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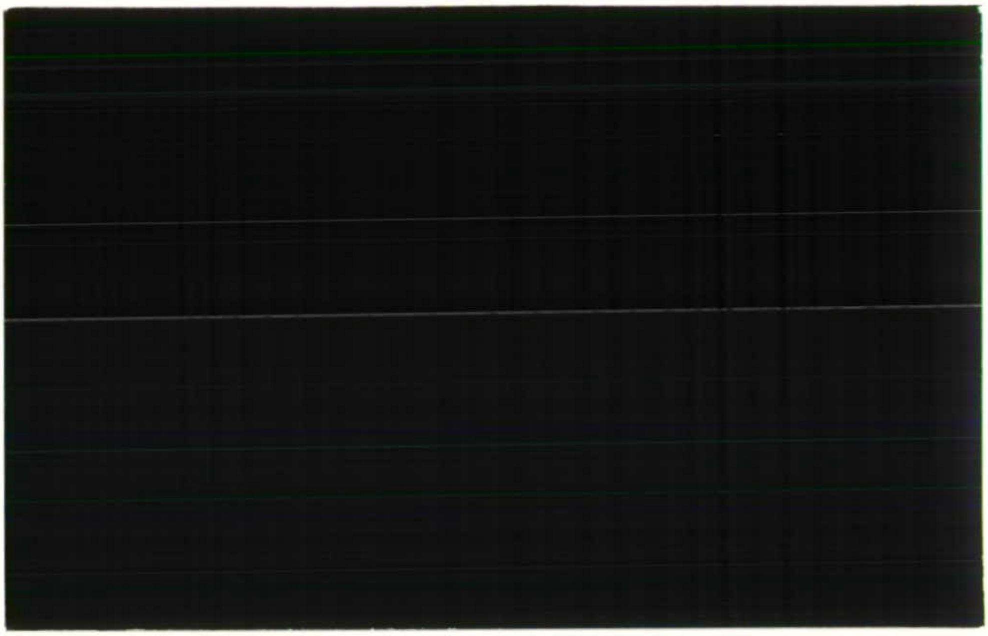

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David Boorman
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THE ESTIMATION OF PERCENTAGE RUNOFF USING SOIL WATER MEASUREMENTS ON THREE LINCOLNSHIRE CATCHMENTS

Final Report

Part II of the Lincolnshire Soil Water Data Study

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Executive Summary

Flood event data from three catchments in Lincolnshire have been collated to enable an investigation of the usefulness of soil water content data for modelling flood flows. The soil water content data come from a network of soil water measurement sites operated by the former Anglian Water Authority, now NRA Anglian Division.

In the Flood Studies Report (Institute of Hydrology, 1975), soil moisture deficit, SMD, was used to index the variation in response runoff between events on a catchment. However, the soil moisture information was not measured directly, but estimated using meteorological data, and was available from a sparse network of sites. It was anticipated that measured soil water content, SWC, from on, or close to, the catchment of interest, would provide a better index of between event variability in runoff volumes.

This thesis was tested against data from the Great Eau at Claythorpe Mill, the Partney Lymn at Partney Mill, and the Witham at Colsterworth. Between 40 and 50 events were selected on each of the catchments, but a great many problems were experienced in abstracting, preparing and collating the data, so that only 10, 9 and 12 events on the three catchments were available for further study.

On the three catchments SMD and SWC data were found to have broad correlation but on many events there was a significant disagreement about the moisture content of the soils. SMD data from the Meteorological Office Rainfall Excess Calculation System, MORECS, were compared with the other two measures of catchment wetness, and were found to be more closely related to SMD than SWC data.

None of the three measures was found to be substantially better than the other two in indexing between event variations in percentage runoff, but, on all catchments, all three soil moisture indices were found to be useful. On none of the catchments was the antecedent precipitation index a useful variable, and on only one was the event rainfall significant (both of these terms were present in the Flood Studies Report equation for percentage runoff). Coefficients of significant variables obtained from regression analysis were reasonable, and in sympathy with those published previously.

That the locally measured soil water content data proved no more useful than remote or regional SMD values obtained indirectly, was a disappointing and surprising conclusion. However, this outcome should only be seen in the context of the small data sets available for analysis. Larger data sets would enable the use of alternative approaches to the estimation of runoff volumes that may well demonstrate the benefits of locally measured soil water data.

Contents

1. Introduction

This report describes an investigation into the usefulness of measured soil water content data for modelling flood flows on three catchments in Lincolnshire. The study was conducted by the Institute of Hydrology under contract to the former Anglian Water Authority, now NRA Anglian Division.

Soil water measurements have been made at a number of sites in Lincolnshire; the oldest site is Ulceby Cross which was established in 1973. At the end of 1987 a total of 115 site-years of data had been collected, but the value of continuing with data collection was not clear. Two potentially valuable applications of the data were thought to be in estimating aquifer recharge, and improved flood modelling, and the Institute of Hydrology has studied both. A report on the first of these was completed by Gardner in 1990.

For the estimation of design flood magnitudes in the UK the methods presented in the Flood Studies Report (Institute of Hydrology, 1975), and its various refinements, have become standard techniques recognised and applied throughout the water industry. In the Flood Studies Report (FSR) rainfall-runoff model based approach, catchment wetness was an important factor in the calculation of event percentage runoff. The form of the percentage runoff equation was revised in Flood Studies Supplementary Report No. 16, FSSR16, (Institute of Hydrology, 1986), but still use catchment wetness.

Catchment wetness was assessed by combining the soil moisture deficit (SMD) with an antecedent precipitation index (API). The SMD data used in the FSR come the Meteorological Office's network of ESMD stations. These are a fairly limited set of sites with the meteorological data required for a calculation of SMD using the method of Penman (1950). Because of the sparse nature of the ESMD stations it was frequently necessary to transfer SMD values from sites some considerable distance from the study catchment, and often to average values from two or more distant sites. While these SMD values will no doubt reflect regional variations in the water content of soils, they are not likely to indicate accurately the state of soils except in the very close proximity of the ESMD stations. The API data, on the other hand, come from daily rainfall data collected at daily-read raingauges on or close to the study catchment. The rainfall totals therefore enable a good estimate of the catchment rainfall to be made. However, when they are combined into an index that reflects the short-term rainfall history of the catchment, doubt creeps in as to the relevance of the index for all catchments, since different soils will retain a different memory of past rainfall.

The availability of soil water measurements means that is possible to replace both SMD and API with what should be a more appropriate and useful quantity in the estimation of percentage runoff, and this is the primary objective of this study. Another index of catchment wetness comes from the Meteorological Office Rainfall and Evaporation Calculation System, MORECS, (Thompson, Barrie, and Ayles, 1981). The usefulness the measured water content data was assessed against both the site-based ESMD data, and the 40km grid average SMD from MORECS.

These comparisons are made on three catchments in Lincolnshire. These catchments are described in Section 2, which also contains descriptions of all the data used in the study. Section 3 compares the various indices and uses them to estimate percentage runoff and compares the results between methods and across catchments. Section 4 contains conclusions.

2. Catchments and Data

The criteria for selecting catchments for this study were that they should be able to provide good quality flood event data, and have one, or more, soil water measurement site located on, or close to, the catchment. In addition it was hoped to select catchments on the different geologies occurring within the region, and for which data had been processed in the aquifer recharge component of the study. Sections 2.1 and 2.2 describe the requirements for flood event data and soil moisture data respectively. Section 2.3 gives details of the three catchments that were selected and the data obtained from them.

2.1 FLOOD EVENT DATA

The data required for each event describe flow, rainfall and soil moisture.

Flow data were required at a sufficiently fine data interval to define the flood response of the catchment; this is typically a 1-hour interval. The flows are needed to define the recession prior to, and following, the event as well as the flow peak itself. Some flow data have been assembled for previous studies and were already available at IH, but most of these data were prepared by NRA Lincoln Office and supplied to IH.

The rainfall data were of two types. Data from recording gauges are used to define the distribution of rainfall with time, and data from daily gauges are used to estimate the total volume of rainfall falling over the catchment. As with the flow data, most of the recording rainfall data were supplied by NRA Lincoln Office. The daily rainfall data were available at IH from data supplied by the Meteorological Office(MO).

In standard FSR analyses, the soil moisture status is indexed by the calculated ESMD value obtained by visiting the MO and manually abstracting the required data from hard-copy or microfiche.

Combining data from a number of sources provides an excellent means of quality control as errors are quickly revealed. It is, however, not always quite so straightforward to pin-point the exact source of the error. For example, if the rainfall supposedly causing the increase in flow occurs after the rise in the flow, there may be a data recording or preparation error in either the flow or the rainfall data (or both), or the data may be good but the rainfall as recorded at the gauge may be a very poor representation of the rain falling on the catchment.

Experience gained from other studies has identified the following seven reasons for rejecting events.

i) Insufficient recording raingauge data.
ii) Insufficient flow data.
iii) Insufficient daily rainfall data (sometimes for the period prior to the event which is necessary to assess catchment wetness).
iv) Large artificial influences affecting peak flows.
v) Unreconcilable differences in timing between flow and rainfall.
vi) Snow; either corrupting rainfall records, or contributing melt water to a later flood event.

vii) The event is too small to be of interest. Large rainfall events on dry catchments would be very useful to this study and would be carried forward, but a very small rainfall causing a very small flow response is of no interest.

Since the quality control process was likely to reject many events it was desirable to firstly select catchments that should be able to supply many events (ie. a long period during which rainfall and flow data were available), and then select as many events as possible so that a large number survive to enter the analyses phase of the project.

Application of the FSR rainfall-runoff model to the events would also lead to another categorisation of events: those that could only be used for volume of runoff studies, and those for which unit hydrograph parameters could also be derived. In the present context this distinction is of little relevance since the study is primarily concerned with runoff volumes.

2.2 SOIL MOISTURE DATA

The criterion for selecting catchment based on the soil moisture data was very much more straightforward. One or more soil water measurement site should be located on or close to the catchment. The data that were actually needed were the 09:00 GMT water contents on the day of the event. These data were available from all sites, by interpolating between actual measurements, but for slightly different periods. It would obviously be most useful to use those sites with the longest period of record.

2.3 THE STUDY CATCHMENTS

After examining the possible sites according to the criteria presented above three catchments were selected and are shown on the map in Figure 2.1

Great Eau at Claythorpe Mill

The Great Eau catchment (29002) has a drainage area of 77.4 km^2 and is located predominantly of the southern chalk outcrop. Event data were available from December 1979 to December 1986. Recording rainfall data were from two gauges both located on the catchment. Two daily gauges, both located just off the catchment, provided extra data on the rainfall depth. Soil moisture were available from two sites Driby (reference number 9) and Ulceby Cross (number 25).

A total of 42 flood events were originally selected for the catchment, but a great many of these were rejected during processing and only 10 provided volume of runoff figures. Table 2.1 lists the various reasons for rejecting events.

