150μ. Hydrotech
MM FROM M. TO M: TYPE/SLOT(MM)

SUMMARY OF ~~AQUIFER~~ Water levels ~~CONDITIONS~~

	STRUCK	BH ROSE TO	CASING	ΔITH. (BGL)
7/8/89	0.68	0.46	–	0.41
8/8/89 (am)		0.45	–	0.39
8/8/89 (pm)		4.29	11.0	Not equilibrium.
9/8/89 (am)		1.01	11.0	
10/8/89		0.68	SCREEN!	0.41.

NOTE: GL = 0.68 m below top of casing

DEPTH (M.BGL)	~~GRAIN SIZE ANALYSES~~ (Sample No. and location)		LITHOLOGY	DEPTH (MBGL)	BOREHOLE CONSTRUCTION (Casing/screen (gr. pack)	ELEVATION OF WATER M.AOD	DEPTH TO WATER M.BGL	SYMBOLIC LOG	ELEVATION M. AOD	DEPTH M. BGL.	STRATIGRAPHIC UNITS
			Topsoil						4.8	0.3	
1	12 blows / 17% compaction.	WS1/1 0.3 – 1.38	Spongy, black (N2) fibrous PEAT becoming dusky red (2.5YR 3/2) at about 5m.				0.46 ▽				
		WS1/1 1.38-1.60		1.5							
2	0 blows / 19% compaction.	WS1/2 1.6 – 2.77									Peat
3		WS1/2 2.78-3.00									

