INSTITUTE of HYDROLOGY

HYDROLOGICAL STUDIES OF WEST SEDGEMOOR
1986 - 1989

Report prepared for Wessex Rivers

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1 INTRODUCTION

Hydrologically, West Sedgemoor is one of the simplest of the peat moors of Somerset, occupying a small compact catchment with little building development. The Moor itself is mostly used for low intensity grazing, but there are pockets of more intensive farming activity, and a long history of conflict between various interests, notably agricultural intensification and wildlife conservation. The outfall from the Moor is through the West Sedgemoor Pumping Station (WSPS) at OS grid ref. ST376286, operated by the Wessex Water Authority: the pump is used to remove floodwater and to provide flood storage by maintaining a low water level in the network of ditches, or rhynes, in winter, but in summer a higher level is maintained by the supply of water through a sluice from the River Parrett, to provide "wet fencing" on the Moor.

In 1986 the Institute of Hydrology (IH) was commissioned by the Nature Conservancy Council (NCC) to undertake a programme of hydrological monitoring which could be used as a basis for decisions about the penning levels of West Sedgemoor. The Wessex Rivers Division of Wessex Water Authority supplemented this study with backing for an investigation of the consumptive use of wet fencing, and provided assistance in the form of construction and operation of a gauging station and staff gauges, topographic survey and the provision of data from the Pumping Station. Figure 1.1 shows the layout of measurement sites on and around West Sedgemoor.

This report summarises the work on the consumptive use project, funding for which comes to an end in March 1989. It is expected that the continuing NCC project will furnish further information relating to the water balance, and it is proposed to carry on the operation of water level recording stations, dipwells and the lysimeter.

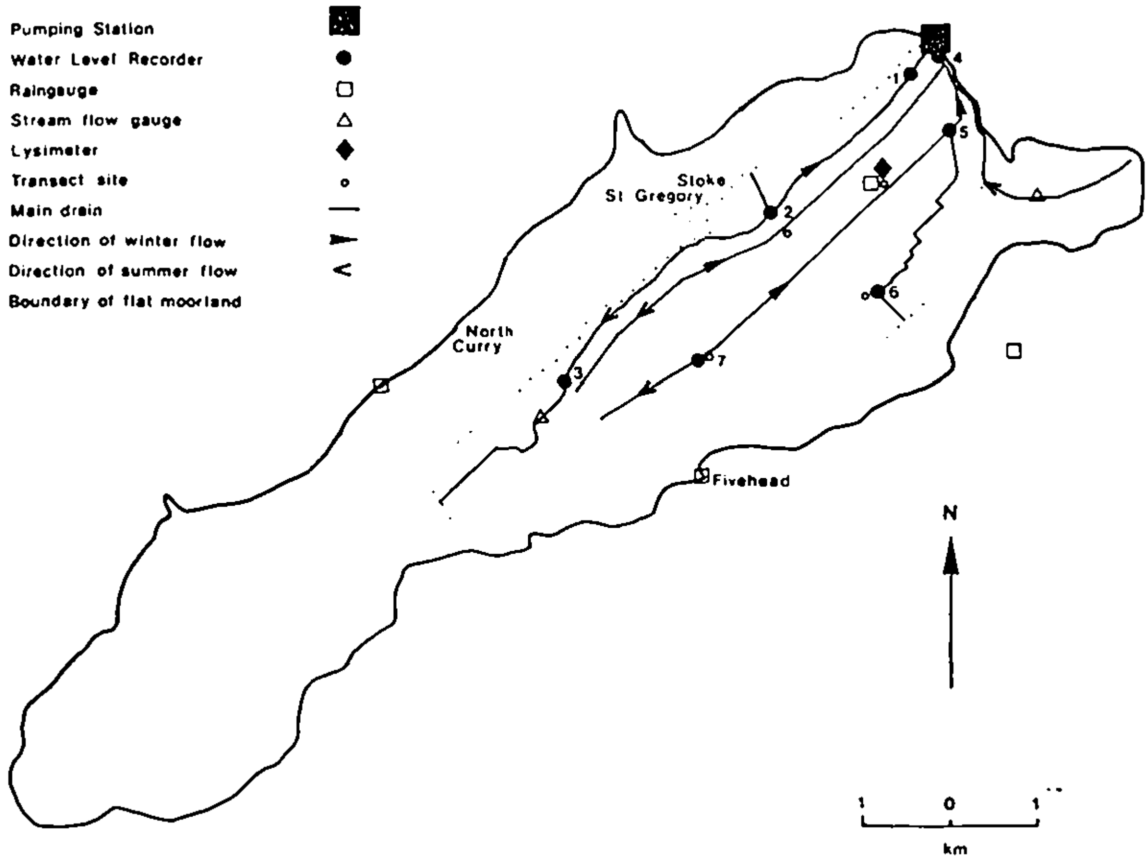

Figure 1.1 Location plan of rainfall and surface water measurement stations

2 WATER BALANCE STUDIES

It was the intention from the beginning of this study to use the water balance method for the determination of evaporation from West Sedgemoor. This method requires the accurate measurement of all inputs and outputs of water from a catchment area, with the sole exception of the unknown evaporation. The land surrounding West Sedgemoor is underlain by Keuper Marl, an impermeable silty mudstone, capped on the southeast side by the clayey Rhaetic and Lower Lias deposits. There is little prospect of deep infiltration to a groundwater body in the bedrock of the catchment, or of groundwater supply to the Moor.

For the purposes of quantifying input, the West Sedgemoor catchment has been divided into three distinct zones:

(i) the area above the Wessex Rivers gauge at Helland

(ii) the areas of highland surrounding the Moor to the north west and south east

(iii) the Moor itself.

Five inputs of water to West Sedgemoor have been identified, and one surface outflow. These inflows and outflow are discussed in detail in Sections 2.1 to 2.6 of this report. Only during 1988 was the data available in full for all six of the "known" components of the water balance, and this calendar year has therefore been chosen for the water balance studies.

2.1 Rainfall over West Sedgemoor

Rainfall falling directly on the Moor has been measured by a 15 minute recording raingauge sited in a field owned by NCC, at OS grid reference ST371270, field no 0700. It has been established using data collected during a period of a year, October 1987 to September 1988, that there is a small but relatively consistent difference between the rainfall recorded at this gauge and the Wessex Rivers daily rainfall gauge sited at West Sedgemoor Pumping Station (WSPS). The resulting regression equation developed to predict daily rainfall at the IH gauge from that at the pumping station had the form

$$\text{Daily rainfall (IH)} = 0.1 + 1.03 \times \text{Daily rainfall (WSPS)}$$

where the units are mm.

During 1988, the period of the water balance studies, some of the data from the IH raingauge was lost, owing to disturbance of the field equipment by livestock. It was therefore decided that because of the virtually identical data arising at both gauges and the more complete record available at WSPS, the data from the WSPS raingauge would be used in preference to that collected by the IH raingauge.

The WSPS rainfall was applied to the area of the Moor (given by the April 1977 MAFF schedule of land drainage pumping stations as 12.8 km^2), and monthly totals were calculated.

2.2 Rainfall on surrounding highland

Rainfall on the land surrounding West Sedgemoor (within the catchment drained by WSPS, but draining towards the Moor downstream of the Helland gauge) is higher than on the Moor itself, as demonstrated by standard period isohyetal maps. The initial intention to make use of rainfall data from three sites at North Curry, Curry Rivel and Fivehead was frustrated by the closure of the first two of these sites during

1988. Data from the remaining Fivehead rain gauge at OS grid reference ST349235 has been taken as being representative of the 60 m altitude terrain either side of the Moor.

The area of land within the WSPS catchment below the Helland streamflow gauge but excluding the Moor itself, has been calculated as 14.0 km^2. Because this terrain varies between 5 m OD and 60 m OD, the average of the rainfall occurring at the WSPS gauge and that at the Fivehead gauge has been applied to this area in order to compute monthly totals.

2.3 Streamflow gauged at Helland

The Wessex Rivers streamflow gauge at Helland (OS grid reference ST331243) is essentially a velocity-area section with an elm board mounted in the bed to act as a control. Data is recorded at a 15 minute interval and the calibration is by current metering. It became operational in February 1987 and continuous data has been available since the end of March 1987. The station gauges an area of 15.2 km^2 above Helland which rises to a level of 100 m OD and follows a line marked by the villages of Newport, Wrantage and West Hatch.

2.4 Wick Moor Rhyne streamflow

During the period March to December, there is surface water inflow to West Sedgemoor via Wick Moor Rhyne, which enters the Moor near its northeastern end. The streamflow is gauged as it passes through a square orifice in the wing wall of a sluice at OS grid ref. ST387268. To gauge the flow accurately, a thin plate weir incorporating a variable level crest (designed in accordance with BS3680:Part 4A:1965) was attached to the orifice inlet. A water level recorder was located immediately upstream of the sluice to record the head over the crest. The crest level remained under the supervision of Wessex Rivers and was noted by IH at monthly intervals.

2.5 Oath Hill streamflow

Surface water streamflow from the River Parrett enters West Sedgemoor via a sluice/culvert arrangement north of Oath farm, at OS grid ref. ST386276. The inflow takes place during the months of April to December and has been current metered at a weekly interval since October 1987. Linear interpolation has been used to estimate the flow on intervening days.

2.6 Pumping stations

2.6.1 Diesel pumping station

The pumping stations are regarded as the only point at which streamflow is removed from West Sedgemoor. The pump "characteristic curve" allows the pump rate to be determined at pump on/off times when the known static hydraulic head can be computed from the suction and delivery water levels. This information is applied to the operator log sheet data, which consist of records of the periods of operation of the diesel pumps and the associated suction and delivery water levels at pump on/off times, to generate a daily pumped flow record. Such derived data has been computed for the period November 1963 to December 1988.

2.6.2 Electric pumping station

The electric pumping station, which commenced operation in January 1987, was fitted with a cumulative pumped flow meter in September 1987. Prior to September 1987, an estimate of the pumped flows was made based on the "hours run" data and the pump running speed. Following September 1987, derived daily pumped flows were generated from a daily reading of the cumulative pumped flow meter.

A comparison was made between the post-September 1987 derived daily pumped flows generated using the flow meter information and those predicted by using the same approach as had to be used for the pre-September 1987 data before the flow meter had been installed. The daily flows derived from the flow meter information were on average 18% lower than those derived using the "hours run" and pump running speed method. The pre-September 1987 derived daily pumped flows were accordingly reduced by 18%. Daily pumped flows have been calculated for the electric pumping station between January 1987 and December 1988 inclusive.