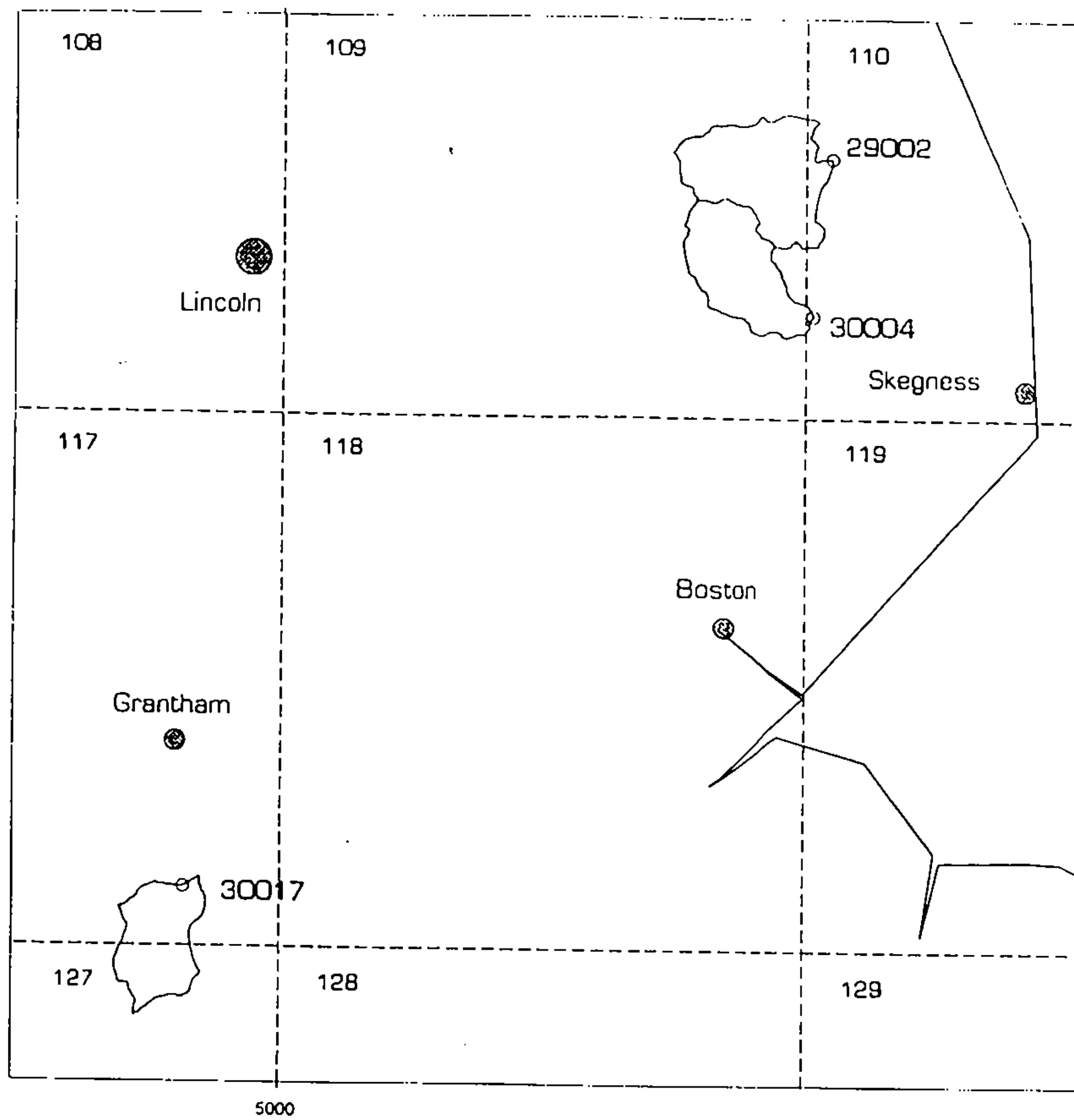


Figure 2.1 *Location of the three study catchments with major towns and MORECS 40km grid squares*

Table 2.1 *Summary of event processing for the three catchments.*

Catchment		29002	30004	30017
Initially selected and digitised at Lincoln[1]		42	48	49
Re-submitted from punch tape		13	35	42
Charts digitised at IH		10	-	-
Rejected:	Snow	-	2	3
	Rainfall and flow inconsistent	4	1	5
	Insufficient rainfall data	-	5	11
	Artificial influences	3	-	-
	Too small	2	-	1
	Insufficient flow data	-	2	-
	No antecedent rainfall data	4	5	2
TOTAL		13	15	22
Remaining events		10	20	20
Results	losses only	2	-	-
	unit hydrograph	8	20	20
FSR results[2]	losses only	-	2	-
	unit hydrograph	-	9	-
TOTAL	Losses only	2	2	-
	Unit hydrograph	8	29	20
	Total	10	31	20

Notes: 1 Events were initially selected and digitised from charts in the Lincoln office but these data proved unreliable and it was decided to use the PTR data instead. However, not all events were available in this format.

2 These events were already at IH from earlier analysis carried out as part of the FSR.

Figure 2.2 shows the location of the gauges used in the rainfall processing for the event occurring on the 26th December 1979, and Figure 2.3 shows the flow and rainfall for the same event. Table 2.2 gives a summary of event parameters, observed and derived, for the remaining 10 events.

The columns headed SMD in the table are ESMD values at 09:00 GMT on the day of the event, and a value adjusted to the start of the rainfall event. The two figures are presented since in previous studies (eg. the FSR) the start-of-event value has been used. Since this is not available from the MORECS data, or the observed data set both are given and will be compared across all three catchments at the end on this section.

Where gaps exist in the time-to-peak column, the event was considered suitable for volume of runoff studies only and a time-to-peak was not derived, or not considered reliable. These data are presented for information only and are not used in the later section of this report.

Table 2.2 *Summary of event characteristics and derived parameters for catchment 29002*

Start date	Rainfall total	Initial flow	Flow peak	API	Event SMD	9am SMD	Time to peak	Percentage runoff
26-Dec-79	24.1	.62	2.55	1.0	8.4	10.0		8.4
24-Feb-80	28.0	1.35	4.13	2.5	.0	.0	6.5	10.2
17-Dec-80	8.7	1.02	2.33	4.7	10.0	10.0	7.7	10.8
08-Feb-81	35.0	.84	3.88	.5	.3	.4	7.3	9.5
24-Apr-81	84.9	1.15	8.80	2.3	11.1	11.9		15.4
15-Mar-82	15.0	.81	2.14	4.6	9.0	10.1	8.3	5.4
26-Nov-83	27.4	.38	1.51	2.4	85.6	85.8	11.7	3.9
01-Feb-86	23.7	.92	2.40	2.3	.6	.9	21.0	10.8
29-Dec-86	29.0	.74	3.47	.6	6.0	6.5	7.2	9.7
31-Dec-86	17.2	1.24	2.77	8.6	.0	.0	11.2	9.7

From this table it can be seen that the observed peaks flows for the events range from 1.51 to 8.8 m^3s^{-1}. Comparing this range with the estimated mean annual flood of 4.1 m^3s^{-1} (Institute of Hydrology, 1988) implies a good representation of the larger events on the catchment has been obtained in the data set. Only one of the events has a substantial SMD but several others have small SMDs. As would be expected for a catchment of this size that has such a small mean annual flood, the percentage runoff figures are very low, the observed range being from 3.9 to 15.4%, with a median value of 9.7%.

The location of the catchment relative to the soil moisture measurement sites and the 40 km MORECS grid is shown in Figure 2.4. Tube 9 is on the catchment and tube 25 is close to the catchment boundary; data from both have been abstracted and are listed in Table 2.3. The catchment is located 95% in MORECS square 109 and 5% in square 110; a weighted average SMD has been calculated for each event using these percentages and is listed in Table 2.3.

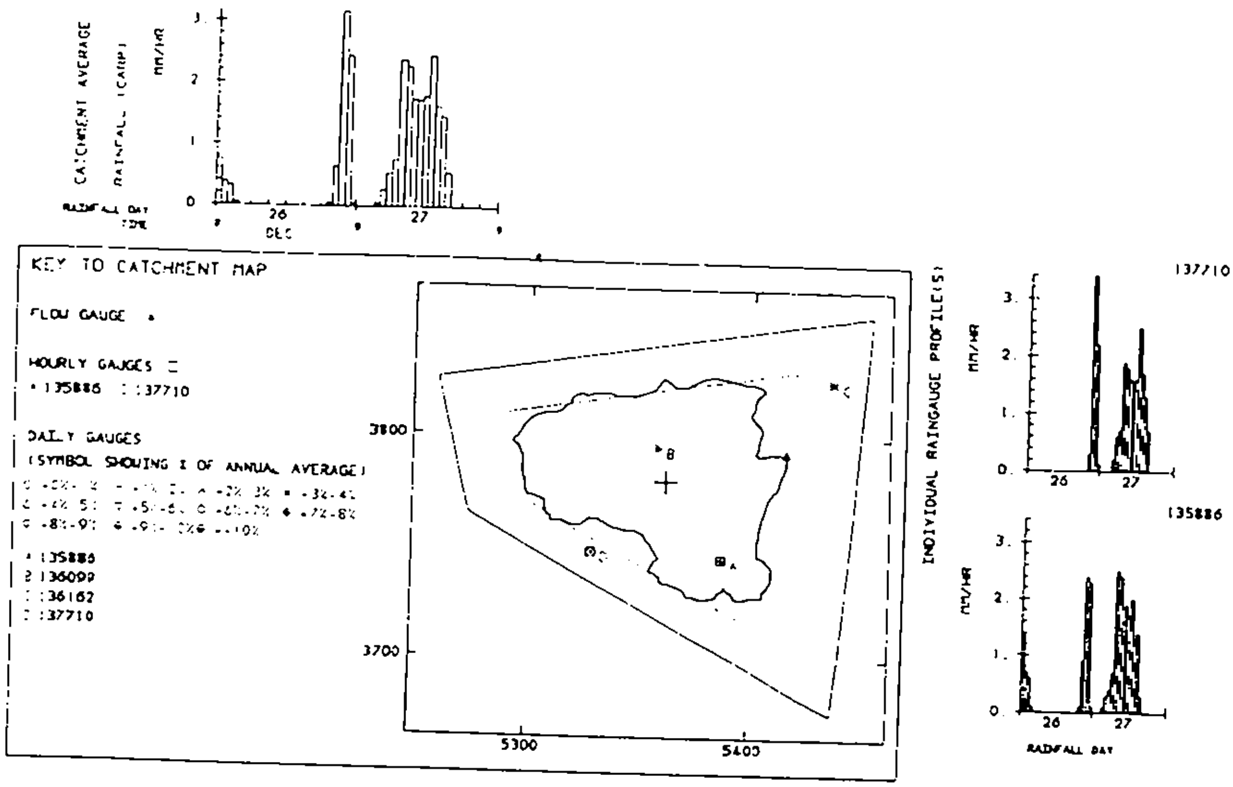


Figure 2.2 *Rainfall processing for the event on 26/12/79 on the Great Eau catchment*

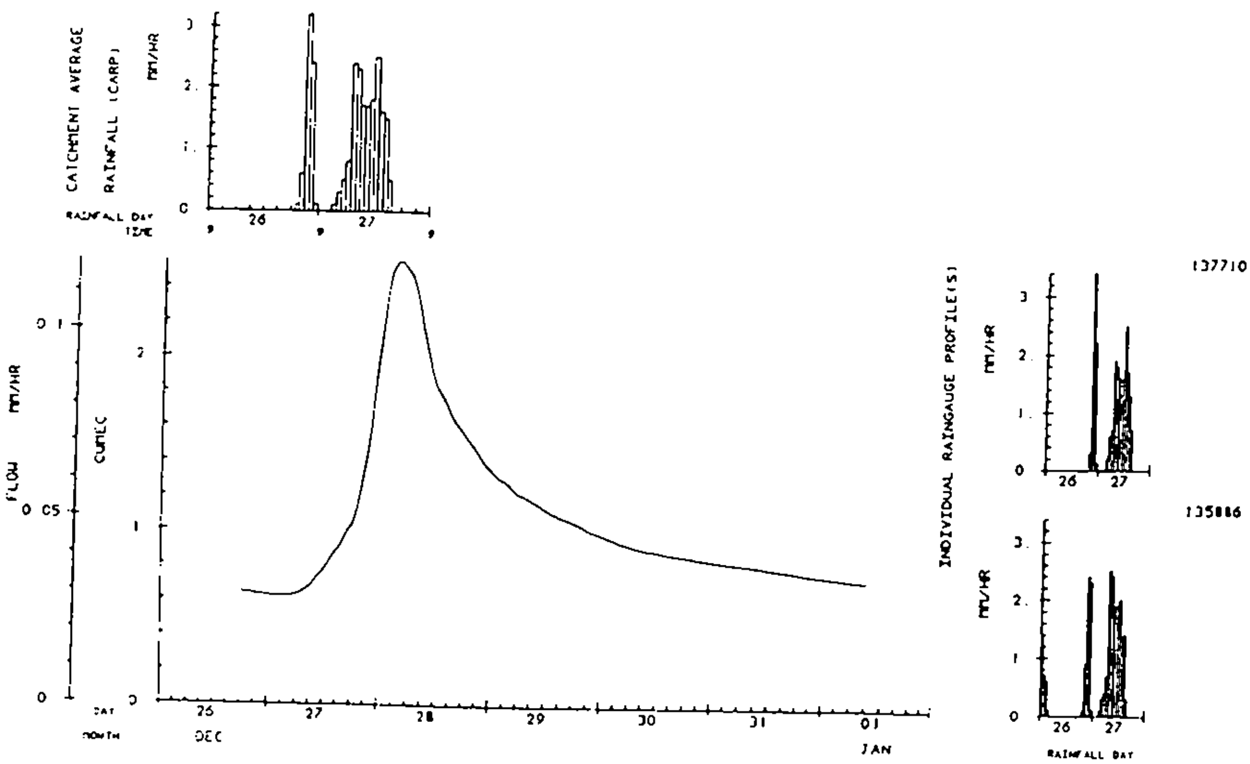


Figure 2.3 *Flow and rainfall data for the event on 26/12/79 on the Great Eau catchment*