Figure 5.1 Borehole log of the West Sedgemoor borehole

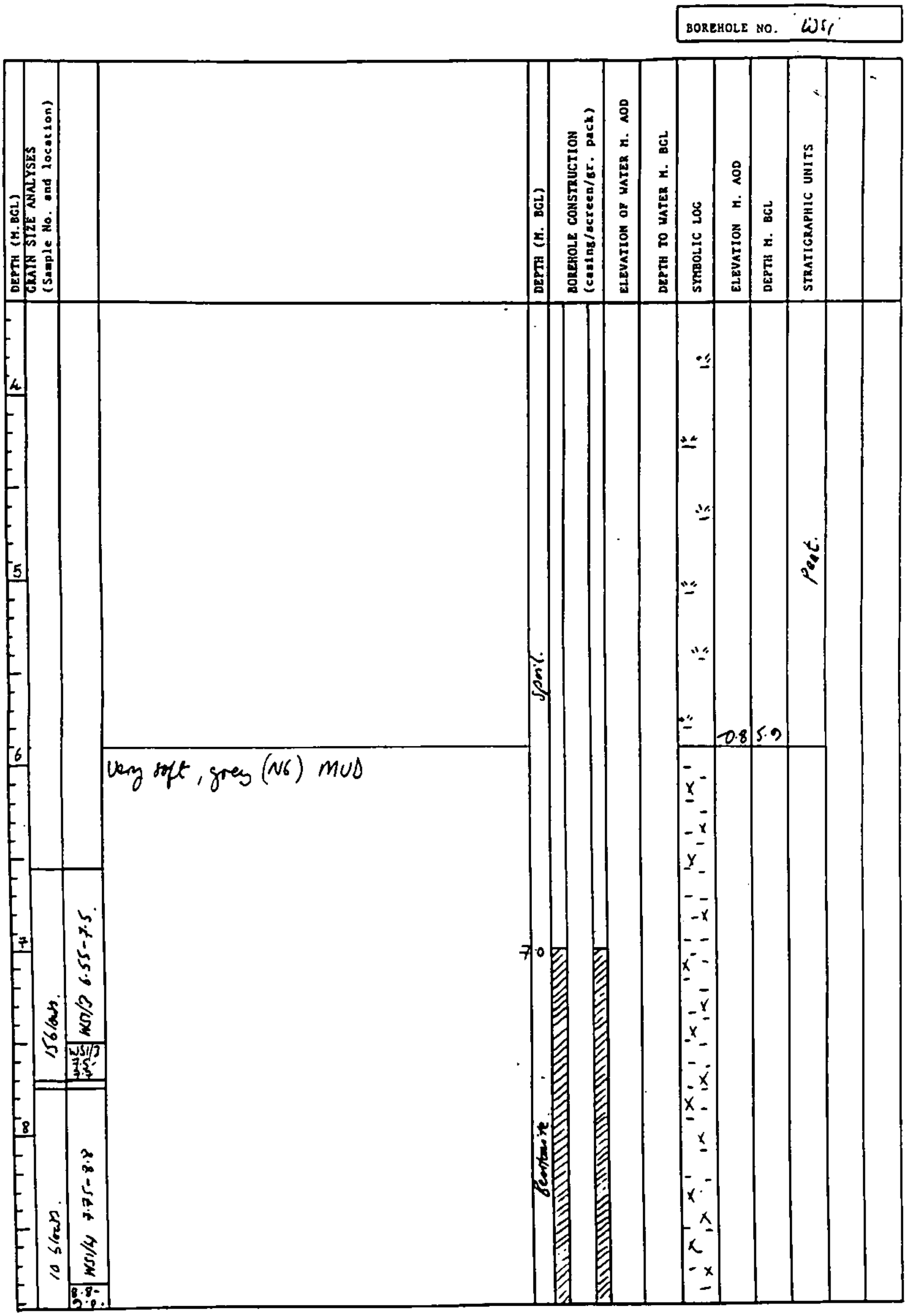
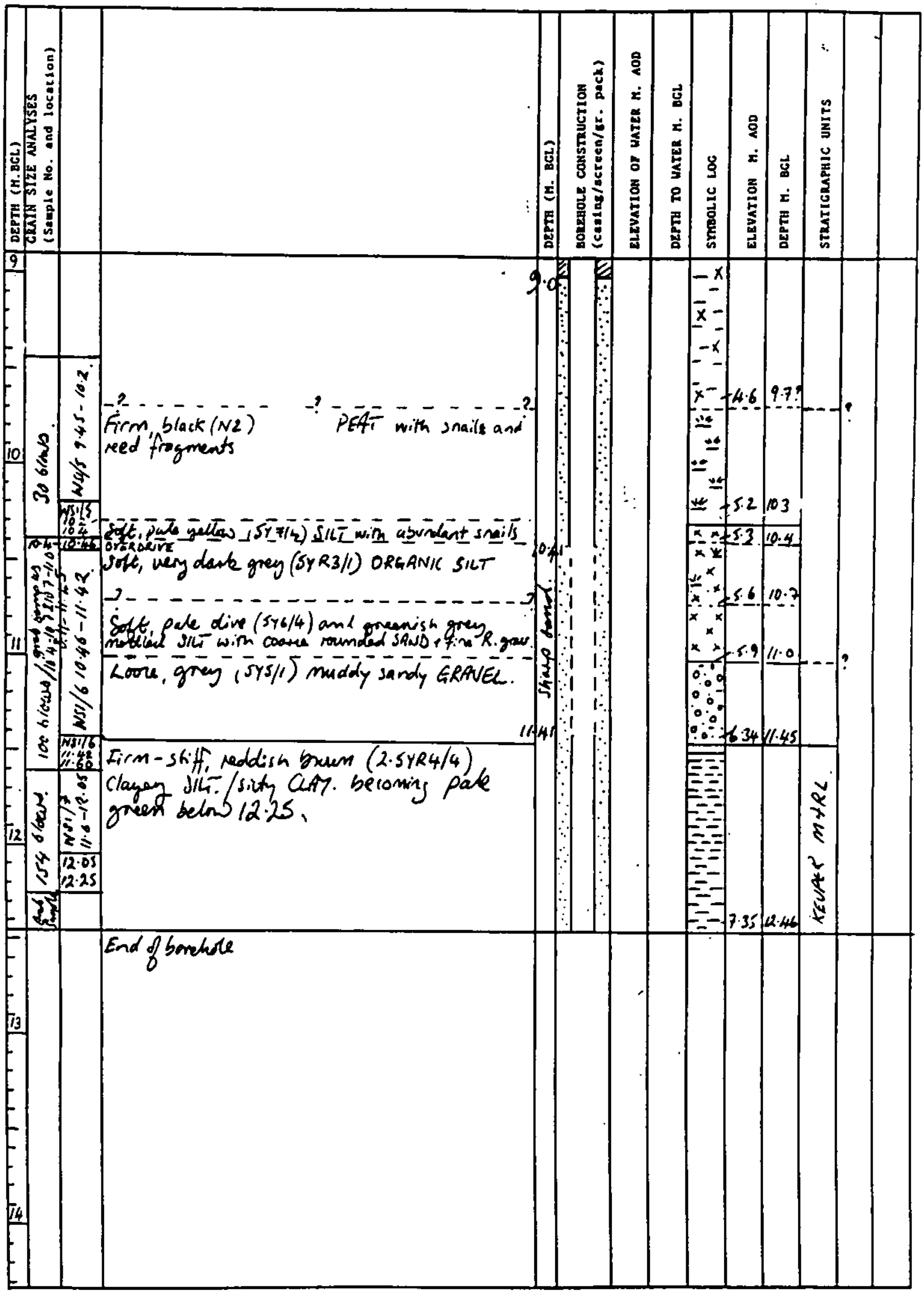