2.7 Water balance over catchment above Helland gauge

The Helland streamflow gauge allowed an estimation of evaporation over the catchment area above the gauge which could be used as an indicator of evaporation over that part of the catchment discussed in section 2.2 above. Table 2.1 illustrates the monthly components of the water balance. Data for an 18 month period are included in the table, although the period to be selected for a water balance should extend between dates on which the soil moisture deficit is the same: normally a period of 12 consecutive months between dates when there is a zero soil moisture deficit.

Water balance July 1987 - June 1988

Rainfall = 666 mm

Streamflow = 268 mm

Evaporation = 666 - 268 = 398 mm

Water balance January 1988 - December 1988

Rainfall = 612 mm

Streamflow = 215 mm

Evaporation = 397 mm

[cf Shaw ([illegible]) [illegible] for 1987 [illegible] 441 [illegible] 4/6/89]

Table 2.1 Monthly rainfall and streamflow for Helland catchment

Month	Rainfall at Fivehead (mm)	Streamflow (mm over 15.2 km^2 catchment)	Rainfall minus streamflow (mm)
Jul 87	42.4	3.5	38.9
Aug 87	31.2	1.2	30.0
Sep 87	30.7	1.9	28.8
Oct 87	137.3	27.5	109.8
Nov 87	52.0	30.2	21.8
Dec 87	35.4	15.9	19.5
Jan 88	112.1	73.0	39.1
Feb 88	56.0	64.9	-8.9
Mar 88	62.1	30.0	32.1
Apr 88	21.7	10.9	10.8
May 88	42.4	5.6	36.8
Jun 88	42.8	3.6	39.2
Jul 88	83.5	4.4	79.1
Aug 88	65.1	3.5	61.6
Sep 88	31.1	3.8	27.3
Oct 88	61.2	5.6	55.6
Nov 88	17.0	3.4	13.6
Dec 88	16.5	6.3	10.2
Totals			
Jul87-Jun88	666.1	268.2	397.9
Jan88-Dec88	611.5	215.0	396.5

The 12 month period chosen for a water balance can influence the result if part of the year is unusually wet or dry and there is a significant groundwater storage element in the catchment. The Helland gauge hydrograph, supported by a study of the last 25 years of records from the WSPS raingauge, shows the end of 1988 to have been unusually dry, so the water balance calculations have been executed for two overlapping 12 month periods. The resulting two estimates of evaporation are very similar.

2.8 Water balance over West Sedgemoor

The period selected for the West Sedgemoor water balance was the calendar year 1988. Table 2.2 details the monthly inflows to West Sedgemoor, Table 2.3 the monthly outflows.

Table 2.2 Inflows to West Sedgemoor

Month	WSPS rainfall mm	Fivehead rainfall mm	Helland streamflow cumec-days	Wick Moor streamflow cumec-days	Oath Hill streamflow cumec-days
Jan 88	92.9	112.1	12.834	nil	nil
Feb 88	51.2	56.0	11.426	nil	nil
Mar 88	59.0	62.1	5.270	nil	nil
Apr 88	17.3	21.7	1.920	0.503	nil
May 88	48.9	42.4	0.992	1.143	2.291
Jun 88	45.3	42.8	0.643	0.923	2.275
Jul 88	99.2	83.5	0.790	1.082	2.472
Aug 88	54.0	65.1	0.620	1.030	2.807
Sep 88	29.6	31.1	0.660	0.869	2.507
Oct 88	63.4	61.2	0.992	1.418	2.666 E
Nov 88	18.8	17.0	0.600	1.003	2.580 E
Dec 88	18.3	16.5	1.116	0.603	1.720 E
Total	597.9	611.5	37.863	8.574	19.318

Wick Moor Rhyne central sluice closed 21 March 1988 - 21 December 1988

E estimated

Table 2.3 Pumped outflows from West Sedgemoor

Month	Diesel station (cumec-days)	Electric station (cumec-days)
Jan 88	19.804	10.044
Feb 88	35.685	8.584
Mar 88	11.001	5.859
Apr 88	0.000	3.510
May 88	0.000	3.193
Jun 88	0.000	3.570
Jul 88	0.118	4.867
Aug 88	0.000	1.922
Sep 88	0.369	2.730
Oct 88	0.030	6.696
Nov 88	0.000	3.870
Dec 88	0.000	4.464
Total	67.007	59.309

The water balance was carried out over the area of West Sedgemoor and the area of highland below the Helland gauge. The area above the Helland streamflow gauge generates an input to the water balance in the form of streamflow, but is not included in the area of the analysis.

The area of West Sedgemoor itself has been taken as 12.8 km^2.

The area of highland surrounding the Moor, below the Helland gauge, has been digitised as 14.0 km^2.

2.8.1 Inflows

2.8.1.1 Rainfall over West Sedgemoor

The 1988 annual rainfall at the pumping station was 598 mm, which when applied to the 12.8 km^2 area gives rise to a volume of

$$(12.8 \times 10^6) \times 0.598 = 7{,}654{,}000 \text{ m}^3$$

2.8.1.2 Rainfall over highland below the Helland gauge excluding the Moor

The 1988 annual rainfall at Fivehead was 611.5 mm. The average of the Fivehead and pumping station rainfall (605 mm) when applied to the 14.0 km^2 area gives rise to a volume of

$$(14.0 \times 10^6) \times 0.605 = 8{,}470{,}000 \text{ m}^3$$

2.8.1.3 Streamflow recorded at the Helland gauge

The figure of 37.9 cumec-days representing the total streamflow during 1988, shown in Table 2.2, is equivalent to a volume of 3,275,000 m^3

2.8.1.4 Streamflow recorded at Wick Moor Rhyne sluice

Although the sluice gate was closed on 21 March 1988, the rhyne water level did not rise above the weir crest level until mid-April, and this accounts for the absence of a figure for March 1988 in Table 2.2. The total streamflow recorded during 1988 was 8.6 cumec-days, which is equivalent to 740,800 m^3.

2.8.1.5 Streamflow recorded at Oath Hill sluice

The assessment of inflow at this point is probably not as accurate as that of the other inputs, because the flow is measured at weekly intervals rather than continuously. In particular the time at which the sluice was first opened during 1988 is not certain; it is believed that it was opened and shut several times during April before being left open at some point in May. In addition, the current metering was discontinued during October 1988, the fieldworker incorrectly believing the sluice had been shut. The best estimate of the total 1988 streamflow is 19.3 cumec-days, a figure that translates to 1,669,000 m^3.

2.8.2 Outflows

The outflows from the diesel pumping station and the electric pumping station total 126.3 cumec-days, which is equivalent to 10,910,000 m^3.

2.8.3 Water balance

The sum of the inflows is computed to be

Rainfall on West Sedgemoor	7 654 000
Rainfall on highland below Helland gauge	8 470 000
Helland streamflow	3 275 000
Wick Moor rhyne streamflow	743 000
Oath Hill sluice	1 668 000
Total	21 810 000 m^3

The result of subtracting the outflow from the several inflows is a net inflow volume of 10,900,000 m^3.

Figure 2.1 illustrates the seasonal development of the net inflow figure.

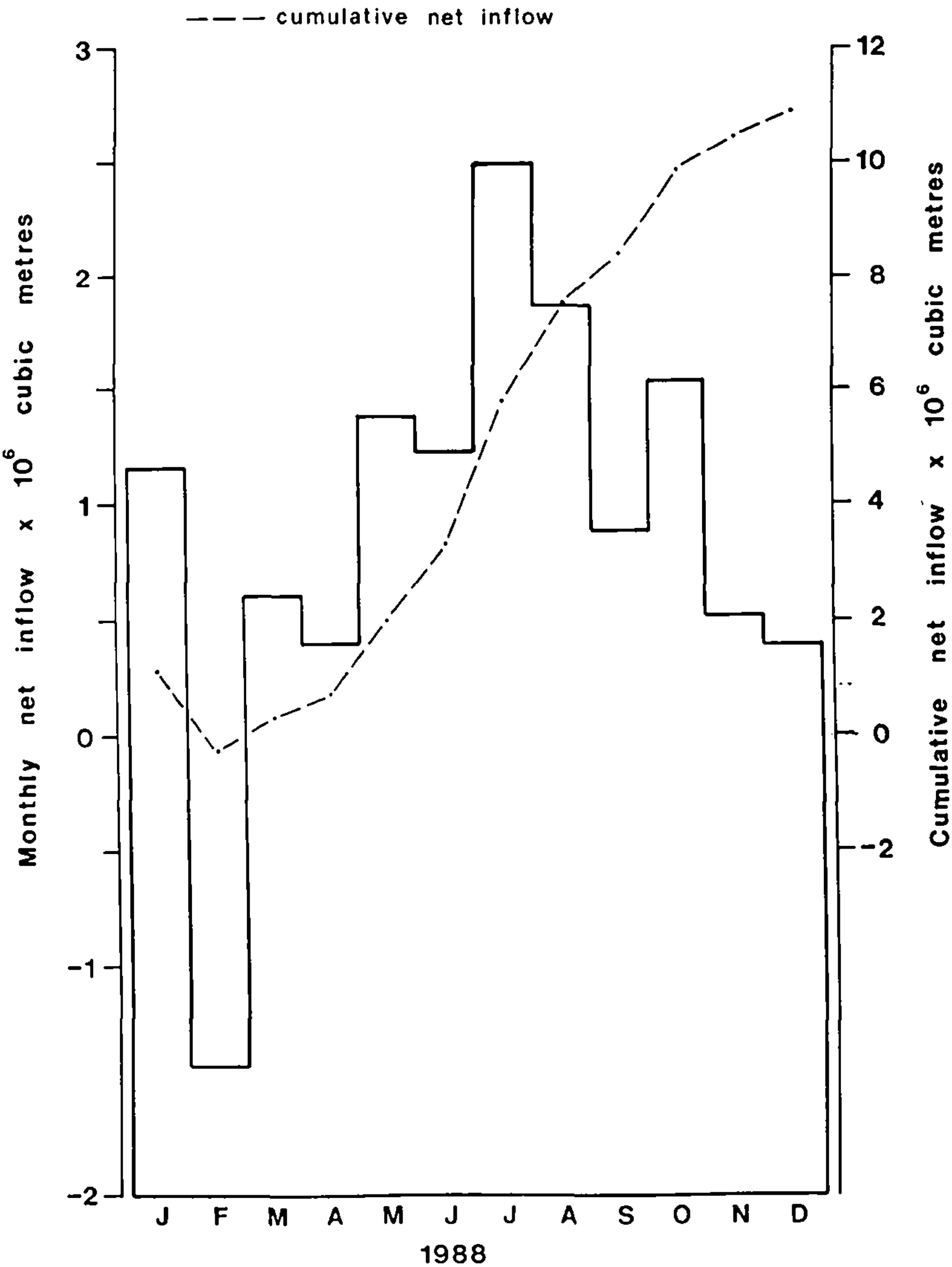

Figure 2.1 Monthly net inflow to West Sedgemoor

The evaporation from the highland below the Helland gauge (E_H) is likely to resemble that of the area above the Helland gauge rather than that of the Moor itself. The evaporation calculated for the area above the Helland gauge is 397 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 gauge, and is termed E_M.