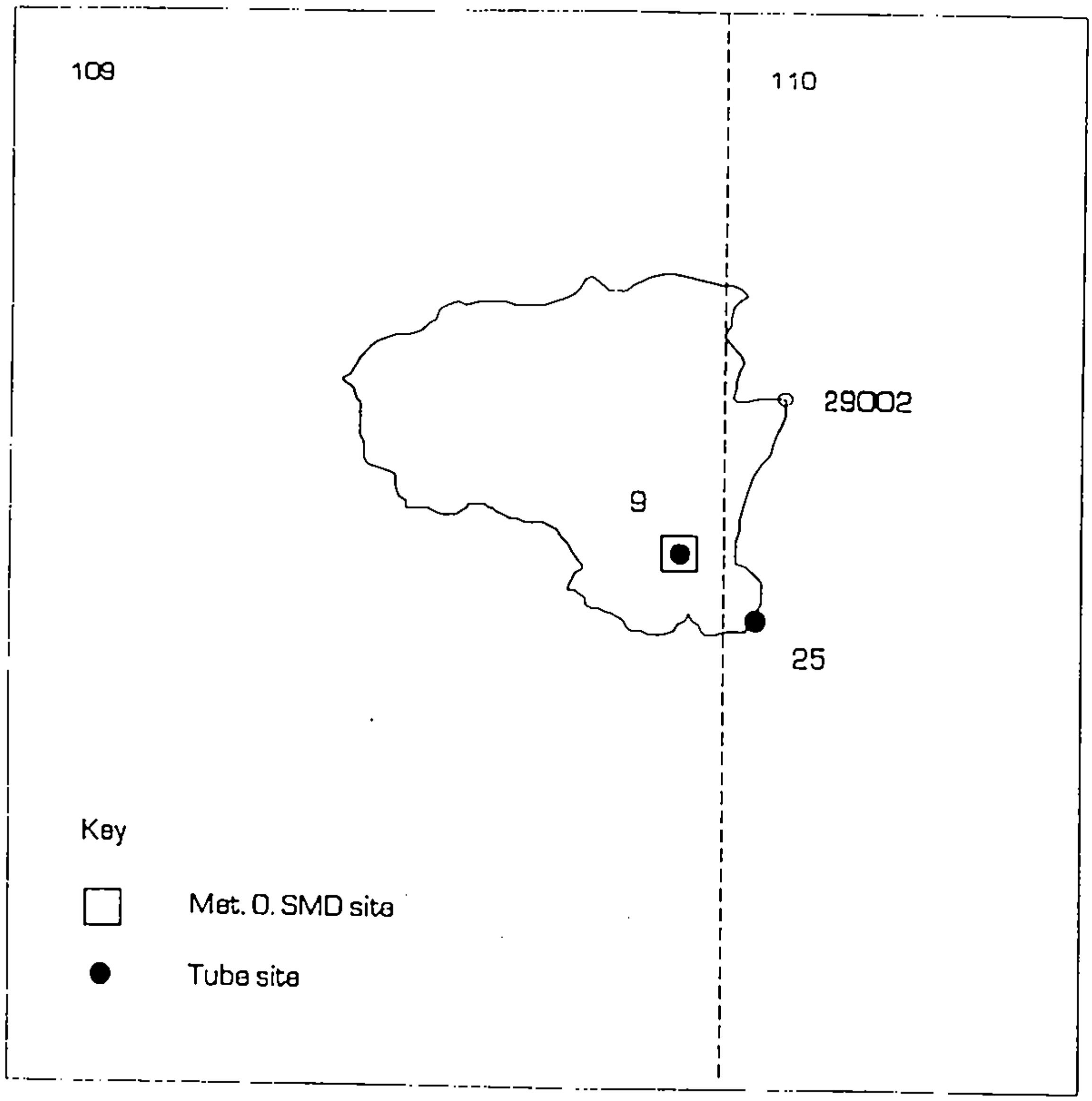


Figure 2.4 *Soil moisture sites and MORECS squares for the Great Eau catchment*

Table 2.3 *ESMD, MORECS and measured water content for the Great Eau catchment*

Start date	API	Event SMD	9am SMD	Water Tube 9	content Tube 25	MORECS average
26-Dec-79	1.0	8.4	10.0	370.0	313.5	55.0
24-Feb-80	2.5	.0	.0	365.0	308.6	.0
17-Dec-80	4.7	10.0	10.0	376.0	320.6	28.9
08-Feb-81	.5	.3	.4	379.7	326.0	6.4
24-Apr-81	2.3	11.1	11.9	326.9	251.8	21.5
15-Mar-82	4.6	9.0	10.1	377.5	324.9	.0
26-Nov-83	2.4	85.6	85.8	322.4	297.5	84.7
01-Feb-86	2.3	.6	.9	373.1	320.3	.0
29-Dec-86	.6	6.0	6.5	351.0	325.0	.0
31-Dec-86	8.6	.0	.0	373.5	349.9	.0

Figure 2.5 shows the various soil moisture indices plotted against each other. The plot showing the measured water contents has seven points on a straight line and three on a parallel line. The three events are those on 26/11/83, 29/12/86 and 31/12/86 and form no obvious subset of the data. The range of water contents is twice as large at site 25 than it is at site 9. The ESMD data and MORECS data are similar; only one event, the first, is substantially different between the two data sets. It is harder to directly compare the water content and moisture deficit data, since the water content equivalent to zero SMD is not known (and different at the two sites), and because the water content can represent a wetness state above zero SMD. However, one event (24/4/81) stands out as being different in the two sets, and especially at site 25, as having the lowest water contents but only a small SMD.

Partney Lymn at Partney Mill

The Partney Lymn catchment (30004) borders the Great Eau catchment to the south but is underlain by the Spilsby sandstone not chalk. It has an area of 61.6 km^2. Following event processing and analysis 31 events between December 1962 and January 1988 were available for further study. Recording rainfall data were from one gauge located on the catchment; two daily gauges also provided data. Soil moisture measurements are made on the catchment at Tetford (number 24) and close to the catchment at Ulceby Cross (number 25). Summary data for the events are presented in Table 2.4.

Seven events are greater then the mean annual flood, estimated value 7.8 m^{3}s^{-1} (Institute of Hydrology, 1988), and eleven have substantial soil moisture deficits. The range in percentage runoff is from 2.5% to 30% and the median is 21.8%. An example of the rainfall processing for the event is shown for the event on 13 November 1982 in Figure 2.6; the flow and rainfall for the same event are shown in Figure 2.7.

The location of the catchment relative to the soil moisture measurement sites and the 40 km MORECS grid is shown in Figure 2.8. Tube 24 is on the catchment and located on the sandstone that underlies most of the catchment. Tube 25 is close to the catchment boundary, but is on a different geology. Data from both have been abstracted and are listed in Table 2.5. The catchment is located almost entirely in MORECS square 109 and data for this square have been abstracted and are also listed in Table 2.5.

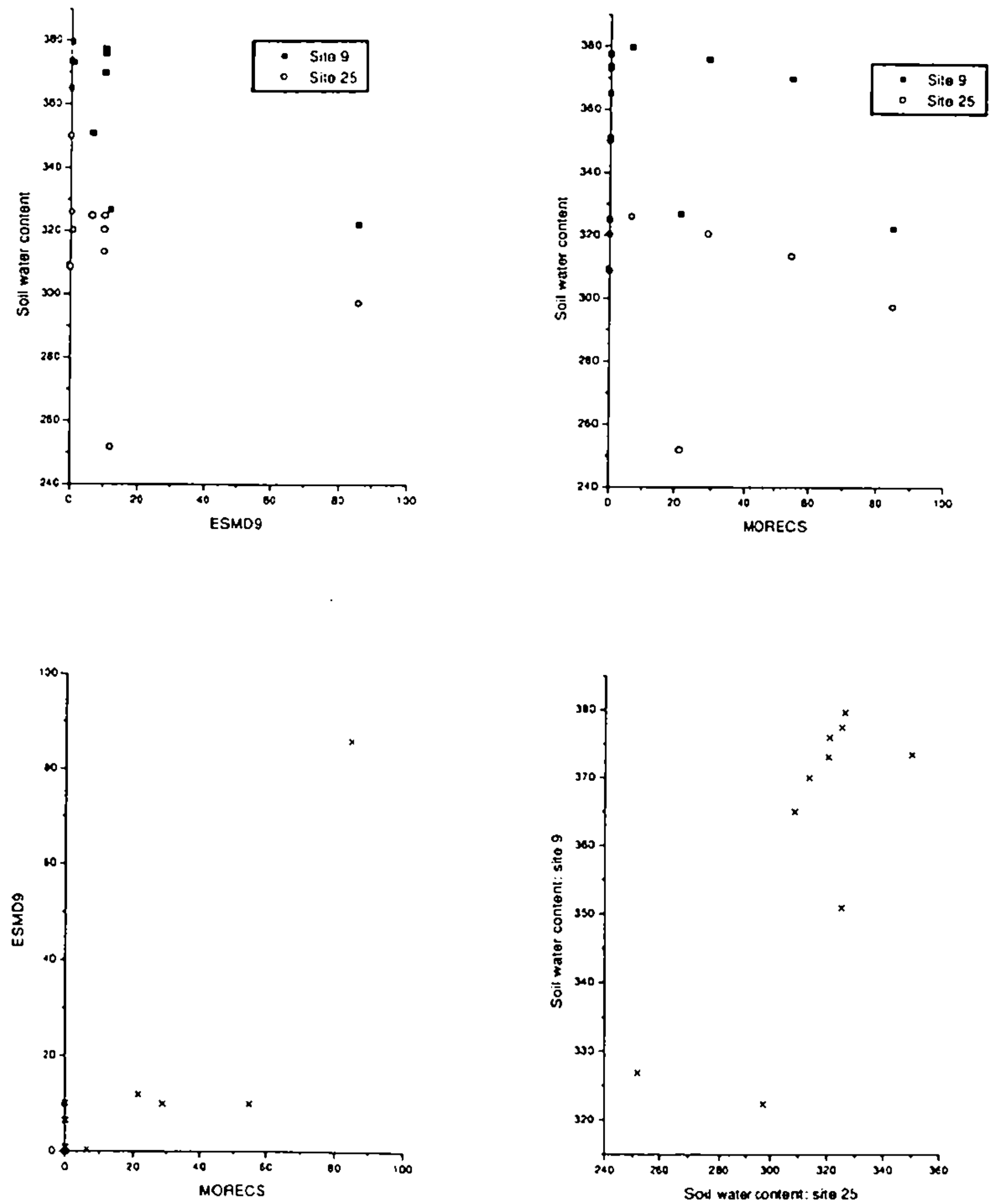


Figure 2.5 Comparison of soil moisture indices for the Great Eau catchment.