Figure 5.1(cont) Borehole log of the West Sedgemoor borehole

BOREHOLE NO. WS1



DEPTH (M. BGL)	GRAIN SIZE ANALYSES (Sample No. and location)			DEPTH (M. BGL)	BOREHOLE CONSTRUCTION (casing/screen/gr. pack)	ELEVATION OF WATER M. AOD	DEPTH TO WATER M. BGL	SYMBOLIC LOG	ELEVATION M. AOD	DEPTH M. BGL	STRATIGRAPHIC UNITS
9				9.0							
	30 blows	WS1/5 9.45-10.2	? - - - ? - - - ? Firm, black (N2) PEAT with snails and reed fragments						-4.6	9.7?	?
10		WS1/5 10.2-10.4							-5.2	10.3	
	10.4-	10.4-10.46	Soft, pale yellow (5Y 7/4) SILT with abundant snails						-5.3	10.4	
	100 blows/10.4-[illegible] good samples	WS1/6 10.46-11.42	OVERDRIVE Soft, very dark grey (5YR 3/1) ORGANIC SILT	10.41					-5.6	10.7	
			? - - - ? Soft, pale olive (5Y 6/4) and greenish grey mottled SILT with coarse rounded SAND + fine R. grav.	Sharp band					-5.9	11.0	?
11			Loose, grey (5Y 5/1) muddy sandy GRAVEL.	11.41					-6.34	11.45	
		WS1/6 11.42 11.60	Firm-stiff, reddish brown (2.5YR 4/4) Clayey SILT/silty CLAY. becoming pale green below 12.25.								KEUPER MARL
12	154 blows	WS1/7 11.6-12.05									
		12.05 12.25									
	End Sample								-7.35	12.46	
			End of borehole								
13											
14											

Figure 5.1(cont) Borehole log of the West Sedgemoor borehole

5.4 Completion

A nominal 100 mm 'Demco' well casing was installed to the total depth of 12.46 m with a screened section between 10.41 m and 11.41 m below ground level (BGL). The screen was 150 µ gauge 'Demco' filter mesh. The annulus between the well and the casing was filled with sand as the casing was withdrawn up to 9.0 m BGL. Bentonite pellets were then emplaced between 7.0 m and 9.0 m BGL. The rest of the annular space was backfilled with soil.

5.5 Discussion

The thin gravel layer resting on the Mercia Mudstone is interpreted as a fluvial or soliflucted deposit of the Devensian or early Holocene. The overlying sequence of silt, lower peat, mud and upper peat is considered as infill of a buried valley system with sedimentation 'keeping pace' with the Holocene rise of sea level.