(Area below Helland gauge x E_H) + (Area of Moor x E_M) = 10,900,000 m^3

$$(14 \times 10^6) \times 0.397 + (12.8 \times 10^6) \times E_M = 10,900,000$$

Therefore the evaporation over the Moor (E_M) = 417 mm.

2.9 Sensitivity analysis

It is instructive to consider the implications of uncertainties in the water balance calculations included in sections 2.7 and 2.8.

2.9.1 Catchment above the Helland gauge

There is a single inflow and single outflow for this catchment, the rainfall and the Helland streamflow. The gauge used to estimate the rain over the catchment was that at Fivehead. This raingauge is 5.5 km from the centroid (Meare Green) of the catchment and at a comparable altitude. It is probable that a gauge near the centroid would have recorded a slightly different rainfall, but unlikely that the error introduced by using the Fivehead data would have been more than 5%.

The flow data from the Helland streamflow gauge was calculated by Wessex Rivers and have been accepted and used as supplied.

The post July 1987 current meter gaugings used in the construction of the (Wessex Rivers) rating curve for the Helland gauge, have been applied to a program which computes a 'best fit' rating curve of the type

$$Q = C\,(H + A_0)^B$$

In doing so, one gauging (that taken on 21 October 1987) was considered such an outlier that it was omitted from the analysis.

The coefficients of the resulting equation were found to be

C = 4.84
A_0 = -0.01
B = 2.17

r^2 = 0.974

H, A_0 are expressed in metres to give Q in m^3/s

The (IH) rating curve thus derived was not used to recompute the Helland flow data.

95% confidence limits on the above rating curve have also been computed and are shown in Table 2.4.

During 75% of the year, the flow was between 0.017 and 0.095 cumecs, where the 95% confidence limits on the rating curve are +29% and -22%.

Table 2.4 95% confidence limits on Helland rating curve

Flow (cumecs)	95% limits upper (%)	lower	Number of days during 1988 when flow is between these values
			0
0.009	+38	-27	
			19
0.017	+30	-23	
			166
0.025	+28	-22	
			49
0.044	+27	-21	
0.049	+27	-21	
			30
0.073	+29	-23	
			20
0.095	+31	-24	
			40
0.941	+69	-41	
			32
1.076	+72	-42	
			3

The error bands calculated are far wider than would be expected for a streamflow gauge. It is recognised that the spread of spot gaugings used in the derivation of the rating curve derived from the enforced selection of what was not an ideal site and that there was little or no scope for the selection of a better site.

If the rainfall was in error by +5% and the streamflow volume was in error by +29% or -22%, the worst case outcomes of a water balance over the catchment above the Helland gauge for 1988 would be as follows

Water balance on catchment above Helland gauge - 1988

1. If rainfall was in error by +5%
   True rainfall = 0.95 x 611.5 = 581 mm

   If streamflow was in error by -22%
   True streamflow = 1.22 x 215 = 262 mm

   Therefore true evaporation = 581 - 262 = 319 mm

   i.e. In these circumstances, the original value of 397 mm could be thought of as being 78 mm too high.

2. If rainfall was in error by -5%
   True rainfall = 1.05 x 611.5 = 642 mm

   If streamflow was in error by +29%
   True streamflow = 0.71 x 215 = 153 mm

   Therefore true evaporation = 642 - 153 = 489 mm

   i.e. In these circumstances, the original value of 397 mm could be thought of as being 92 mm too low.

These values of -78 mm and +92 mm could be regarded as very extreme error bands on the figure of 397 mm derived in section 2.7. The extreme error is often stated as three standard errors either side of the mean: approximations for the 95% confidence limits (two standard errors), between which the true evaporation would be expected to lie are

$$397 - 78 \times 2/3 = 345 \text{ mm}$$
$$\text{and } 397 + 92 \times 2/3 = 458 \text{ mm}$$

2.9.2 Water balance over West Sedgemoor

Each of the five inflows and two outflows is subject to uncertainty. The significance of uncertainty in each depends upon the proportion of the total input or output that each constitutes. Section 2.8 included the various fractions of the inflow and outflow that derived from the various sources. These are reproduced below and expressed as a percentage of their contribution to the total, calculated on the assumption that the estimates are accurate.

Inflows	(m^3)	(%)
Rainfall on West Sedgemoor	7 654 000	35.1
Rainfall on highland below Helland gauge	8 470 000	38.8
Helland streamflow	3 275 000	15.0
Wick Moor rhyne	743 000	3.4
Oath hill sluice	1 668 000	7.7
Total	21 810 000	100.0

Outflows	(m^3)	(%)
Diesel pumping station	5 782 000	53.0
Electric pumping station	5 128 000	47.0
Total	10 910 000	100.0

The water balance calculation in section 2.8 included the equation

$$(14 \times 10^6) \times E_H + (12.8 \times 10^6) \times E_M = 10\ 900\ 000$$

which sought to distribute the evaporation between the area of the Moor and the surrounding highland.

The possibility of uncertainty in the estimate of E_H has been discussed earlier. The only other source of uncertainty in the above equation is in the estimate of evaporative loss from the Moor and its surrounding highland, Inflow minus Outflow (10 900 000).

2.9.2.1 Inflow uncertainty

Rainfall (either over the Moor itself or over the surrounding highland below the Helland gauge) accounts for 74% of the inflow and the maximum likely uncertainty in measuring rainfall is assessed at 5%.

The uncertainty inherent in the Helland streamflow, here considered as an inflow, has been discussed above in detail. The 95% confidence limits on the data were assessed as +29% and -22%.

The inflow via Wick Moor Rhyne constitutes only 3.4% of the total. The measurement uncertainty at this thin plate weir, constructed in accordance with BS3680, should in theory be very small. There will in practice be error introduced by the fact that the exact times and dates that the weir crest was moved are unknown. The crest setting was recorded at monthly intervals during data retrieval. The program used to compute the flow, averaged the "last" and "next" known crest level setting when calculating each daily average flow. Uncertainty in these data is difficult to assess but in any case is not important because of the low level of the contribution of the Wick Moor Rhyne flows to the total. An uncertainty of 10% was thought reasonable.

The flow through the Oath hill sluice was recorded at weekly or fortnightly intervals according to the time of year. The uncertainty in each individual reading is assessed as less than 10%, the area of flow being regular (rectangular) and accurately measurable. As with the case of the Wick Moor Rhyne, no information was available as to sluice movements on the days between current meter gaugings. In calculating each daily inflow, a linear variation in inflow was assumed between the "last" and "next" recorded flow. The maximum uncertainty in these data is assessed at 10%.

2.9.2.2 Outflow uncertainty

The derived data for the diesel pumping station was generated by applying the known hydraulic head across the pumps during pumping, to the characteristic curve, having regard to any change in the head during the pumping. This approach is subject to uncertainty from three sources.

Problems could arise if the pumps have frequently been run "throttled", i.e. prevented from pumping as much as they could have. The pump operating log does not contain any suggestion that this has been done. During 1988 when the electric pumping station was available as the duty pump, there would be no logical reason for running the diesel pumps in a "throttled" state and so error from this source is thought to be unlikely.

The pumps at West Sedgemoor are understood to be 25 years old, and the question of whether general wear on the pumps and bearings might have reduced the amount calculated as having been pumped, was considered. Advice was obtained from an engineer with a background in land drainage pump manufacture, to the effect that significant wear of this type was very unlikely. Extreme cases of pumps deteriorating to the point where they pump 25% less than their design flow rate have occurred, but only in cases where the geology of the drained area is responsible for releasing coarse sand and gravel into the drains, which is eventually ingested by the pumps.

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 15 minutes. The maximum error in a start or stop time is therefore 7.5 minutes, and in a pumping run (7.5 + 7.5) = 15 minutes. The significance of this uncertainty is dependent 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 .25/24 x 100 or 1%. This uncertainty increases with a reduction in pumping duration. A 1 hour pump run could generate an uncertainty of .25/1 x 100 or 25%. The operator log sheets for

1988 show that the average pump run time was 6.8 hours. Therefore the associated uncertainty is assessed as .25/6.8 = +3.7%. A figure of +3.7% 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. Wessex Rivers staff assess the accuracy of this meter as +0.25% but the possibility of an increase in this with time cannot be overlooked. In comparison with the diesel pumping station, this uncertainty is negligible and need not be considered further.

2.9.2.3 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

Rainfall, Streamflow, Wick Moor, Oath Hill

$$= \frac{(1.05 \times 73.9) + (1.29 \times 15.0) + (1.1 \times 3.4) + (1.1 \times 7.7)}{100.0}$$

= 1.09 or +9%

Maximum negative uncertainty

Rainfall, Streamflow, Wick Moor, Oath Hill

$$= \frac{(0.95 \times 73.9) + (0.78 \times 15.0) + (0.9 \times 3.4) + (0.95 \times 7.7)}{100.0}$$

= 0.92 or -8%

Outflow

Estimated maximum positive error

Diesel, Electric

$$= \frac{(1.037 \times 53.0) + (1.0 \times 47.0)}{100.0}$$

= 1.0196 or +2%

Estimated maximum negative error

Diesel, Electric

$$= \frac{(0.963 \times 53.0) + (1.0 \times 47.0)}{100.0}$$

= 0.98 or -2%

Water balance over West Sedgemoor and surrounding highland - 1988

1. Inflow subject to maximum positive error and outflow subject to maximum negative error.

   If the inflow was in error by +9% and the outflow subject to -2% error.

   True loss by evaporation = Inflow - Outflow
   (0.91 x 21 810 000) - (1.02 x 10 910 000)

   = 8 718 900 m^3

2. Inflow subject to maximum negative error and outflow subject to maximum positive error.

   If the inflow was in error by -8% and the outflow subject to +2% error.