Table 2.4 *Summary of event characteristics and derived parameters for the Partney Lymn catchment*

Start date	Rainfall total	Initial flow	Flow peak	API	Event SMD	9am SMD	Time to peak	Percentage runoff
20-Dec-62	15.5	.38	3.09	.6	.0	.0	8.2	14.7
29-Nov-65	36.9	.93	11.05	3.1	.0	.0	11.5	27.4
18-Dec-65	18.9	1.43	5.45	8.4	.0	.0		27.2
05-Nov-67	15.2	.96	3.72	6.6	9.9	9.9	11.1	21.9
10-Jul-68	105.5	.19	13.34	3.1	57.2	57.2		15.3
08-Aug-68	33.8	.21	5.09	2.3	32.3	32.2	6.0	8.6
15-Sep-68	30.1	.48	6.58	1.9	2.8	2.8	10.0	22.0
01-Nov-68	48.7	.76	10.17	6.4	.0	.0	10.7	25.0
08-Feb-74	11.9	.94	4.33	5.2	.0	.1	10.0	20.1
07-Oct-74	27.7	.88	7.88	5.4	50.4	54.2	11.6	24.3
18-Apr-75	22.0	1.08	8.64	6.3	.0	.0	5.0	22.4
13-Dec-79	27.6	1.15	8.41	7.1	9.5	10.0	7.3	24.5
27-Dec-79	16.7	.63	5.32	4.5	4.8	5.0	6.1	25.8
07-Aug-80	35.6	.27	1.75	4.7	91.0	90.0	9.5	3.8
14-Aug-80	32.6	.27	7.06	.9	83.2	80.0	6.1	20.3
06-Mar-82	21.4	.53	4.73	1.9	18.9	19.2	8.3	18.9
15-Mar-82	16.0	.60	4.14	5.0	8.8	10.1	6.1	19.5
21-Jun-82	65.3	.27	5.37	4.0	90.2	89.7	8.2	10.3
25-Jun-82	23.2	.52	5.86	10.9	46.8	45.7	5.1	15.0
13-Nov-82	26.7	.59	4.32	1.5	5.3	5.5	7.2	21.8
09-Dec-82	18.3	.72	6.39	3.7	.0	.0	6.0	20.9
01-May-83	21.2	.90	5.02	5.8	4.1	1.9	11.3	23.9
31-Jul-83	36.0	.21	1.74	.1	101.9	100.5	6.7	2.5
26-Nov-83	29.7	.31	3.09	2.8	85.5	85.8	8.7	9.7
26-May-84	38.0	.33	3.65	4.8	50.1	47.5	5.3	11.2
02-Aug-84	53.0	.16	5.19	9.1	101.3	101.3	5.4	4.4
29-Jan-85	18.9	.89	8.32	4.4	.0	.0	9.1	30.0
29-Dec-86	29.5	.57	7.61	1.1	4.9	6.5	15.4	26.7
31-Mar-87	24.2	.73	4.94	1.5	1.9	2.0	4.5	26.9
14-Oct-87	30.3	.71	7.25	2.9	5.2	5.3	6.2	28.4
01-Jan-88	17.0	.67	6.85	1.6	.0	.1	7.8	25.1

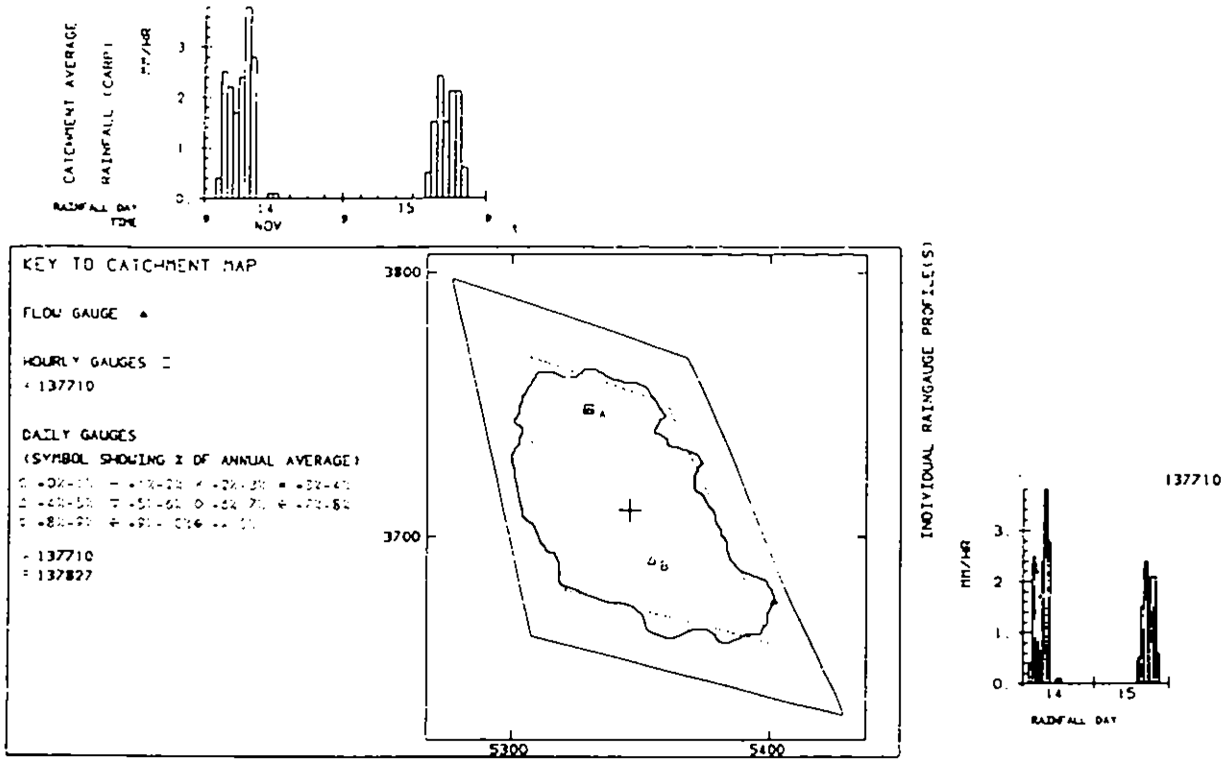


Figure 2.6 *Rainfall processing for the event on 13/11/82 on the Partney Lymn catchment*

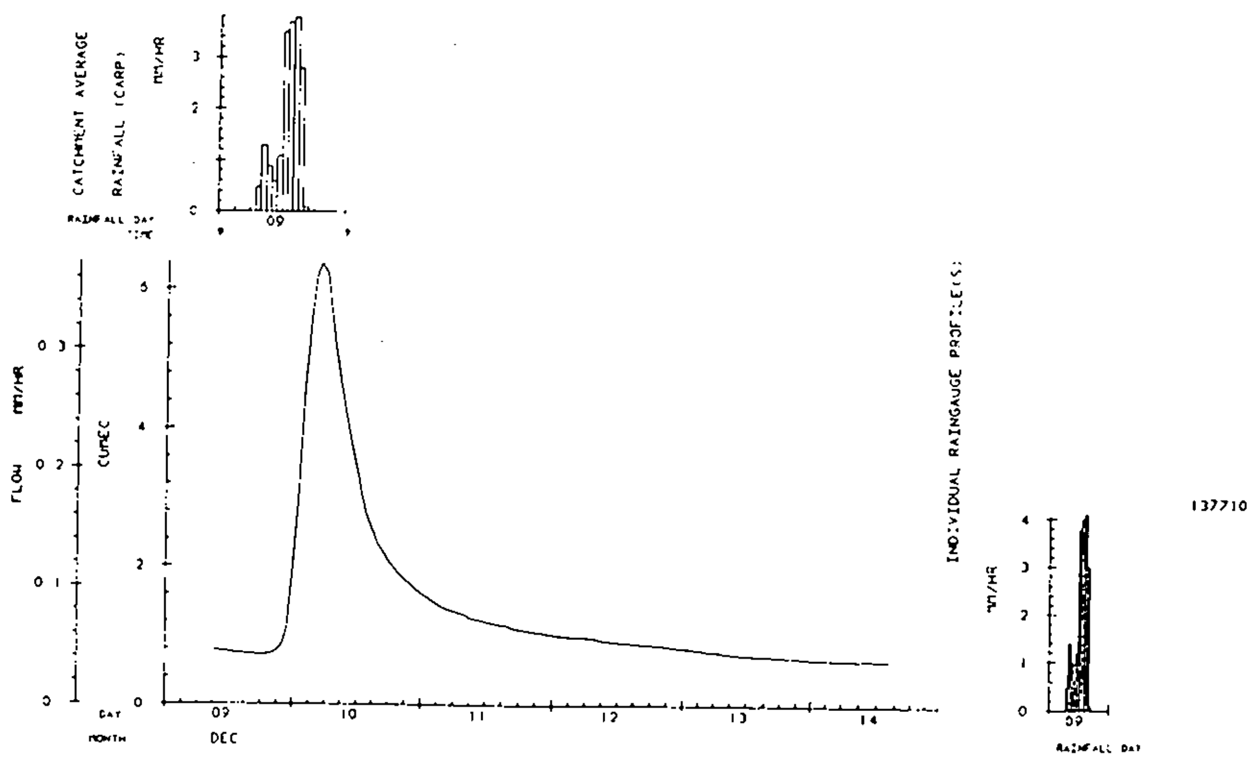


Figure 2.7 *Flow and rainfall data for the event on 13/11/82 on the Partney Lymn catchment*

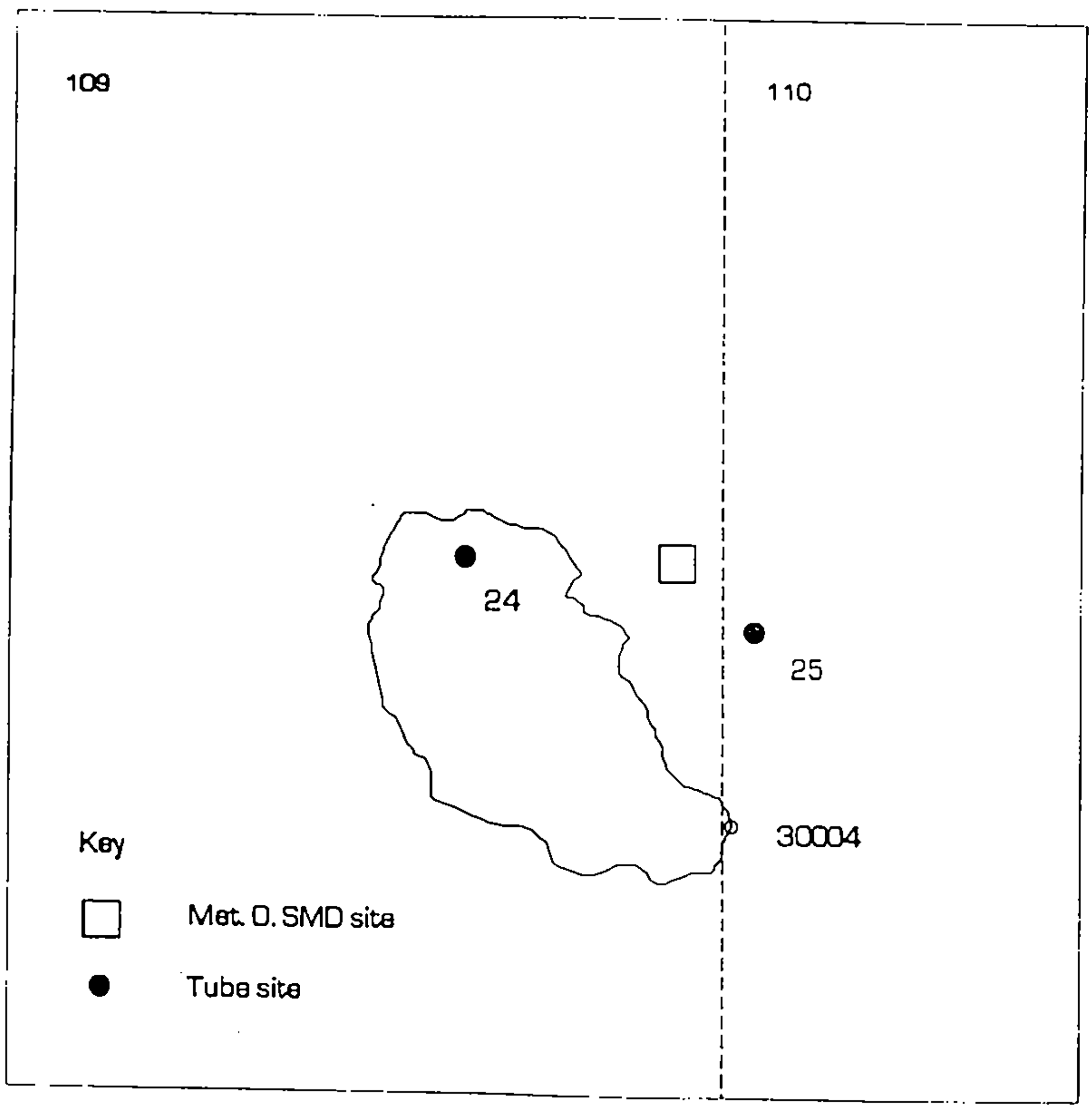


Figure 2.8 Soil moisture sites and MORECS squares for the Partney Lymn catchment

Table 2.5 *ESMD, MORECS and measured water content for the Partney Lymn catchment*