The cores must be cut and palaeontologically analysed in order to determine whether the deposits are marine or freshwater. Kidson and Heyworth (1976, Figure 11a) suggest that marine sedimentation extended as far inland as West Sedgemoor at about 6000 BP.

The Mercia Mudstone can be considered as effectively impermeable. The overlying Holocene sequence can be expected to have hydraulic conductivity values ranging from high in the gravel layer, low to moderate in the peat and silt, to low in the mud. Specific yield will vary from high in the gravel to low in the peat, silt and mud.

Water was struck in the borehole at 0.68 m BGL and rose to 0.46 m BGL. This level was found to be 0.05 m lower than the water level in the Middle Drain adjacent to the borehole site. This is consistent with monitoring results elsewhere (e.g. rhyne water level recorder 5 plotted against dipwell T4-1) which show rhyne levels to be higher than the water table in the peat in summer (as the rhyne levels are kept high during this season) and the reverse to occur in winter.

Water level after installation of the well screen showed a drop of 0.22 m (over 3 days) with rhyne level remaining more or less constant. This suggests a vertical flow component downwards, with the screened zone possessing different areas of recharge and discharge.

Monitoring results from the borehole (Table 5.1) show a similar pattern on the dipwell water levels in the peat in relation to rhyne water levels. However there is a significant drop of 0.21 m between 11 October 1989 and 18 October 1989, which is not mirrored in the dipwell monitoring results. Borehole levels before 10 October 1989 are higher for example than levels in dipwell T4-1, but are lower after 11 October 1989.

To assist the interpretation of Table 5.1, on each day where data are available for all three sources, the water level from each of the three sources is indicated in bold denoting highest, normal text for middle and italics for lowest.

Table 5.1 Relationship between water levels in borehole, Middle Drain and adjacent dipwell (mOD).

Date	Borehole water level (ST 365263)	Rhyne recorder 5 water level (ST 378276)	Transect 4 2 m dipwell (ST 371270)
13 Sep 89	4.656	**4.680**	*4.589*
27 Sep 89	4.667	**4.717**	*4.634*
11 Oct 89	*4.675*	**4.678**	---
18 Oct 89	4.465	**4.676**	*4.615*
25 Oct 89	*4.470*	4.682	**4.697**
1 Nov 89	*4.538*	**4.703**	---
15 Nov 89	*4.572*	4.636	**4.732**
20 Nov 89	*4.603*	4.623	**4.648**
29 Nov 89	*4.591*	4.666	**4.669**
20 Dec 89	*4.611*	**5.083**	---
10 Jan 90	**4.827**	*4.640*	4.779
24 Jan 89	**4.868**	*4.591*	4.807
14 Mar 89	**4.847**	*4.399*	4.527
30 Mar 90	**4.774**	*4.313*	4.416

6 CONCLUSIONS

Over the course of this study, the actual evaporation from West Sedgemoor has been determined for the years 1987 to 1989 by a variety of methods, ranging in scale from the 0.6 m^2 lysimeter to the entire 42 km^2 West Sedgemoor catchment. In the March 1989 report, three rather different estimates were derived for 1988, ranging from 70% to 98% of MORECS PE (averaged over four 40 km squares), and the estimate for 1987, derived only from dipwell data, was 88% of MORECS PE.

The extension of the study to cover the 1989 season has made it possible to obtain comparable estimates of 1989 actual evaporation from the three methods, the installation of new raingauges on the highland has improved the quality of the water balance estimate and the larger data set now available from the dipwell transects has refined the estimates from the lysimeter and the dipwell method.

The catchment water balance (Section 2.8.3) yields an estimate of 688 mm (102.4% of MORECS PE), but this estimate is still haunted by the uncertainty of the Helland gauging station, linking the two areas considered in the catchment water balance. Refinement of the rainfall estimates (Section 2.11.1) has made it possible to re-compute the 1988 figure with more confidence: this estimate was revised upwards to 446 mm (77.3% of MORECS PE).