True loss by evaporation	=	Inflow	-	Outflow
		(1.08 x 21 810 000)	-	(0.98 x 10 910 000)

$$= 12\ 863\ 000\ m^3$$

The calculations of section 2.8 are now repeated to determine the possible uncertainty in the figure of 417 mm of evaporation for West Sedgemoor. The original equation

$$(14 \times 10^6) \times E_H + (12.8 \times 10^6) \times E_M = 10\ 900\ 000$$

is solved again using the new values of evaporation in place of 10 900 000 and having regard to possible uncertainty in the figure of 397 mm for E_H. It should be noted that a high value of the net input to the Moor corresponds with a high discharge at Helland gauging station and hence with a low value of E_H. Correspondingly a low value of the net input to the Moor relates to a high value of E_H.

Table 2.5 illustrates the variation in estimates of E_M as a result of maximum errors in E_H and the total evaporative loss.

Table 2.5 Maximum and minimum possible values of E_M

Highland evaporation E_H, mm	Net input to Moor m^3	Moor evaporation E_M, mm
397 - 78 = 319	12 863 000	656
397	10 910 000	417
397 + 92 = 489	8 718 900	146

It is clear that there is a considerable range of variation about the computed value of 417 mm for E_M, and it will be necessary either to refine the accuracy with which water balance components are measured, or to seek corroborating evidence from other methods. It should be emphasised that the errors shown in Table 2.5 are considered to be the maximum possible. Attention is therefore drawn to the good agreement between the central values in columns (1) and (3) of the Table, indicating a slightly higher evaporative demand from the Moor than from the highland areas.

3 LYSIMETER STUDIES

The use of a lysimeter offers a useful alternative method for the determination of actual evaporation, and it was decided to take advantage of the regular visits to the site by installing a simple lysimeter near one of the dipwell transects. The lysimeter tank contains a block of soil, disturbed as little as possible in the installation process, with the turf reinstated. At each routine visit, the water levels in dipwells inside and outside the lysimeter were equalised by the addition or removal of a quantity of water, so that the soil moisture deficit inside the lysimeter would be similar to that outside. Under these conditions, the water lost from the lysimeter through evaporation could be determined from a record of the quantity of water added and removed, and the rainfall.

As with the catchment water balance, the lysimeter method in its simplest form requires an accounting period between two dates on which the soil moisture deficit, as indicated by the dipwell level, is the same. However, the results can be analysed in more detail to give an indication of the seasonal pattern of actual evaporation.

The West Sedgemoor lysimeter was implemented by Ivan Wright of IH Wallingford on 23 September 1987. It was clear from the outset that the design of the lysimeter did not need to be complicated. The intended maximum interval between consecutive visits was expected to be two weeks and during the majority of the year, would be one week. The adoption of a more sophisticated piece of equipment than that eventually chosen would have taken far longer to design and build and would have required the installation to be contracted out at unjustifiable cost. The period remaining for the collection of data, inclusive of the settling in period, would have been shorter than the 18 months (to 31 March 89) which has resulted.

3.1 Installation

The lysimeter was installed in the field owned by NCC (OS grid ref. ST371270, field No: 0700). A transect of dipwells (T4) had already been in operation within this field, adjacent and perpendicular to the Middle Drain, which is a distance of 60 m to the southeast of the lysimeter. The data acquired from the dipwell furthest (42 m) from the rhyne, T4-5, was taken as being representative of the seasonal variation in groundwater level within the central area of the field.

3.1.1 Design

During the period August 1986 - August 1987, the highest groundwater level recorded by dipwell T4-5 was 4.9 m OD (10 April 1987), while the lowest was 4.2 m OD (19 August 1987). The field level at the dipwell was 4.9 m (Wessex Rivers survey 8 October 1987). If the groundwater level within the lysimeter were to be maintained at the level corresponding to that recorded at dipwell T4-5, then the indication from the pre-September 1987 data was that the annual variation in ground water level would require a lysimeter of greater than (4.9 m - 4.2 m) = 0.7 m depth. The internal dimensions of the lysimeter were chosen to be 0.8 m depth x 1.0 m diameter.

The vertical sides of the lysimeter were constructed from two well liner sections which were bolted and sealed together with resin-impregnated fibreglass. A circular prefabricated fibreglass base was attached to one end of the resulting open cylinder to complete the assembly. A vertical perforated PVC tube 100 mm diameter was located in the centre of the lysimeter to allow the addition and removal of water. This pipe was fitted with a cap when not in use to prevent evaporation from the water within the tube. Plates 3.1a and 3.1b show the lysimeter with central tube in position, before installation.

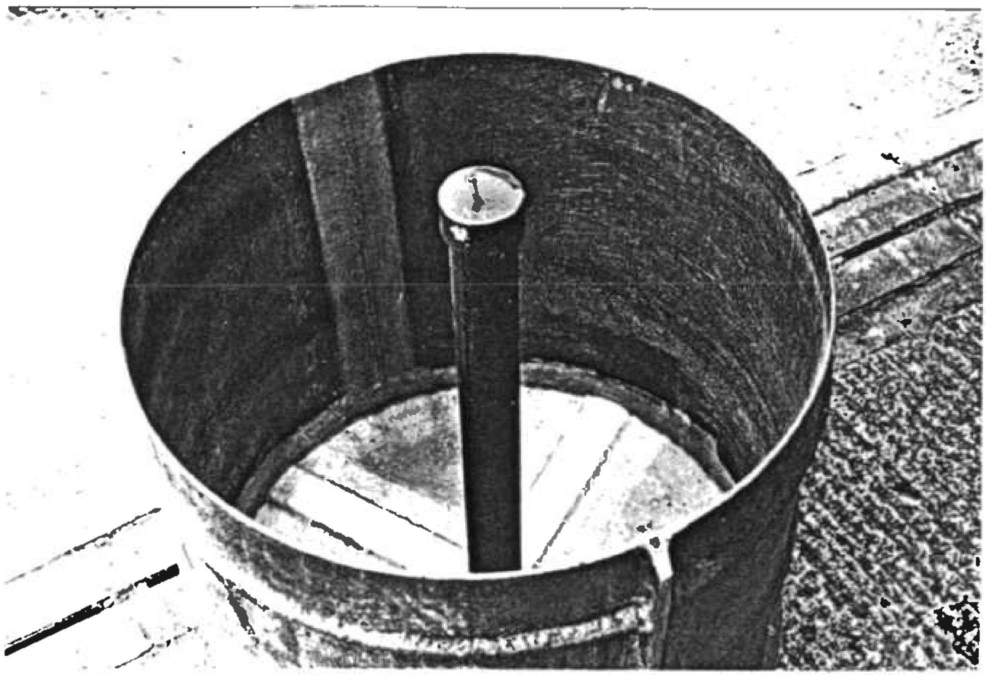

Plate 3.1a Lysimeter before installation

Plate 3.1b Lysimeter before installation

3.1.2 Installation procedure

(i) The peat surrounding the vertical cylindrical mass which would eventually form the contents of the lysimeter was excavated to a distance of 0.5 m out from the circumference.

(ii) The cylindrical block of *in situ* peat was cut with wire into three horizontal sections of 0.25 m height and each section was further cut vertically into nine pieces. A careful note was kept of the exact order of the various pieces.

(iii) With the contents and surrounding peat removed, the lysimeter tank was positioned and levelled. The contents were then placed into the tank in the exact order and position that they had been removed.

Some drying out of the contents, which expressed itself as cracking, was noticed during the period they were out of the ground. While the ground within 0.5 m of the lysimeter had to be cut away completely as part of the implementation process, attempts were made to disturb the remaining nearby ground as little as possible. At the end of the installation, the lysimeter and surrounding ground were completely drenched with water in the hope that it would assist the grass to recover as much as possible at what was assumed to be the end of the growing season.

3.2 Lysimeter monitoring

The dipwell transects and gauging stations of West Sedgemoor, and hence also the lysimeter, were visited for the purpose of data collection weekly during the period April - October and fortnightly during the remaining months. Between September 1987, when the lysimeter was installed, and the end of 1988, water was added or removed from the lysimeter on all but nine of the site visits. On two of those occasions the internal water level was "in balance" with the external water level. The remaining seven occasions were due either to site access problems or breakage of the water level measuring equipment.

The procedure for attempting to keep the water level within the lysimeter as close to the external level as possible was changed in July 1988 when it became clear that the approach that was being used was not adequate.

The level of the lysimeter dipwell had been determined with respect to dipwell T4-5. This meant that if the water level in both the lysimeter tube and dipwell was recorded relative to their tops, the absolute difference in water level between T4-5 and the lysimeter was easily calculated. A volume of water equivalent to the difference in water level multiplied by the cross-sectional area of the central lysimeter tube could then be added or removed, according to whether the lysimeter level was higher or lower than the external water level, such that the resulting water levels were equalised.

This approach was altered when it became clear that insufficient water was being added to the lysimeter. The water added was draining rapidly into the soil mass of the lysimeter from the central tube and between 25 May 1988 and 7 June 1988 the decline in water level almost left the lysimeter empty. From 6 July 1988, water was added in increments of a litre; the fieldworker simply aimed to balance the internal and external water levels by inspection, allowing additional water for the lysimeter soil block.

3.3 Estimates of evaporation from lysimeter results

The results obtained from the lysimeter between 14 October 1987 and 21 December 1988 are presented in Table 3.1, omitting those visits on which the water level could not be measured for the reasons stated above. The water level in the dipwell is that read on arrival at the site: the decision on how much water to add or remove was taken on comparison between this level and the transect dipwell T4-5. The table also shows the change in water level between visits. The quantity of water added is the total between the dates shown: on a few occasions water was added on days when the water level was not measured. Similarly the WSPS rainfall record has been accumulated to give the total rainfall between the dates shown.

None of the winter, spring and autumn records that could have given rise to overflows from the lysimeter can be used to determine evaporation, as the overflow losses are completely unknown. It was therefore decided, in the calculation of 1988 actual evaporation, to disregard those records which have high water tables, giving little "freeboard" for storage of rainfall, and the period between 7 April 1988 and 7 September 1988 was chosen as the accounting period. The small difference in soil moisture storage was taken into account using a specific yield of 16%. This estimate of specific-yield is somewhat subjective: a full justification must await the results of investigations on peat samples obtained from the site, but the figure of 16% is reasonable for fen peat, and will be justified later in this report when the dipwell transects are considered.