Start date	API	Event SMD	9am SMD	Water Tube 24	content Tube 25	MORECS average
20-Dec-62	.6	.0	.0			
29-Nov-65	3.1	.0	.0			
18-Dec-65	8.4	.0	.0			
05-Nov-67	6.6	9.9	9.9			
10-Jul-68	3.1	57.2	57.2			
08-Aug-68	2.3	32.3	32.2			
15-Sep-68	1.9	2.8	2.8			
01-Nov-68	6.4	.0	.0			
08-Feb-74	5.2	.0	.0			
07-Oct-74	5.4	50.4	54.2			
18-Apr-75	6.3	.0	.0			
13-Dec-79	7.1	9.5	10.0		318.5	87.7
27-Dec-79	4.5	4.8	5.0		314.6	46.5
07-Aug-80	4.7	91.0	90.0		270.6	130.7
14-Aug-80	.9	83.2	80.0		289.0	108.3
06-Mar-82	1.9	18.9	19.2		308.0	.0
15-Mar-82	5.0	8.8	10.1		324.9	.0
21-Jun-82	4.0	90.2	89.7		285.2	96.0
25-Jun-82	10.9	46.8	45.7		317.1	39.0
13-Nov-82	1.5	5.3	5.5		320.8	.0
09-Dec-82	3.7	.0	.0		324.6	.0
01-May-83	5.8	4.1	1.9	297.9		.0
31-Jul-83	.1	101.9	100.5	155.3		115.8
26-Nov-83	2.8	85.5	85.8	236.5		83.8
26-May-84	4.8	50.1	47.5	230.3		35.9
	9.1	101.3	101.3	173.8		108.3
02-Aug-84	4.4	.0	.0	306.9		.0
29-Jan-85	1.1	4.9	6.5	312.7		.0
29-Dec-86	1.5	1.9	2.0	310.0		.0
31-Mar-87	2.9	5.2	5.3	291.1		20.6
14-Oct-87	1.6	.0	.1			.0
01-Jan-88						

From this table it can be seen that the soil moisture data are incomplete. MORECS data are only available from 1979. The best measurement site is Tetford (number 24) since it is on the catchment, but since it started operation in January 1983 this site is only able to supply data for 9 events. Data from Ulceby Cross (number 25) are shown for the earlier events but because these data are from a site located on a different geological unit they need to be treated with caution. These soil moisture indices are shown plotted against each other in Figure 2.9. Again the MORECS and ESMD data are broadly similar although for events with large SMDs, MORECS gives greater deficits, and there are a number of events for which MORECS gives zero SMD when small deficits exist in the ESMD data. For the available events soil moisture values have a greater range from site 24, but data from both sites are well correlated with the SMD values.

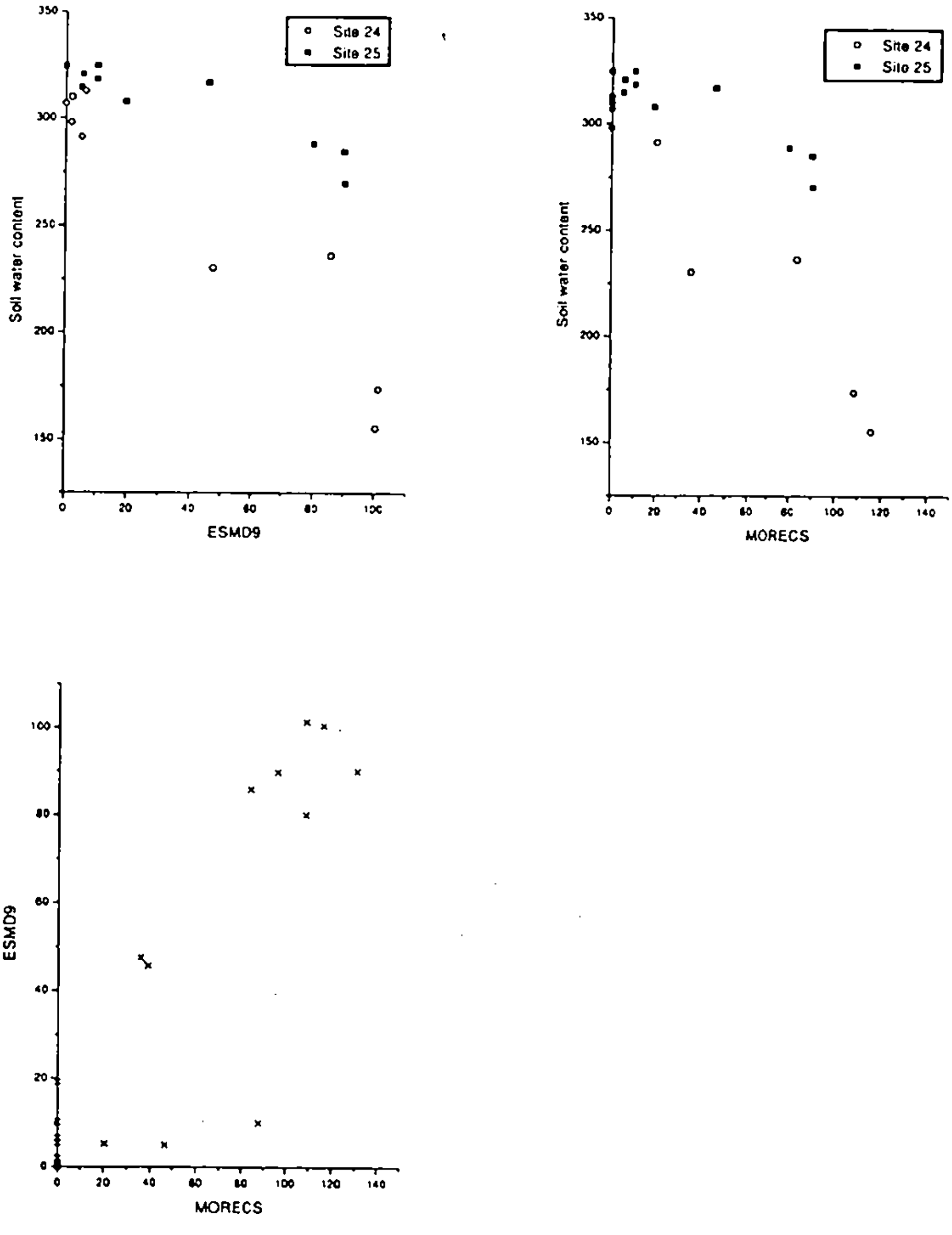


Figure 2.9 Comparison of soil moisture indices for the Partney Lymn catchment

Witham at Colsterworth

The third catchment, the Witham (30017), has an area 51.3 km^2 and is underlain by the Lincolnshire Limestone. Recording rainfall data come from two gauges one on the catchment and one just north of the catchment; daily rainfall data are very limited in general and non-existent for some events. Two soil moisture sites are close to the catchment and on similar geology; these are Corby Glen (number 6) and Saltby (number 22).

Only 20 of 49 events originally selected survived the quality control process. The 20 events analysed are from January 1980 to October 1987; over half of the events have a substantial soil moisture deficit and percentage runoffs are in the range 7.4% to 23.8%, with a median of 18.5%. Event and model parameters are shown in Table 2.6. Figures 2.10 and 2.11 show an example of rainfall preparation and the combined flow and rainfall respectively for the event on 31 May 1983.

Only one event has a peak flow greater than the estimated mean annual flood of 7.6 m^{3}s^{-1} (IH, 1988). A good range of soil moisture deficits is seen in the data set; only three events have ESMD values of zero, most of the others have substantial deficits.

Table 2.6 Summary of event characteristics and derived parameters for the Witham catchment

Start date	Rainfall total	Initial flow	Flow peak	API	Event SMD	9am SMD	Time to peak	Percentage runoff
30-Jan-80	10.3	.33	2.47	2.1	1.5	3.2	9.5	17.5
17-Mar-80	26.9	.38	4.02	4.2	.0	.0	8.4	20.6
15-Oct-80	31.1	.05	3.99	.8	112.6	113.4	8.3	12.6
14-Nov-80	16.6	.16	2.40	1.9	51.9	52.1	10.3	17.7
01-Jun-81	20.1	.15	3.24	2.1	16.0	16.6	7.6	11.2
06-Mar-82	22.7	.16	3.74	1.6	37.4	37.4	9.0	17.4
22-Jun-82	40.4	.06	3.46	5.6	92.9	92.9	9.9	11.3
25-Jun-82	33.6	.30	11.49	11.2	73.4	74.0	7.8	23.4
09-Dec-82	16.3	.34	4.41	4.3	24.5	25.5	8.8	22.1
10-Apr-83	22.7	.11	2.97	2.1	1.7	1.7	12.0	22.2
20-Apr-83	10.4	.42	3.44	5.0	.8	.8	7.2	21.6
24-Apr-83	13.0	.27	2.69	2.2	.0	1.1	7.0	11.8
31-May-83	24.6	.22	5.31	1.1	14.6	11.9	8.9	18.1
23-Nov-84	14.5	.47	3.24	5.7	53.5	60.0	9.4	19.3
29-Jan-86	16.6	.21	2.63	.9	6.5	6.9	8.5	17.0
29-Dec-86	30.5	.17	3.11	.3	49.3	49.8	7.4	20.2
07-Apr-87	17.3	.44	6.13	4.1	.0	.0	5.2	23.8
09-Oct-87	26.5	.03	1.18	4.7	109.0	109.0	14.1	7.4
15-Oct-87	15.8	.14	2.18	4.5	82.2	81.7	8.8	16.4
20-Oct-87	24.4	.15	4.03	1.0	67.4	67.8	10.0	18.8

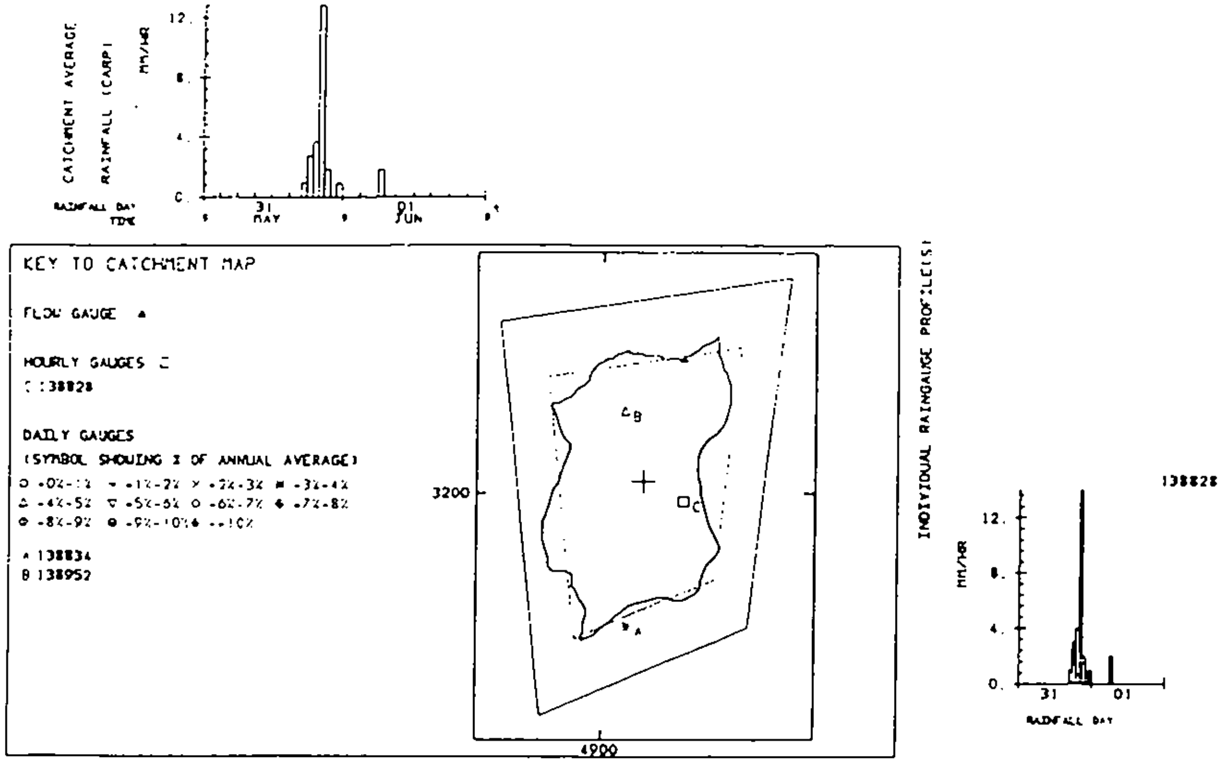


Figure 2.10 *Rainfall processing for the event on 31/5/83 on the Witham catchment.*