The lysimeter was operated through the summer of 1989, but the water level fell to the bottom of the lysimeter, and evaporation estimates over the mid-summer months appear to be affected by the soil moisture deficit. Nevertheless, an estimate of the 1989 total actual evaporation was obtained (Section 3.2.1). This estimate, 590 mm, is 87.8% of MORECS PE. Using a revised value of the specific yield obtained from the extended dipwell record, the 1988 lysimeter figure has been re-computed (Section 3.1.1). For 1988, the lysimeter gives 540 mm, or 93.6% of the MORECS PE.

The extended dipwell data set has been used to obtain a reliable estimate of the specific yield at each of the four transects (Section 4.2.1). The specific yield obtained in this way ranges from 10.4% to 14.3%. When applied to the dipwell water level data using the method described in the March 1989 report, an estimate of summer evaporation can be obtained for each transect, for each of the years 1987 to 1989 (Section 4.4). These estimates can be scaled up to give annual totals:

1987	582 mm (103.4% MORECS PE) with a range of 565 to 590 mm for the four transects
1988	539 mm (93.6% MORECS PE) with a range of 529 to 557 mm
1989	641 mm (95.4% MORECS PE) with a range of 611 to 658 mm

The three methods have yielded altogether seven estimates of annual evaporation from West Sedgemoor:

Year	Water balance (% PE)	Lysimeter (% PE)	Dipwells (% PE)	Average (% PE)	MORECS AE (mm)	MORECS AE (% PE)	MORECS PE (mm)
1987			103.4	103.4	496	88.0	563
1988	77.3	93.6	93.4	88.1	552	95.6	577
1989	102.4	87.8	95.4	95.2	509	75.8	672

In the table the various estimates are expressed as percentages of the MORECS potential evaporation averaged over squares 167, 168, 179 and 180. There does not appear to be any significant systematic variation of the percentage from year to year, for example as a function of potential: it is suggested therefore that the actual evaporation from West Sedgemoor be considered as a constant percentage of the potential. In contrast, the MORECS actual evaporation is controlled by the soil moisture deficit, and was much reduced, as a proportion of the potential, in 1989.

The lowest and highest figures, 77.3% from the water balance method in 1988 and 103.4% from the dipwells in 1987, should be regarded as outliers: the dipwell result for 1987 is unsupported by other results, while the water balance estimate for 1988 is based on synthesised data for the Weaver's Farm and Meare Green Court raingauges (Sections 2.10 and 2.11.1). The mean of the other five values is 94.5%. **The actual evaporation from West Sedgemoor may therefore be taken as 95% of the MORECS PE, averaged over squares 167, 168, 179 and 180.**

Using both the lysimeter results and the dipwell data, it has also proved possible to estimate the lateral inflow from the rhynes into the fields (Section 4.3). This amounted to 122 mm in the summer of 1987, 48 mm in 1988 and 130 mm in 1989. The pattern in the two dry years of the study was of a lateral inflow that increased over the summer, reaching just above 1 mm/day at the end of the summer. This lateral flow is not entirely met from the net surface water input to the Moor, from the Helland Brook, the Oath Hill sluice and the Wick Moor Rhyne, but is partly compensated by an additional source, which is believed to be groundwater flow from the valley flanks (Section 4.3.2).

The Beercrowcombe Drove borehole shows a considerable thickness of soft deposits at West Sedgemoor: 5.9 m of peat on 3.8 m of mud. At the base of the sequence there are horizons of silt and gravel lying on Keuper Marl, and the upper surface of the Keuper Marl was encountered at -6.34 mOD. Some of the peat was too fluid to core: this fits in well with the observations of seasonal ground surface movement, which will be discussed in the 1991 report to NCC and NRA-Wessex.