The total surface area of the lysimeter is 0.6576 m^2, and after allowing for the central dipwell the area available for evaporation is 0.6449 m^2. The total input to the lysimeter over the accounting period was

$$(265.2 \times 0.6576) + 31.211 \text{ litres} = 205.607 \text{ litres}$$

There was a decrease in soil water storage over the period of

$$(4.694 - 4.374) \times 1000 \times 0.6449 \times 0.16 = 33.019 \text{ litres}$$

The corresponding decrease in water contained in the dipwell was

$$(4.694 - 4.374) \times 1000 \times 0.00785 = 2.512 \text{ litres}$$

The total loss from the lysimeter, which was due entirely to evaporation, was

$$(205.607 + 33.019 + 2.512) \text{ litres} = 241.138 \text{ litres}$$

The total evaporation over the accounting period was therefore

$$241.138 / 0.6449 \text{ mm} = 373.9 \text{ mm}$$

In 1988, 66.4% of the Meteorological Office Rainfall and Evporation Calculation System (MORECS) potential evaporation averaged over squares 167, 168, 179 and 180 was within this accounting period. West Sedgemoor lies near the intersection of these four 40 km squares. On the assumption that the actual evaporation figures for 1988 are similarly distributed, the total actual evaporation from West Sedgemoor for 1988 would be

$$373.9 / 0.664 \text{ mm} = 563.1 \text{ mm}$$

Table 3.1 Lysimeter water levels, additions of water and rainfall

Date	Water level in dipwell (mOD)	Change in water level (m)	Quantity of water added (l)	WSPS rainfall (mm)
06/01/88	4.926	0.063	-0.221	26.1
20/01/88	4.920	-0.006	-0.252	20.2
03/02/88	4.869	-0.051	0.159	66.6
17/02/88	4.885	0.016	0.009	42.8
02/03/88	4.681	-0.204	0.419	0.0
15/03/88	4.658	-0.023	0.415	3.2
29/03/88	4.862	0.204	0.022	54.2
07/04/88	4.694	-0.168	0.313	3.0
13/04/88	4.617	-0.077	0.292	0.9
20/04/88	4.664	0.047	0.332	8.1
27/04/88	4.486	-0.178	0.530	0.0
05/05/88	4.624	0.138	0.278	18.2
11/05/88	4.427	-0.197	0.579	0.0
18/05/88	4.316	-0.111	0.579	0.0
25/05/88	4.304	-0.012	0.398	1.1
07/06/88	4.299	-0.005	15.614	41.1
15/06/88	4.364	0.065	0.296	3.1
22/06/88	4.303	-0.061	0.000	0.0
06/07/88	4.664	0.361	2.000	84.7
13/07/88	4.659	-0.005	2.000	7.9
20/07/88	4.461	-0.198	1.000	9.6
27/07/88	4.574	0.113	2.000	25.3
03/08/88	4.449	-0.125	1.000	8.7
10/08/88	4.317	-0.132	1.000	0.0
18/08/88	4.119	-0.198	1.000	3.0
01/09/88	4.439	0.320	2.000	51.0
07/09/88	4.374	-0.065	8.000	2.5
12/10/88	4.856	0.482	0.000	71.1
19/10/88	4.898	0.042	-0.300	9.2
26/10/88	4.849	-0.049	-0.750	8.9
10/11/88	4.715	-0.134	0.000	1.7
07/12/88	4.900	0.185	-0.502	30.5
21/12/88	4.895	-0.005	-0.097	0.9
Total 13/04/88 to 07/09/88			38.606	265.2

Certain anomalies appear in the Table, particularly in the winter months. A high rainfall total corresponds on occasion to a slight water table decline at a time of year when evaporation could be expected to be very small. This is particularly clear in the case of the 3 February 1988 record. Assuming a realistic specific capacity of between 5 and 20%, this rainfall input should have induced a rise in water table of between 0.333m and 1.332m, i.e to the surface, but a fall of 0.051m was observed. The only possible conclusion is that the excess water overflowed the lysimeter walls as surface runoff, probably between visits to the site.

3.4 The seasonal pattern of evaporation

It is possible to use the lysimeter record in more detail to indicate the seasonal pattern of evaporation over that part of the year where evaporation rates are sufficiently high, using an estimate of the specific yield S to correct for the difference in soil water storage. For the interval between any two visits to the lysimeter, assuming that overflow does not occur, there is a balance between the input due to rainfall, the release of water from storage in the soil, and the evaporation. For example, for 20 July 1988 to 27 July 1988 the balance is

$$(25.3 \times 0.6576) = 0.113 \times (0.6449 \times S + 0.00785) + E_a$$

Rainfall — Change in water stored in soil and dipwell — Actual evaporation

The actual evaporation figures calculated in this way are presented in Table 3.2 for a range of possible specific yields from 10% to 20%. In the last two columns, the computed daily evaporation rates, averaged for each month, are compared with the MORECS potential evaporation estimate.

Table 3.2 Actual evaporation figures computed from lysimeter data

Date	Total actual evaporation between visits, based on a specific yield of					Average evaporation rate (mm/day)	
From 7/4/88	S=10%	S=14%	S=16%	S=18%	S=20%	S=20%	MORECS PE
13/04/88	10.0	13.1	14.7	16.2	17.7		
20/04/88	3.4	1.6	0.6	-0.3	-1.3		
27/04/88	20.5	27.6	31.2	34.7	38.3	2.3	1.9
05/05/88	3.9	-1.6	-4.4	-7.1	-9.9		
11/05/88	22.5	30.4	34.3	38.3	42.2		
18/05/88	13.3	17.8	20.0	22.2	24.4		
25/05/88	3.4	3.8	4.1	4.3	4.6	1.9	2.9
07/06/88	43.1	43.3	43.4	43.5	43.6		
15/06/88	20.1	17.5	16.2	14.9	13.6		
22/06/88	7.3	9.7	11.0	12.2	13.4	2.5	2.9
06/07/88	45.9	31.4	24.2	17.0	9.8		
13/07/88	11.7	11.9	12.0	12.1	12.2		
20/07/88	35.1	43.0	47.0	50.9	54.9		
27/07/88	14.7	10.2	7.9	5.6	3.4	2.6	2.8
03/08/88	26.0	31.0	33.5	36.0	38.5		
10/08/88	16.4	21.6	24.3	26.9	29.6		
18/08/88	26.8	34.7	38.7	42.7	46.6	4.4	2.5
01/09/88	17.7	4.9	-1.5	-7.9	-14.3		
07/09/88	12.9	15.5	16.8	18.1	19.4	0.8	1.9
Total 07/04/88 to 07/09/88	354.7	367.5	373.9	380.3	386.7	Mean 2.4	Mean 2.5

The small range in evaporation totals for the various values of specific yield should be noted: it reflects the relative unimportance of the storage term in the lysimeter water balance over the long accounting period. Over shorter periods the soil water store becomes much more important, and the distribution of evaporation over the year is very much affected by the choice of S.

4 WATER TABLE PROFILES WITHIN THE FIELDS

The initial West Sedgemoor project was aimed at investigating the relationship between the penning level at WSPS and hydrological conditions on the Moor. It was recognised at the beginning that the water table within the fields would not correspond exactly to rhyne levels, so four transects of dipwells were installed to monitor the relation between rhyne levels and field water table levels. The locations of the transects were chosen to give a good spatial coverage of the Moor, using land owned by the Royal Society for the Protection of Birds (RSPB) or NCC and subject to as little as possible agricultural activity.

Each transect consists of five dipwells arranged at 10-metre 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

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

The intention was 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 end well would represent the point most distant from the influence of open water. Three transects consist of wells arranged in a straight line at distances of 2, 12, 22, 32 and 42 metres from the water's edge. In the other transect (T1), the final well is 52 metres from the water.

Water levels have been measured in the dipwells at approximately fortnightly intervals from July 1986, using an electric contact gauge. In general, as with the lysimeter, more frequent readings have been taken in summer.

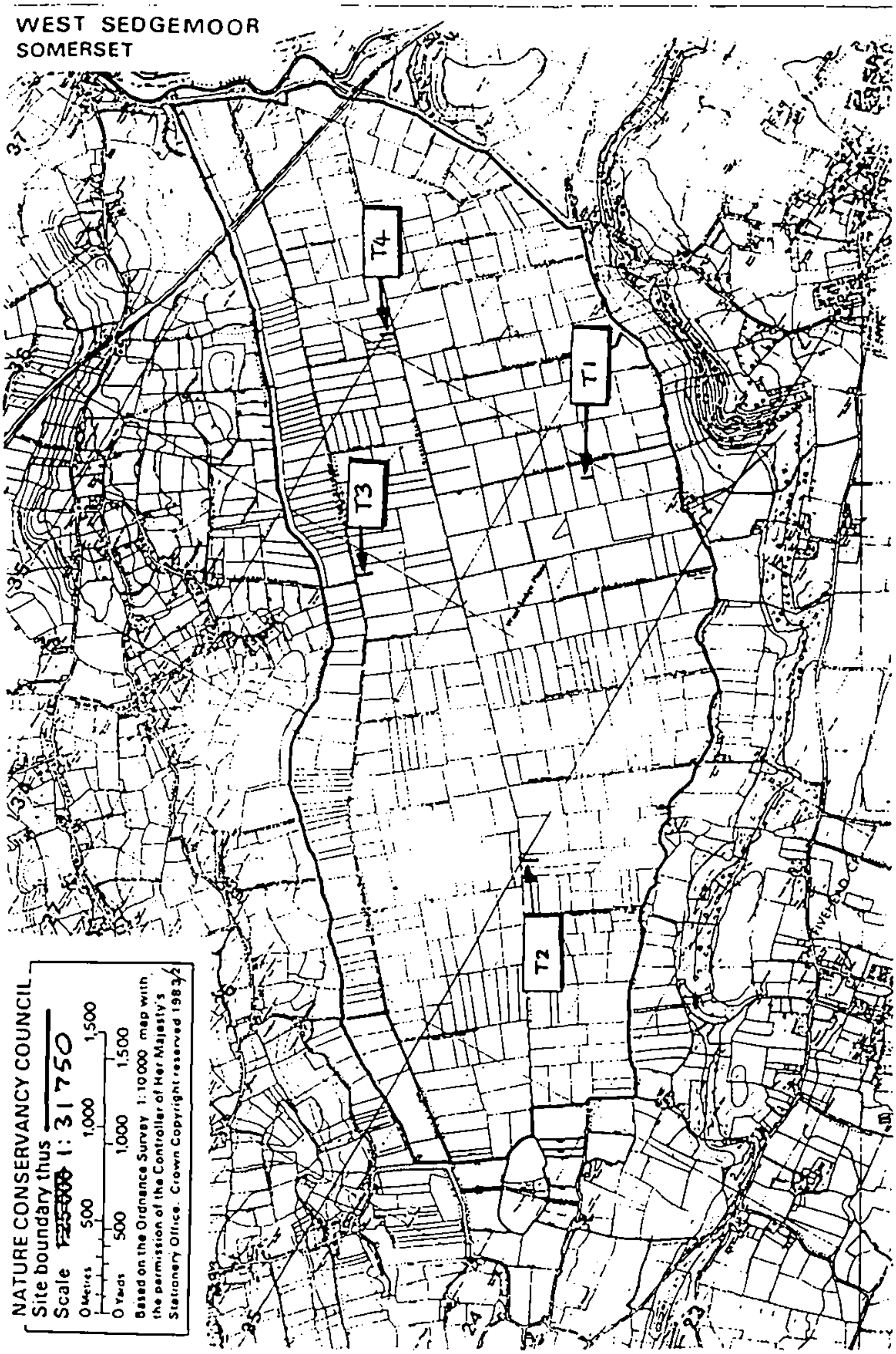

Figure 4.1 Locations of dipwell transects

4.1 Installation of dipwell transects

The dipwells consist of two-metre lengths of 90 mm internal diameter pvc tube, perforated with 10mm holes in a regular pattern over the lower 1.5 metres. The end wells of each transect were fitted with a wide flange to prevent vertical movement of the tube relative to the surface peat.