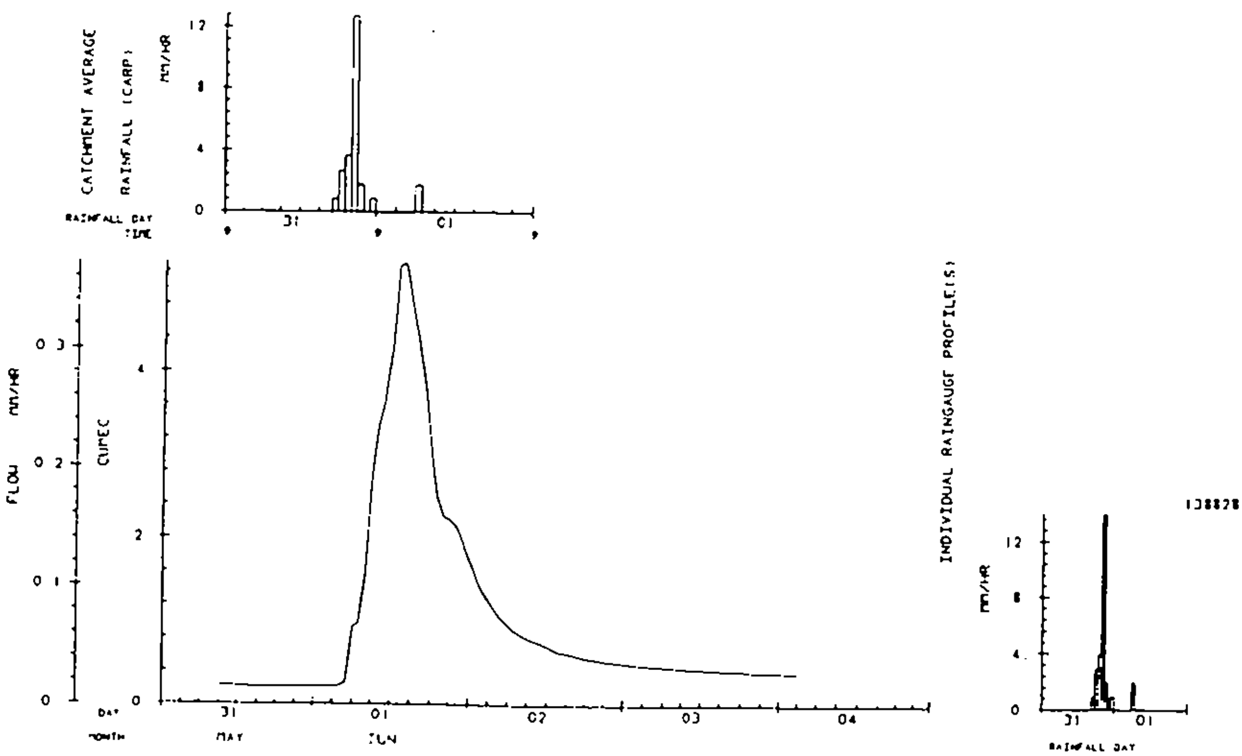


Figure 2.11 *Flow and rainfall data for the event on 31/5/83 on the Witham catchment.*

The location of the catchment relative to the soil moisture measurement sites and the 40 km MORECS grid is shown in Figure 2.11. Data from both soil moisture measurement sites (6 and 22) have been abstracted and are listed in Table 2.7. Both sites start operating in November 1982 and data are therefore not available for the earlier events. The catchment is located on the border of MORECS squares 117 and 127; an average SMD has been calculated as the arithmetic mean of the values from the two squares and is listed in Table 2.7.

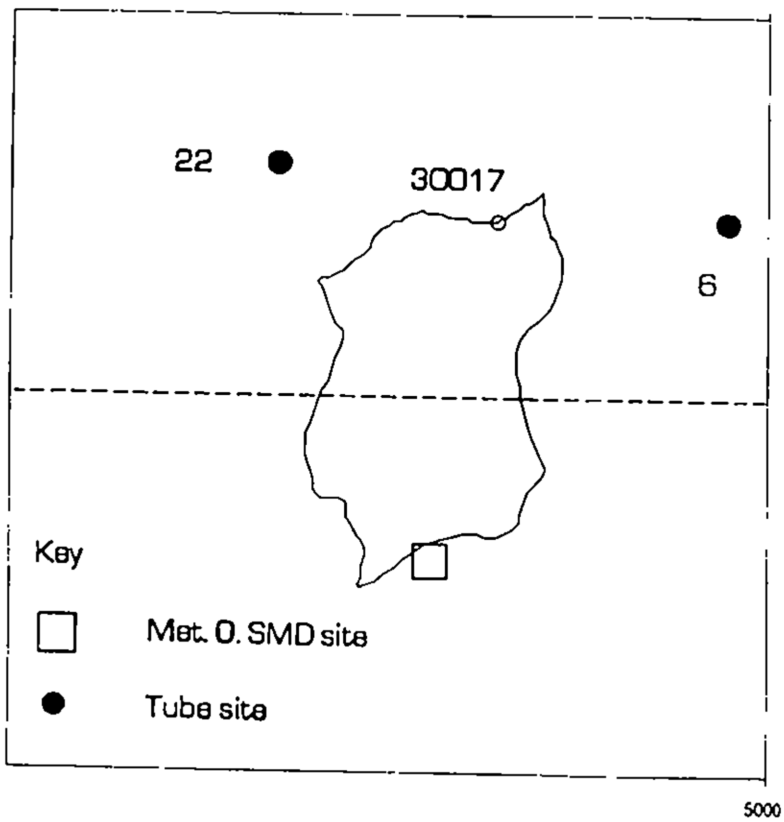


Figure 2.12 Soil moisture sites and MORECS squares for the Witham catchment.

These data are shown plotted in Figure 2.13. The comparison of ESMD and MORECS is very much as on the other two catchments; broad agreement but with substantially different values for larger SMDs, and, as on 30004, many events for which MORECS shows a zero SMD, have a deficit using the ESMD model. The data from the two soil water sites shows almost no correlation with each other. Both sites show decreasing water content in sympathy with the MORECS data for events with SMDs, but for some other events where MORECS indicates no deficit, the water content figures are very low.

Table 2.7 ESMD, MORECS and measured water content for the Witham catchment.

Start date	API	Event SMD	9am SMD	Water Tube 6	content Tube 22	MORECS average
30-Jan-80	2.1	1.5	3.2			.0
17-Mar-80	4.2	.0	.0			.0
15-Oct-80	.8	112.6	113.4			131.0
14-Nov-80	1.9	51.9	52.1			77.2
01-Jun-81	2.1	16.0	16.6			17.3
06-Mar-82	1.6	37.4	37.4			.0
22-Jun-82	5.6	92.9	92.9			60.5
25-Jun-82	11.2	73.4	74.0			29.4
09-Dec-82	4.3	24.5	25.5	296.4	301.3	.0
10-Apr-83	2.1	1.7	1.7	239.5	296.1	.0
20-Apr-83	5.0	.8	.8	258.8	310.2	.0
24-Apr-83	2.2	.0	1.1	267.4	308.3	.0
31-May-83	1.1	14.6	11.9	289.7	297.0	29.3
23-Nov-84	5.7	53.5	60.0	300.8	307.2	8.3
29-Jan-86	.9	6.5	6.9	279.9	293.2	.0
29-Dec-86	.3	49.3	49.8	270.2	290.9	1.7
07-Apr-87	4.1	.0	.0	292.1	308.0	.0
09-Oct-87	4.7	109.0	109.0	275.6	279.5	75.2
15-Oct-87	4.5	82.2	81.7	287.7	296.3	47.3
20-Oct-87	1.0	67.4	67.8	286.7	298.7	35.2

2.4 SUMMARY FOR ALL THREE CATCHMENTS

A summary of the numbers of events from each catchment for which both volume of runoff and soil moisture data are available is given in Table 2.8.

Table 2.8 Summary of events available for further study.

	29002	30004	30017
Events with all required data	10	9	12
Events with data from alternative soil moisture site	-	10	-
Additional events with MORECS and ESMD data	-	1	8
Events with only ESMD	-	11	

The data sets available for further analysis are small with the catchments having only 10, 9 and 12 events with the most reliable and suitable data.

From Tables 2.2, 2.4 and 2.6 it can be seen that there is little difference between the ESMD data at the start of the event and at 09:00 on the day of the event; it was therefore decided that all of the 09:00 data should be used without adjustment; the ESMD at 09:00 are referred to as ESMD9 in the remainder of this report. The soil moisture indices show some consistency but also many differences. The ESMD and MORECS models are in broad agreement, but ESMD often has small deficits when MORECS shows none. The soil water content data is well related to the SMD measures on catchment 30004. On the other two catchments there is reasonable correlation with SMD where there are substantial deficits, but also low water content values where SMDs are low. There appear, therefore, to be real differences in what the various measures indicate in terms of soil moisture.

Within these limited data samples there are substantial variations in percentage runoff; the next section attempts to model these variations using the various soil moisture indices.

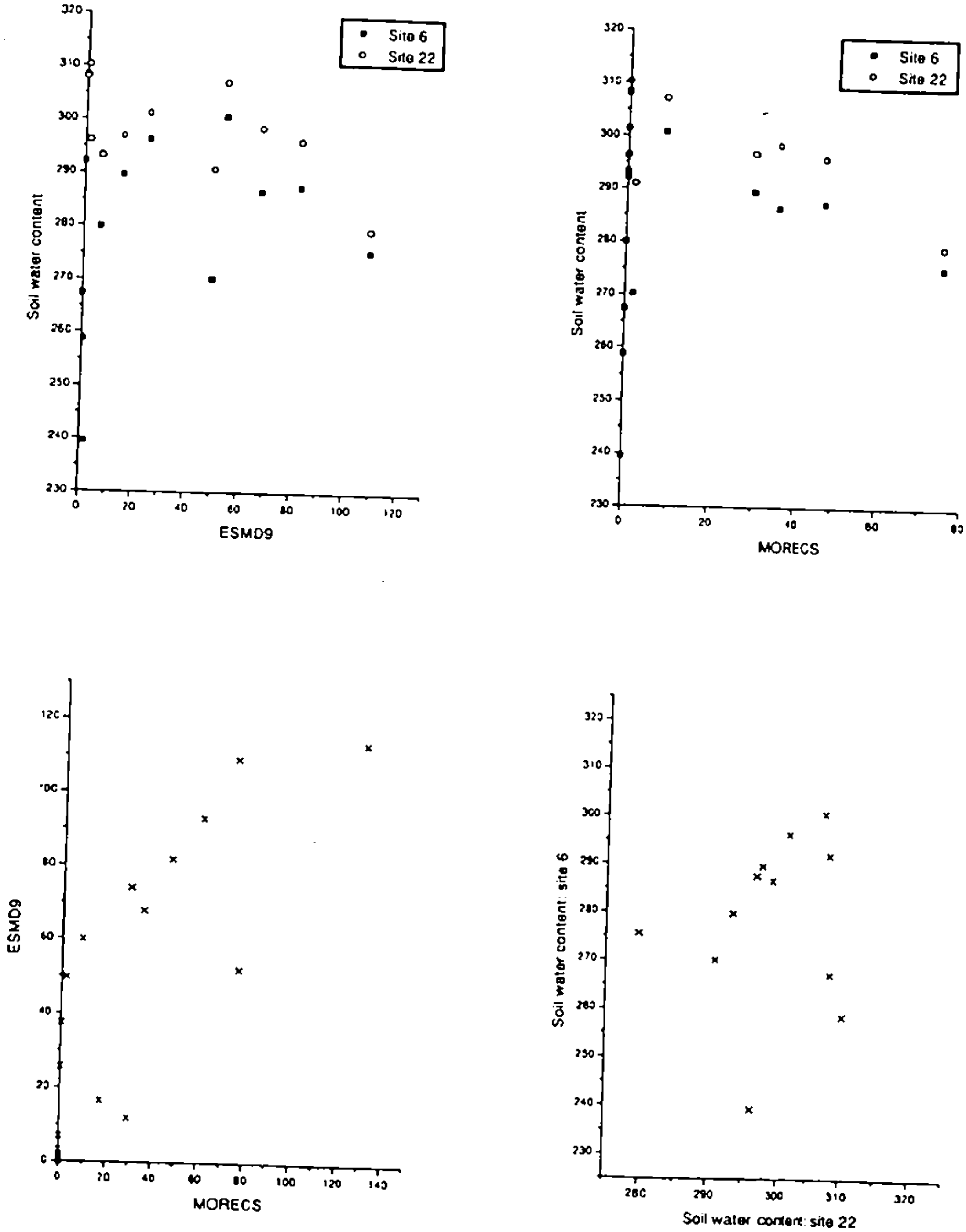


Figure 2.13 Comparison of the soil moisture indices for the Witham catchment

3. Modelling runoff volumes

3.1 FITTING FSR-TYPE MODELS TO THE CATCHMENT DATA

In the FSR, runoff volumes are examined in terms of percentage runoff, PR, the flow volume expressed as a percentage of the event rainfall. The differences in PR are explained in two ways; variations between catchments, and within catchments. The former are indexed within the FSR by the soil type and the degree of urbanization.