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The terms of reference of both this and the original March 1989 report were defined by Dr A T Newman, Divisional Engineer, NRA-Wessex.

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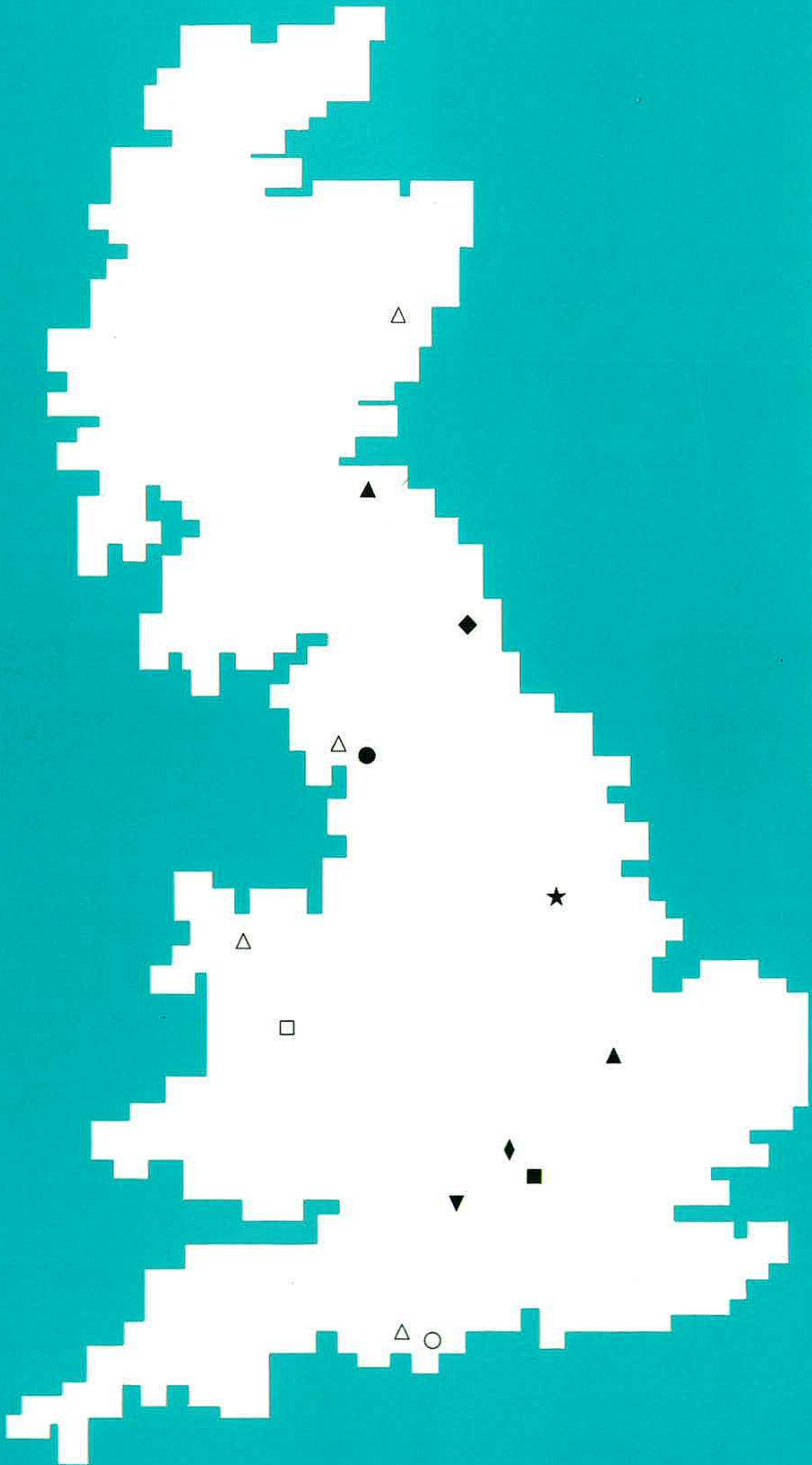

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