The dipwells were installed by hand using a Jarrett post-hole auger, the rim of each tube being set at about ground level, and they were pumped out repeatedly to remove peat slurry and ensure a good hydraulic connection with the groundwater body.

4.2 Seasonal variation of water table profiles

The well records follow a familiar seasonal pattern. High relatively constant levels in winter, with fluctuations induced by rainfall events, give way in late spring to a decline which becomes very steep as evaporation rates build up. Rainfall events during the summer may have an effect, but it takes a particularly large event to bring the water table back to its winter level. In autumn the reduction in transpiration, and heavier rains, induce a rapid rise back up to winter levels. In retrospect, it is usually easy to see the dates on which summer and winter conditions have begun and ended, but the dates, and hence the length of the water level "seasons", vary strongly from year to year.

At West Sedgemoor, the tendency towards very heavy rainstorms during the months of July and August, well shown in the 25-year record, leads to very irregular patterns of summer water levels. 1987 was a relatively quiet year, and the summer decline followed a classic pattern. On the other hand 1988 was characterised by periods of high rainfall at the beginning and end of July, and at the end of August. The July rains almost restored the water table to its winter level (Figures 4.2 and 4.3).

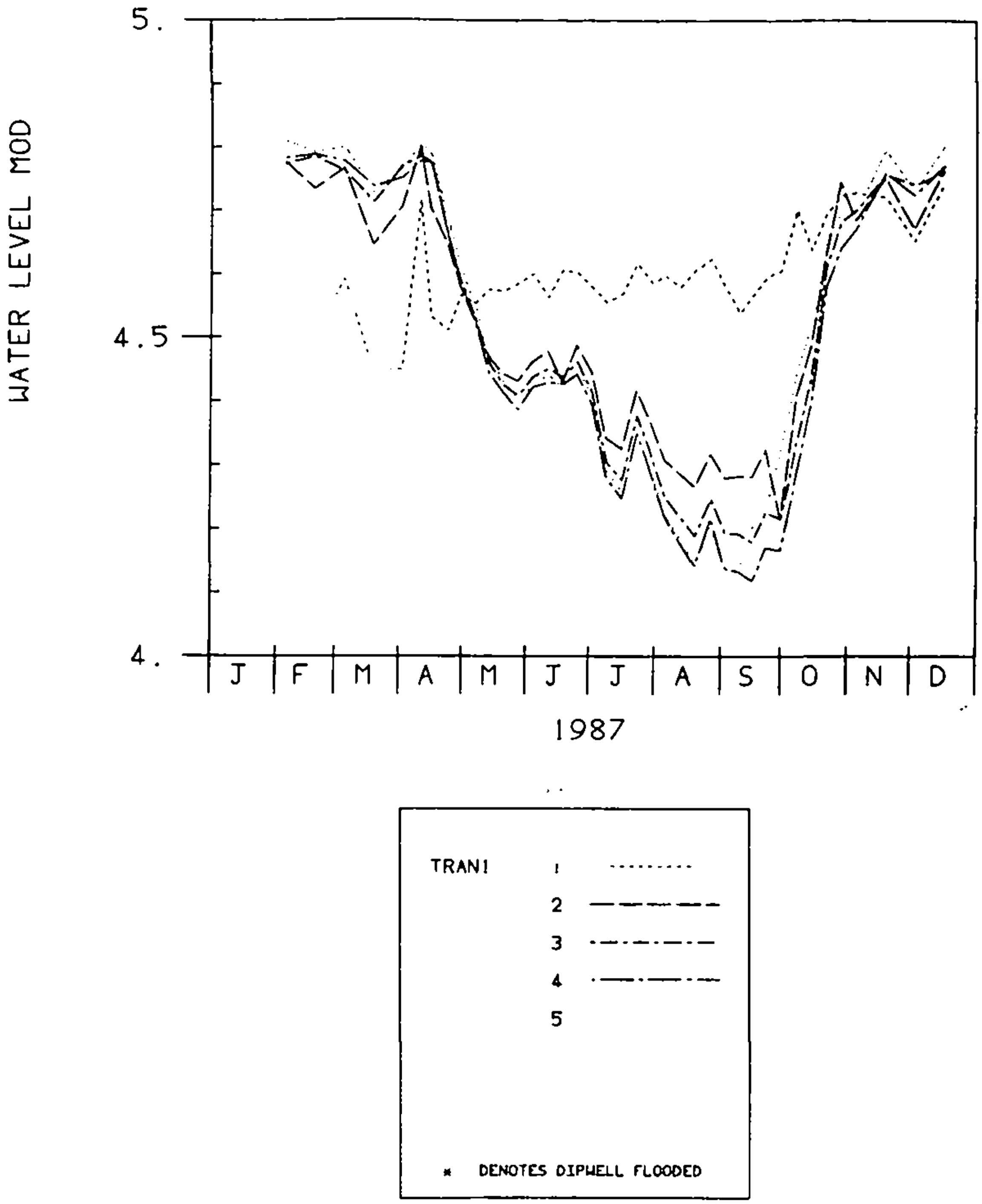

Figure 4.2 Water levels in dipwell transect T1, 1987

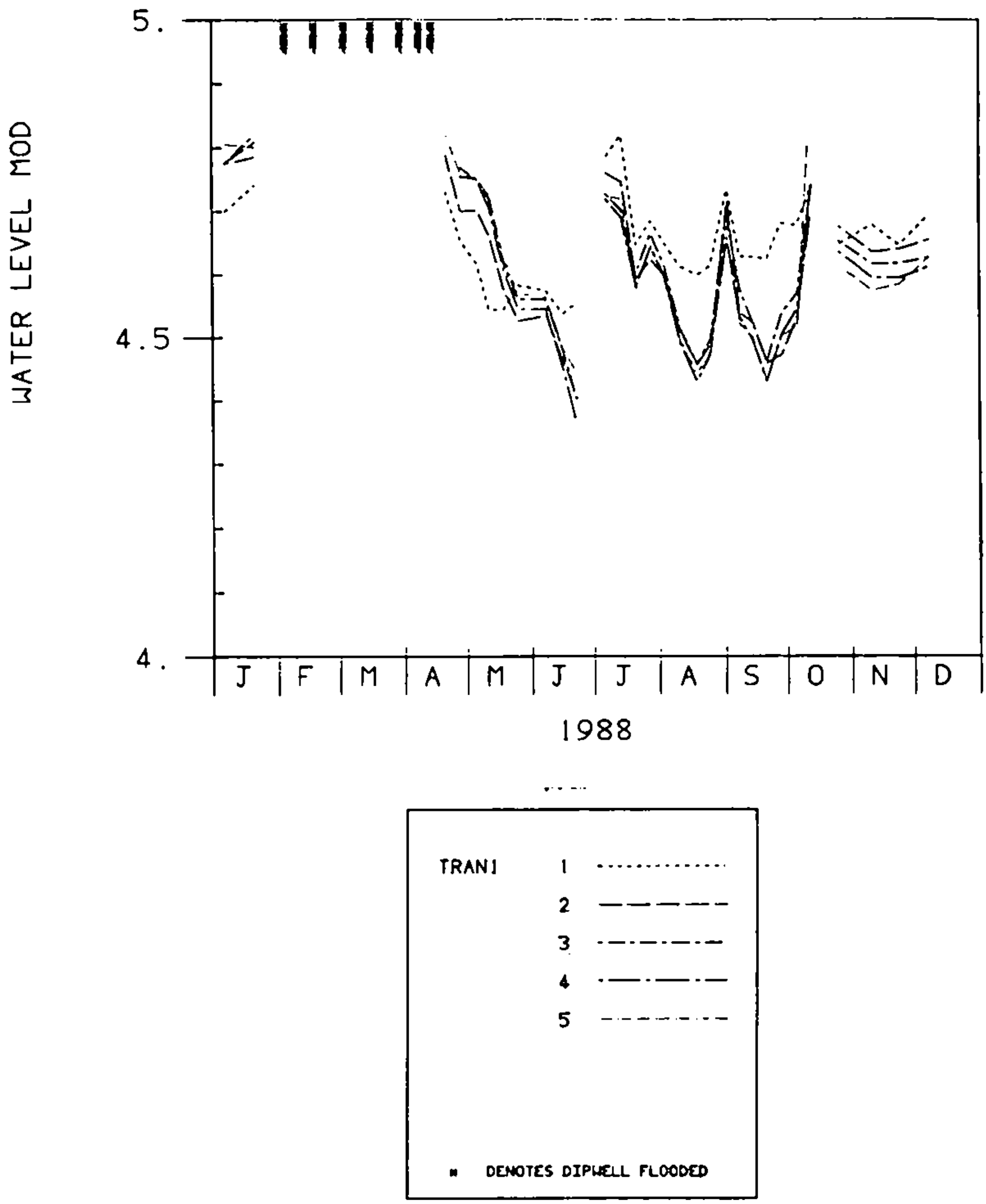

Figure 4.3 Water levels in dipwell transect T1, 1988

4.3 Relationship to rhyne water levels

It was expected that the water table under the fields of west Sedgemoor would exhibit a seasonal fluctuation between a winter dome shape, with the water table falling radially towards the rhynes and drains, and a summer saucer shape, with a reversal of the hydraulic gradient. This pattern has been borne out by the data obtained in this study, but the decline in influence of open water with distance has been much more sudden than expected, with little detectable influence of the rhyne water level at 12 metres from the water's edge.