The within catchment variation is explained in the FSR model by the event rainfall depth (RAIN) and the catchment wetness index (CWI) defined as

$$CWI = 125 + API - SMD \quad (1)$$

where the constant 125 is intended to keep CWI positive as SMD is expected to be less than 125.

The percentage runoff model for undeveloped catchments is

$$PR = SPR + DPR_{RAIN} + DPR_{CWI} \quad (2)$$

in which the dynamic terms (DPR_{RAIN} and DPR_{CWI}) are defined by

$$\begin{aligned} DPR_{RAIN} &= 0 \; for \; RAIN \leq 40 \\ &= 0.45 \; (RAIN-40)^{0.7} \; for \; RAIN > 40 \end{aligned} \quad (3)$$

and

$$DPR_{CWI} = 0.25 \; (CWI-125) \quad (4)$$

The dynamic rainfall term has been derived partly through fitting to data from many catchments that contain a number of large events and also by considering the application of the equation to the estimation of PMFs (ie. trying to limit the percentage runoff so that they approach, but do not exceed 100%). It is not reasonable to try to fit this type of relationship to the event data available in this study; a more meaningful dynamic term to use for comparison is derived from the FSSR16 data set, and presented in Boorman (1985):

$$DPR_{RAIN} = 0.13 \; (RAIN-40.7) \quad (5)$$

Substituting equations 4 and 5 into equation 2 gives:

$$PR = SPR + 0.25 \; (SMD-125) + 0.25 \; API + 0.13 \; (RAIN-40.7) \quad (6)$$

or

$$PR = Constant + 0.25 \; SMD + 0.13 \; RAIN + 0.25 \; API \quad (7)$$

The first stage in the comparison of the usefulness of the various soil moisture measures was to fit models of this type (ie. linear multiple regression models) to the three catchments. The form of model chosen for this exercise corresponds to equation 7:

$$PR = a_0 + a_1 SMI + a_2 RAIN + a_3 API \qquad (8)$$

where SMI is one of the soil moisture indices and each a is a regression coefficient.

Great Eau at Claythorpe Mill

For catchment 29002 the results are shown in Table 3.1, with corresponding plots of the various soil moisture indices against percentage runoff shown in Figure 3.1. On this catchment soil water content data from site 25 (SWC #25)are not useful in estimating PR, but data from site 9 (SWC #9) are useful. Since site 9 is located more centrally within the catchment it is perhaps not surprising that site 9 provides more useful data; it is, however, disappointing that site 25, located near the catchment boundary produces data that are of no use in estimating PR. The best estimation equation, however, comes from using the ESMD data. With each of the three soil moisture indices, a rainfall term was included in the regression but, since the coefficient of the API term was not significantly different from zero, each regression was re-run excluding the API term.

The regression equation using the water content data from site 9 can be re-written as:

$$PR = 6.64 - 0.088\ (380 - SWC) + 0.148\ RAIN \qquad (9)$$

and this form the equation closely resembles the regressions using the SMD data. The value of 380 has been chosen as a round number approximately equal to the maximum water content recorded at this site.

Table 3.1 *Fitting FSR-type models on the Great Eau catchment.*

SMI	a_0	a_1	a_2	a_3	s.e.e.	r^2
ESMD9	7.62	-0.0731	0.0939	ns	1.78	0.748
MORECS	7.54	-0.0475	0.0945	ns	2.30	0.580
SWC #9	-26.8	+0.088	0.148	ns	2.26	0.593
SWC #25		ns				

Number of observations: 10 (ns=not significant)

Partney Lymn at Partney Mill

On catchment 30004 only 9 events are available with data from the best soil water site (number 24). Using these events only gives the regression results presented in Table 3.2 and the plots shown in Figure 3.2. The regression equations on this data set are all excellent, but caution is required. If the regressions are repeated for the extra events with ESMD and MORECS data then the results given in Table 3.3 are obtained and these tell a very different story. Figure 3.3 shows plots that correspond to the larger data set, and for ten events with data from soil water site number 25. These data and results show a very much poorer fit and suggest a very fortunate sampling of events in the smaller set.

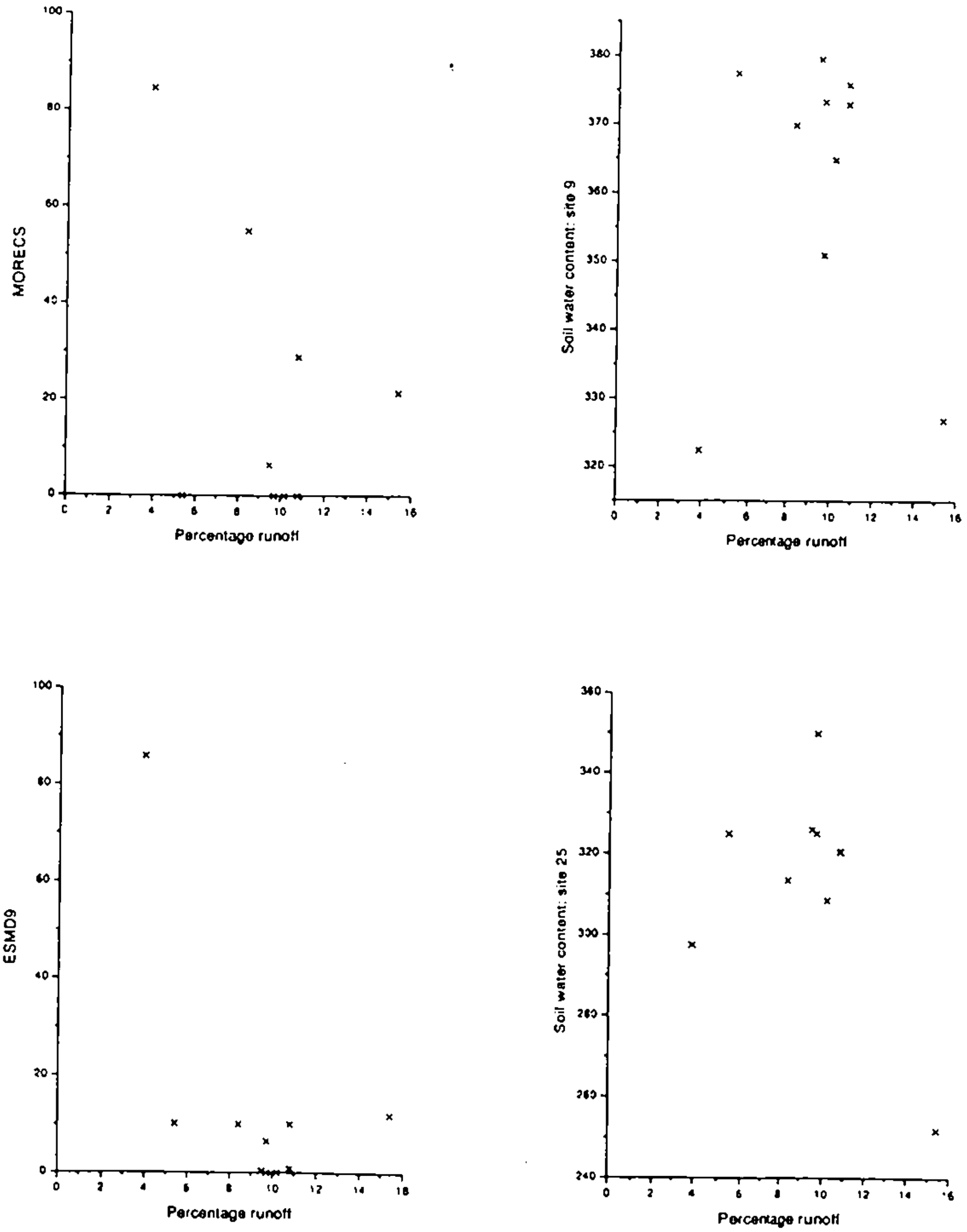


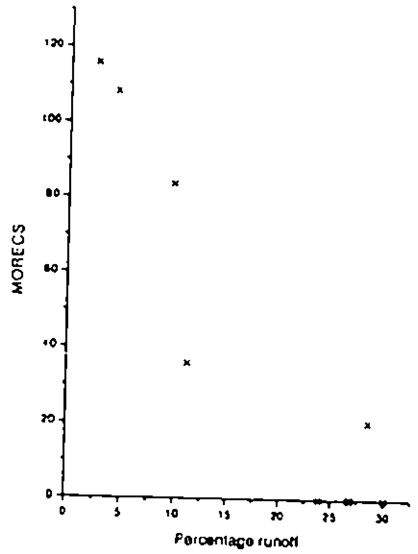
Figure 3.1 *Soil moisture indices plotted against PR for the Great Eau catchment.*

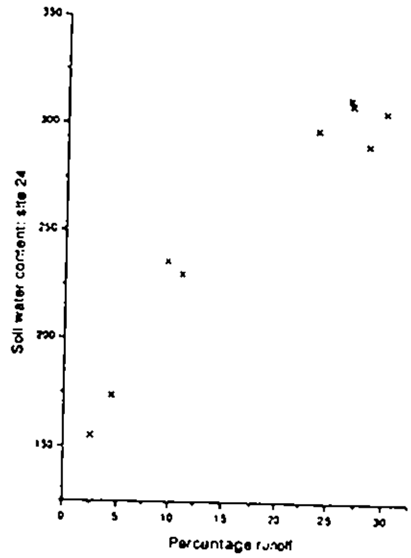
In none of these regressions is either the rainfall or the API term significantly differently from zero at the 5% level.

$$PR = 29.32 - 0.176\ (320 - SWC) \qquad (10)$$

Table 3.2 *Fitting FSR type models on the Partney Lymn catchment*

SMI	a_0	a_1	a_2	a_3	s.e.e.	r^2
ESMD9	27.5	-0.238	ns	ns	2.81	0.944
MORECS	26.8	-0.212	ns	ns	4.12	0.878
SWC #24	-27.0	+0.176	ns	ns	3.07	0.933
Number of observations: 9						





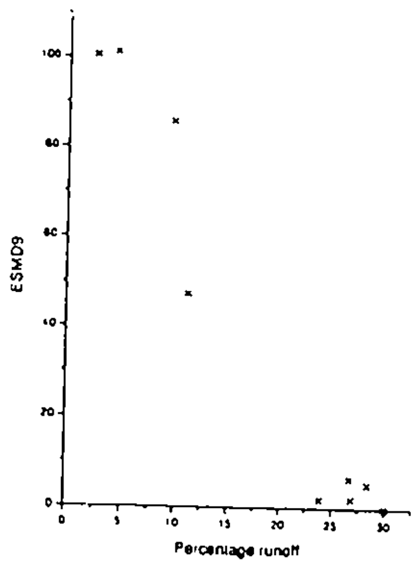


Figure 3.2 *Soil moisture indices plotted against PR for the Partney Lymn catchment (best data)*