In each transect, the dipwell nearest the rhyne has been influenced clearly by rhyne water levels, while the remaining dipwells have shown a "field-centre" seasonal pattern, dominated by rainfall and evaporation. In transects 1, 3 and 4 only the influence of the rhyne is detectable in the end dipwell, while dipwell 1 of transect 2 shows a transitional pattern midway between rhyne and field expanse. In transects 1 and 3 there is a measurable hydraulic gradient towards the rhyne in all dipwells, particularly in the later part of the summer, when the water table is low, but transects 2 and 4 show no gradual change between rhyne and field-centre behaviour.

The rapid transition to field-centre conditions indicates that the quantity of water supplied from the rhynes to the fields in summer is less than might be supposed, and that the hydrology of the fields is dominated by the seasonal cycle of rainfall and evaporation. In an attempt to explain the lack of a good hydraulic connection between rhyne and field, in situ permeability tests have been carried out near dipwells T1-1, T1-5, T3-1 and T3-5, i.e. at the ends of dipwell transects T1 and T3. Table 4.1 shows the values obtained.

Table 4.1 Permeability tests near dipwell transects T1 and T5

Depth below ground surface	Permeability, m/d			
	Dipwell T1-1	Dipwell T1-5	Dipwell T3-1	Dipwell T3-5
0.50 m		0.120	0.24	2.3
0.75 m	0.0068	0.150	0.017	0.083
1.00 m	0.0076	0.092	0.026	0.25
1.25 m	0.105	0.103	0.161	0.22
1.50 m	0.038	0.147	0.0094	0.048
2.00 m	0.126	0.138	0.024	

It is clear from the limited amount of data available to date that the permeability of the peat varies over a wide range. However, there does appear to be a zone of reduced permeability near the rhyne, particularly in the upper horizons of the soil. This may be due to compaction by vehicles and the weight of spoil on the rhyne banks. Only one high value occurs in the Table: transect T3 crosses one of the more peaty fields, and the high permeability may reflect the absence of the clay flood deposit that is present near the surface at other sites. Samples have been obtained for the determination of dry bulk density and fibre content, and it its expected that these properties will help to explain the variation in permeability.

4.4 Evaporation estimates from dipwell data

It is possible, by an extension of the methods applied to the lysimeter on transect 4, to use the dipwell data to obtain yet another estimate of evaporation from the Moor. Because the dipwells were read in 1987 and 1988, while lysimeter and catchment data is only complete for 1988, this is the only method that can be used to obtain an estimate of evaporation in 1987 from our data.

The lysimeter is essentially a device in which the unknown lateral groundwater flow in the water balance is replaced by the addition or removal of known quantities of water:

outflow	=	inflow	±	change in storage
evaporation	=	rainfall + lateral inflow		change in soil/dipwell storage

At a dipwell site, there is no way of measuring the lateral groundwater flow, but if the dipwell is away from the immediate influence of open water, this component of the water balance if likely to be small. The net supply of water to the lysimeter over the summer of 1988 was 31.221 litres, equivalent to 48.4 mm. Little error would be incurred by assuming that this figure for lateral flow applied to all dipwell sites 12 metres or more from the rhynes: it has been observed that within each transect the four dipwells distant from the rhyne behave in a similar way. The lysimeter itself is 52 metres from a rhyne.

As with the lysimeter, the water balance is taken over the summer period, when surface runoff is nil, and it can be assumed that there is a balance between evaporation, rainfall and change in soil storage. The dates of the start of the early summer decline and the end of the autumn rise were determined from the records of all dipwells distant from the rhynes. In 1987 water levels had just started to fall on 10 April, and had returned to their winter level by 16 December. In 1988 the corresponding dates were 20 April and 12 October. Between these dates it was considered unlikely that rainfall on the Moor would result in surface runoff, so this component of the water balance could be disregarded.

The first requirement was an estimate of the specific yield of the peat for each dipwell transect: without this the small change in soil storage over the summer period could not be estimated. For each interval between readings of the dipwells, the WSPS rainfall was summed, and a comparison was made between the change in water level between visits and the net input of water to the soil store, i.e. the rainfall minus an evaporation figure. In the absence of a better figure for evaporation, the mean daily MORECS potential evaporation for the given month was used, multiplied by the number of days between visits. The uncertainty of the evaporation amount, only those intervals with a high rainfall could be used for the determination of the specific yield. Intervals with more than 20 mm of rainfall, in the months of April to October 1987 and 1988, were selected. For each such interval, the specific yield, expressed as a percentage

$$S = 100 \times (\text{rainfall} - \text{evaporation}) / (\text{change in water level})$$

Not all the figures obtained were in the possible range of zero to 100%, or the likely range zero to 50%. Disregarding all results less than zero or greater than 50%, but retaining all others, the mean specific yields were

Transect	Specific yield, %
T1	18
T2	12
T3	17
T4	16

The figure of 16% was applied to the lysimeter records.

The total evaporation over each summer period was estimated for each transect from the total rainfall and the change in soil water storage calculated by multiplying the change in water level in mm by the specific yield. Table 4.2 shows the results.

Table 4.2 Evaporation totals for dipwell data

Transect	Evaporation	
	10 April 1987 to 16 December 1987	20 April 1988 to 12 October 1988
T1	360.3	322.8
T2	375.2	336.9
T3	384.3	352.8
T4	371.7	327.2
Mean	372.9	334.9

Assuming that

(i) as with the MORECS potential evaporation estimate, the summer periods in 1987 and 1988 account for 85.0% and 71.9% respectively of the total annual evaporation

and

(ii) the lateral inflow can be assumed to be 48.4mm,

the annual total evaporation is

(372.9 + 48.4)/0.850 = 495.6 mm in 1987 (88.0% of MORECS PE)
and (334.9 + 48.4)/0.719 = 533.1 mm in 1988 (92.3% of MORECS PE).

5 RHYNE WATER SURFACE ESTIMATES

5.1 Aerial photographs

The Ministry of Agriculture (MAFF) have used their own aircraft to take infra-red and conventional black and white photographs of West Sedgemoor. Both types of photographs were shot vertically at a scale of 1:10,000 and were taken on 8 May 1987. MAFF use the photographs for their ESA monitoring. The quality of the black and white photographs is rather poor although the infra red photographs are very clear indeed. The definition of these is so good that with the help of an optical enlarger the position of the top of a 300 mm diameter water level recorder can be located. The water within the rhynes is sufficiently clear to prevent any significant amount of infra red radiation's being reflected, so the rhynes appear black and very well defined.

5.2 Rhyne width

The infra-red photographs were used in conjunction with a 1:10000 map to determine the state of each rhyne on West Sedgemoor. The width of the two major rhynes (Main Drain & Middle Drain) was estimated at each location where it changed significantly. Other smaller rhynes were assigned an average width over a length which depended on the overall drainage configuration.

Using the optical measurement equipment at the MAFF offices, which had a scale marked in 1/10 mm units, the rhyne widths were scaled correct to the nearest 1/2 of one of these units. A 1/10 mm unit on the photographs represented 1 m on the rhyne, so half a unit represented 0.5 m and the maximum error in width measurement was therefore (0.5)/2 = 0.25 m. The rhyne widths ranged from 18 m at the Main drain weedscreen down to 0.5 m. The minimum error was therefore (0.25/18) x 100 = 1.4%, while the maximum error on a 0.5 m drain would be (0.25/0.5) x 100 = 50%. Apart from the Main & Middle drains, a typical smaller rhyne width is of the order of 2 m leading to a percentage error of (0.25/2) x 100 = 12.5%. However, in common with the rhyne length measurements discussed below, the smaller drains, while giving rise to high percentage errors, give rise to small errors in terms of square metres of water surface.

Some problems were experienced in this exercise. A few rhynes were obscured by trees along their total length. Rather than disregarding them completely, they were assigned a width similar to that of nearby rhynes. Some of the rhynes had their water surface covered in duckweed and this had the effect of making such rhynes appear to have been filled in. For this reason a few rhynes will have probably been wrongly classified as no longer operating. As the rhynes get smaller, there comes a point where it is difficult to decide if there is open water or not. Some 0.5 m width rhynes will probably have been graded as defunct and vice versa.

5.3 Rhyne length

The average error involved in measuring the rhyne lengths on the 1:10,000 map was estimated at +0.5 mm (equivalent to 5 m) with a maximum error of +1.0 mm (equivalent to 10 m). Clearly, this will represent a larger percentage error on the smaller rhynes but conversely the actual error in water surface square metres will be less than for the larger rhynes. Excluding the Main and Middle drains, a typical map measured rhyne length is 20mm (equivalent to 200 m). The average error of 0.5mm (equivalent to 5 m) therefore represents an error of 2.5%

Example

A typical feeder rhyne is of length 200 m and width 2 m.

If both are exact measurements, the surface water area is 400 m^2. If the length and width are recorded incorrectly as 205 m and 2.25 m the water surface area would be calculated as 461.25 m^2 or 15.3% too large. If the length and width were recorded as being short by the same amount resulting in measurements of 195 m an d 1.75 m, the resulting water surface area would be calculated as 341.25 m^2 or 14.7% too small. There is no reason to think that the signs of these errors are in any way biassed.

5.4 Summary of results

Drain or Area	Water surface area (m^2)	% of total
Main drain (WSPS to Pincombe Br)	35,218	15.2
Sedgemoor Old Rhyne (Pin-combe Br to Fosse Br	13,888	6.0
Middle Drain	27,568	11.9
Feeder drains between Main & Middle Drains	70,489	30.45
Feeder drains southeast of Middle Drain	84,368	36.45
Total	231,531	

5.5 Monthly surface water changes

The figure of 231,531 m^2 of rhyne surface constitutes 1.8% of the area of the 12.8 km^2 of West Sedgemoor.

Table 5.1 illustrates a comparison, made by applying the change in monthly average rhyne level to the known rhyne surface area, between the net inflow of surface water to the Moor and the change in volume of water stored in the rhynes.

Table 5.1 Change in net surface water inflow and rhyne storage 1988

	Surface water net inflow (10^3 m^3)	Inter-month average surface water net inflow (10^3 m^3)	Monthly average rhyne surface level (m)	Change in average rhyne water level (m)	Change in rhyne volume (10^3 m^3)
Jan	-1470		4.477		
		-2154*		-0.067	-15.51*
Feb	-2838		4.410		
		-1920*		-0.147	-34.03*
Mar	-1002		4.263		
		-548*		+0.297	+68.76*
Apr	-94		4.560		
		+6		-0.007	-1.62
May	+106		4.553		
		+65		+0.037	+8.57
Jun	+24		4.590		
		-16		+0.028	+6.48
Jul	-56		4.618		
		+81		-0.021	-4.86
Aug	+219		4.597		
		+150		+0.035	+8.10
Sep	+81		4.632		
		-30		-0.005	-1.16
Oct	-142		4.627		
		-57		-0.014	-3.24
Nov	+27		4.613		
		-31		-0.123	-28.48
Dec	-89		4.490		
	A	B	C	D	E

When the data marked * in columns B and E are omitted from consideration (because of the comparatively low evaporation and high rainfall in Jan, Feb and March), the remaining points, graphically displayed, cluster evenly about the origin. Thus the monthly average rhyne surface level appears to be independent of the net surface water inflow.

<u>5.6 Defunct rhynes</u>

An estimate of the lengths of rhynes which were no longer active was also made. This category covers all rhyne conditions between those which were so faint on the photographs that they were almost invisible to those which were very clearly visible but which were dry.

north west of middle drain 28,105 m

south east of middle drain 18,925 m

The figure 18,925 m includes a length of 3,355 m within the area owned by the RSPB.

6 RSPB development areas

The RSPB have been undertaking work in three areas largely owned by them totalling 1.82 km^2 (or 14.2% of the area of West Sedgemoor) to the south east of the Middle Drain.

RSPB ref	AREA km^2	Limits of area
A	0.38	Swell Drove to drove between Broadway and Hatch
B	0.67	drove between Broadway and Hatch to Beercrowcombe Drove
C	0.77	Beercrowcombe Drove to Curry Rivel Rhyne

Their work has been directed toward the construction of low banks around the periphery of the three areas, the objective being to retain water on their land after the winter for longer than would otherwise be possible. While some of this water will be winter rainfall, the RSPB have installed pumps, thus affording additional control over the extent and duration of the flooding of their areas during the late winter/early spring. The low banks have been created by widening some rhynes and positioning the material removed close to the new edges of the rhynes involved. This has had the effect of slightly increasing some of the rhyne surface area calculations in sub-Section 5.1.

The RSPB pumping could effect the hydrology of West Sedgemoor in two ways. The pumping of water out of the rhynes on to the fields and the delay on part of the rainfall reaching the main rhynes has the effect of adding to the storage capacity of the catchment and will tend to spread the volume of water requiring pumping, over a longer period. In addition, the act of pumping water on to the surface of fields will increase the free water surface area and hence increase the volume being evaporated.

7 OVERVIEW OF EXPERIMENTAL RESULTS

7.1 Evaporation estimates for 1988

The study has produced three rather differing estimates of the evaporation from West Sedgemoor, and it is necessary to reconcile these if further progress is to be made.

The catchment water balance yields an estimate of 417 mm (70% of the MORECS estimate of potential evaporation) for the Moor, and a rather low estimate of 397 mm for the highland catchment, but the uncertainties on this measurement are high because of uncertainty about the Helland gauging station, which links the two areas considered in the catchment study. A higher value of the total flow through the Helland station would lead to a lower estimate of the highland evaporation and hence a higher estimate of Moor evaporation.

In its first year of operation, the lysimeter has given an estimate of evaporation during the summer months which is almost equal to the potential evaporation (98% of MORECS). While it must be admitted that this estimate depends to a small extent on the adoption of a value for the specific yield, the similarity between estimates of daily rates of evaporation over the summer and the distribution of potential evaporation adds to its credibility.

The third estimate comes from the dipwell records. Using a similar method to those employed on the lysimeter, and depending to a degree on the results from the lysimeter, it is possible to obtain an approximation to the evaporation rate from water level records and rainfall alone. The method could be further refined by continuous recording of water level, which would allow a better estimate of the specific yield to be made, by reducing the influence of the initial evaporation estimate. Perhaps the method should be formalised as a computer model operating on a daily timescale: it would then be possible to eliminate some of the problems caused by the choice of accounting periods. Nevertheless, the values obtained are well within the range expected (88% and 92% of the MORECS estimate), and all the dipwell transects give 1988 values higher than 1987, in line with the MORECS estimate.

The lysimeter experiment has given an indication of the quantity of lateral groundwater flow which helps to sustain water levels within the fields. While the dipwell transect data show clearly that the main influence on water levels in the fields during the summer is the balance between local rainfall and evaporation, the "vertical" components of the water balance, about 48 mm of water leaks into the fields from the rhynes during the summer (April to August), and, bearing in mind the uncertainties on both figures, this is in good agreement with the figure of 58 mm for the net surface water inflow to the Moor during these months.

7.2 Future progress of hydrological work on West Sedgemoor

Although the Wessex Rivers study has come to an end, IH hydrological investigations will continue at West Sedgemoor, with funding from NCC, and continuing hydrometric support from Wessex Rivers. The dipwell transects and the lysimeter will continue in operation, and it is hoped that a longer run of data from both will reduce the uncertainties in the measurements of the important hydrological variables. In addition, investigations of soil hydraulic properties will be intensified: it is intended that more in situ permeability measurements will be carried out at the remaining dipwell transects, and the relationships between soil composition and compaction and hydraulic properties will be studied.

The RSPB's efforts to maintain a regime of higher water table levels in the area surrounding dipwell transect T1 will be watched with interest, and it is intended to install another lysimeter in this area, subject to RSPB's permission. The new lysimeter is of a type that performs irrigation and monitoring functions automatically, and can be used to compute daily values of evaporation rates and lateral flow.

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The study could not have been undertaken without considerable assistance from Wessex Rivers.

Chris Birks and Linda Aucott provided data from the two pumping stations and the Helland streamflow gauge and assisted with other information required by the study. Andrew Gardner provided rainfall data from five gauges. Peter Rossiter provided details of sluice movements.

Colin Hanks and Brian Sharp supplied details of the operating characteristics of the new pump, and arranged for a cumulative flow meter to be installed, within the West Sedgemoor electrical pumping station.

Wessex Rivers built the streamflow gauge at Helland specifically to assist the study and installed seven staff gauges. Their surveying staff completed four surveys of the dipwell transects and staff gauges during the period of the study.

The terms of reference of the study were defined by Dr A T Newman, Divisional Engineer, Wessex Rivers.

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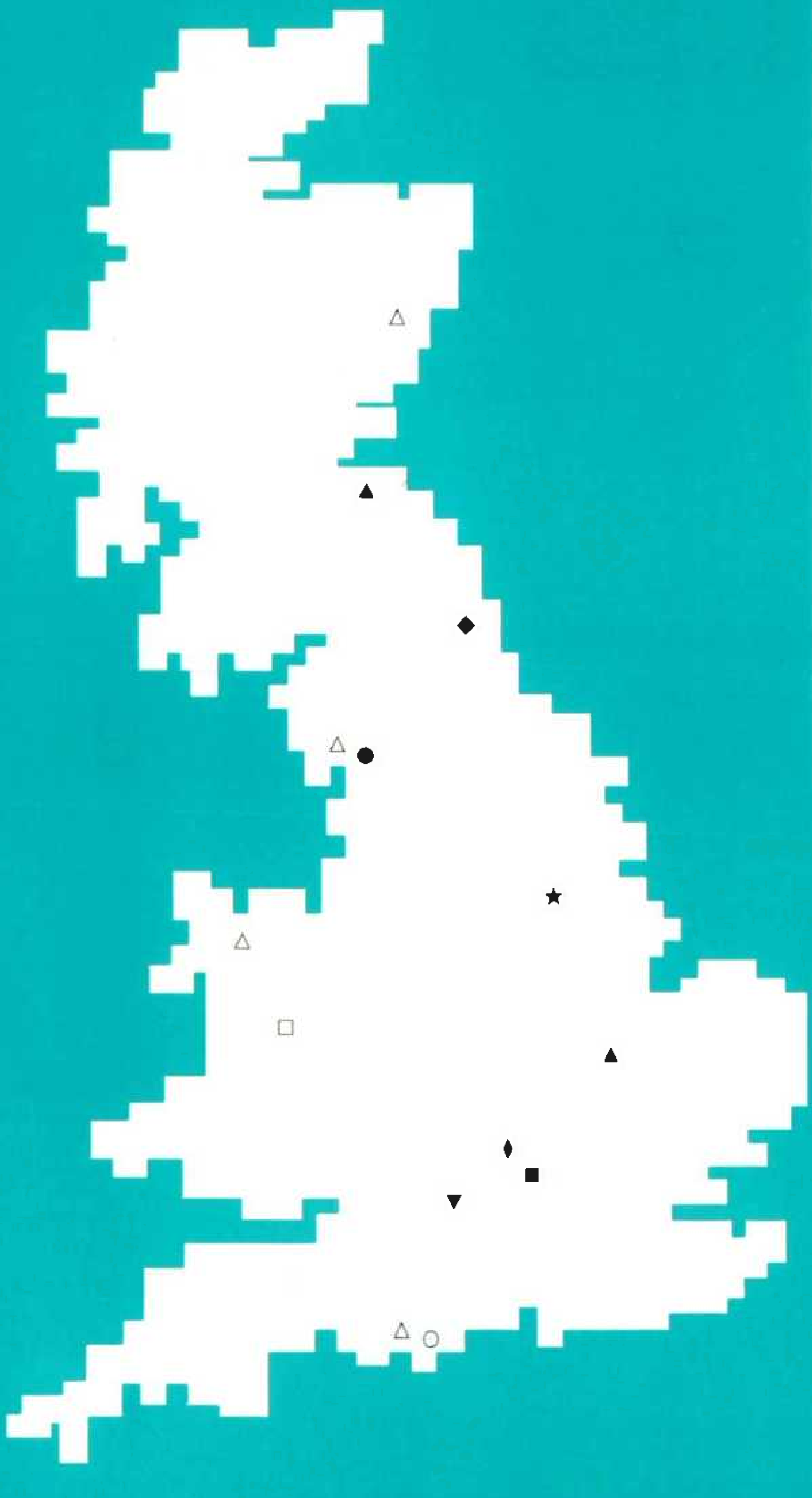

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