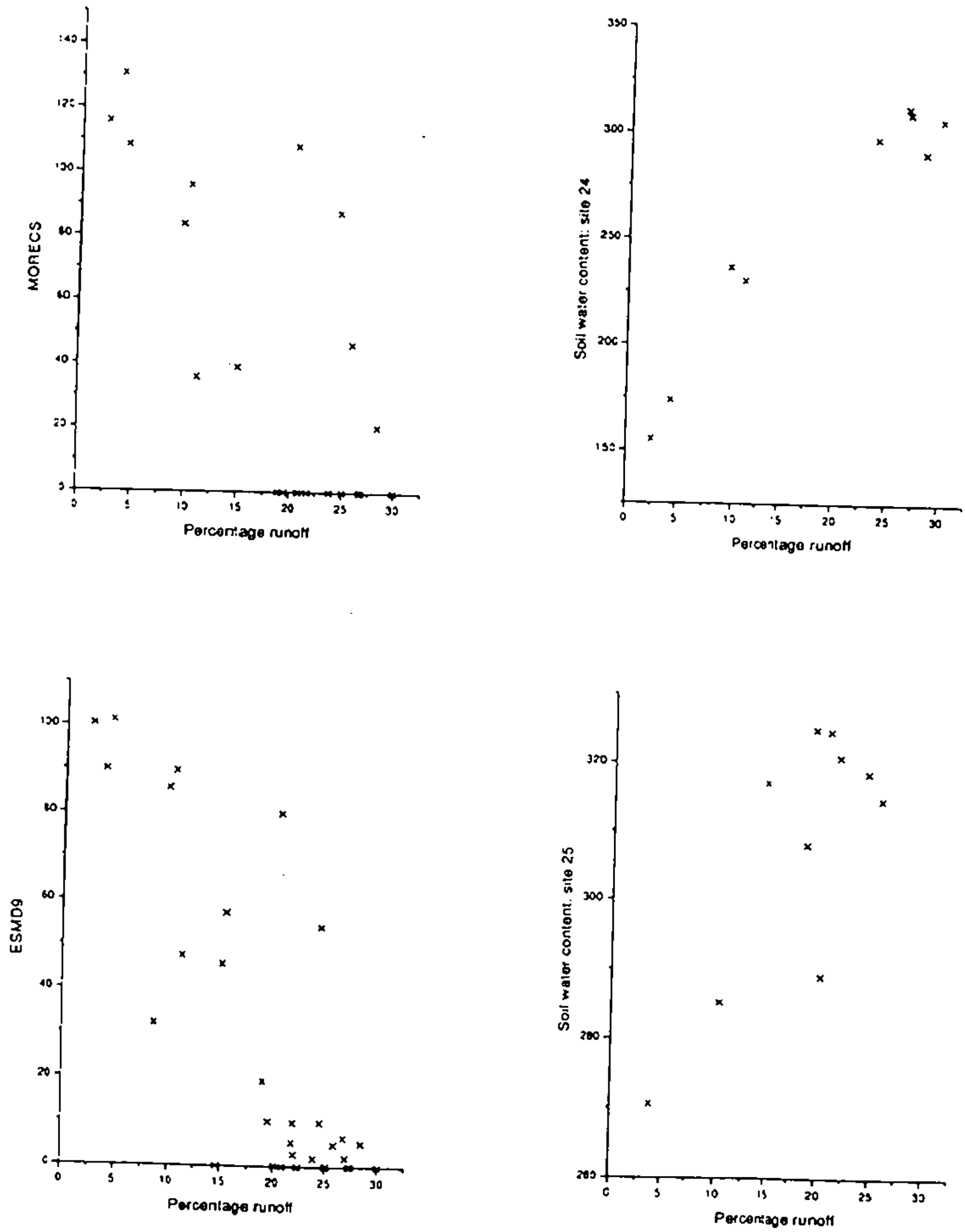


Figure 3.3 *Soil moisture indices plotted against PR for the Partney Lymn catchment (all data)*

Table 3.3 *Fitting FSR type models to all data on the Partney Lymn catchment*

SMI	a_0	a_1	a_2	a_3	s.e.e.	r^2
ESMD9	25.4	-0.195	ns	ns	3.90	0.809
MORECS	24.2	-0.131	ns	ns	6.01	0.545
Number of observations: 20						

Witham at Colsterworth

The regression results from the 12 events on catchment 30017 are shown in Table 3.4, with the corresponding plots presented in Figure 3.4. On this catchment the MORECS data provides the best equation, and ESMD the worst. The soil water content data from site 22 are useful in estimating PR but not so the data from site 6. The rearranged version of this equation is:

$$PR = 15.62 - 0.502\ (310 - SWC) + 0.427\ RAIN \qquad (11)$$

In no equation is the API term significant, and a rainfall term is only valid using the soil water content data.

Table 3.4 *Fitting FSR-type models on the Witham catchment*

SMI	a_0	a_1	a_2	a_3	s.e.e.	r^2
ESMD9	20.5	-0.066	ns	ns	4.16	0.283
MORECS	20.3	-0.128	ns	ns	3.62	0.460
SWC #22	-140.1	+0.502	0.427	ns	3.96	0.417
SWC #6		ns				
Number of observations: 12						

Summary

When the results are examined across the three catchments a number of points emerge. Most noticeable, perhaps, is that on no catchment are the API data useful in estimating PR. The ESMD and MORECS data give broadly comparable results, and always give rise to equations with the same terms (ie. they both have a rainfall term on catchment 29002 but not on the other two catchments). In most of the regression equations, the coefficient of the soil moisture term is slightly less that the 0.25 of the FSSR16 equation. In the one exception to this (using soil water content data on catchment 30017) the rainfall term is larger that than 0.13 derived from the FSSR16 data set, suggesting some compensation between these two terms. In the other cases where there is a rainfall coefficient is included in the regression equation (only catchment 29002), its value is close to 0.13.

In seeking to explain differences between the national regressions in the FSR and FSSR16 and those obtained from these catchments, it is necessary to remember that in those studies data from all catchments were considered together whereas in this study the catchments have been analysed individually. Within a large catchment data set, API is no doubt useful in indexing variations in catchment wetness on catchments that rarely have SMDs. On these Lincolnshire catchments there are large SMDs and, on the small data sets available, the value of an API term is not apparent. On catchment 29002 the constant term of the regressions, roughly equivalent to SPR, is less than the SPR value for WRAP type 1 soils (10% in FSSR16). Starting from this lower standard value, it is to be expected that the coefficient of the SMI term is smaller than in the FSR and FSSR16 equations. On the other two catchments, where the constant is larger the SMI coefficients are closer to those in FSSR16.

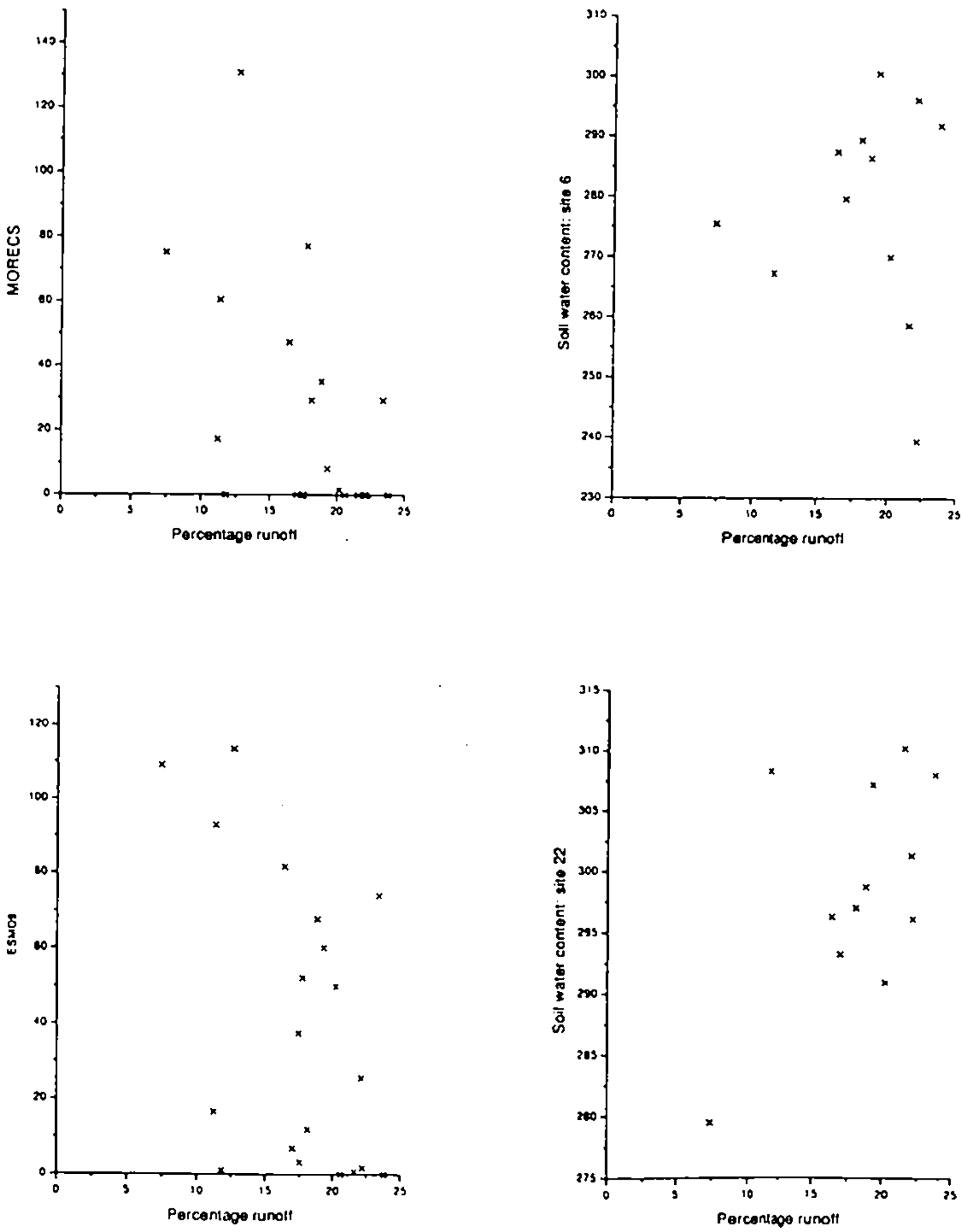


Figure 3.4 *Soil moisture indices plotted against PR for the Witham catchment*

No soil moisture index consistently gives a better or worse estimation of PR. The s.e.e. figures are comparable in magnitude between the different indices on each catchment and would suggest that any of these equations would give a good estimate of PR.

However, caution should be exercised in using any of these equations since they are derived from extremely small data sets that do not adequately represent the various combinations of catchment state and rainfall depth that the catchments will experience. The results from catchment 30004 for the 9 and 31 event data sets show how seemingly good results derived from a small data set appear less good when more events are examined.

3.2 FITTING OTHER TYPES OF MODEL

In Section 3.1 the estimation of runoff volumes has only used percentage runoff as this is the form of the model used in the FSR. Perhaps some other form of model, for example one in which the magnitude of a loss is related to SMD, would offer a better way of estimating runoff volumes. The fitting of this type of model is investigated in this section.

Before looking at any new forms of model, it is helpful to express the results obtained in Section 3.1 in terms of the volume of runoff. For catchment 29002, the estimated PR and flow volumes, using the ESMD equation presented in Table 3.1, are shown plotted against the observed values in Figure 3.5. It can be seen that the estimation of flow volumes is excellent; it is unlikely that a significantly better model exists.

On catchment 30004 the estimation of PR on the set of events with all SMIs was good, and therefore the flow volumes will also be well estimated. This is confirmed by the plots in Figure 3.6 for the best equation from Table 3.2, ie. the equation using ESMD.

Figure 3.7 shows the equivalent plots for catchment 30017 for the equation using MORECS data in Table 3.4. While the figure shows only poor estimation of PR, the volumes are reasonably well estimated.

The three diagrams show how well flow can be estimated via regressions that fit to PR data. It is possible to produce better estimates of the flow volumes by using this, and not PR, as the dependent variable. Thus the PR model:

$$PR = a_0 + a_1 SMI + a_2 RAIN \qquad (12)$$

which is used to estimate flow:

$$FLOW = RAIN\ (a_0 + a_1 SMI + a_2 RAIN) \qquad (13)$$

could be replaced by an equation such as

$$FLOW = b_0 + b_1 RAIN + b_2 SMI\ RAIN + b_3\ RAIN^2 \qquad (14)$$

obtained from direct regression against the flow data. The distribution of the estimated volume through an event can be obtained by applying a constant percentage runoff to each ordinate, as for the PR equation. Overall equation 12, which has been fitted to the flow data, will give more accurate estimates of flow volumes than equation 11, which has been fitted to the PR data.

If the term b_0 in equation 12 is negative, then it can be thought of as a loss rate, or initial loss component. Perhaps the magnitude of such a loss is related to the water content of the soil and an SMI term should have been added to equation 12. There are clearly a number of terms that could be added to equation 12, but it would be unreasonable to fit a model with a large number of parameters to data sets with only, roughly, 10 events. A complete investigation of all possible models of this type with up to two variables (three parameters since each equation also has a constant term) has been made, and the best with 2 and 3 parameters, for each of the three catchments are shown in Table 3.5. Note that in the case of the three parameter equations slightly better equations could be found, but these were not sensible equations in that they contained two different soil moisture measures.

Table 3.5 *Best regression equations for FLOW*

Catchment	r^2	s.e.e	Regression equation for FLOW	Events
29002	0.977	0.58	1.00 + 0.00168 $RAIN^2$	10
	0.993	0.35	1.17 + 0.00175 $RAIN^2$ - 0.00063 RAIN*ESMD9	
30004	0.782	1.28	6.86 - 0.050 ESMD9	9
	0.897	0.83	-9.12 + 0.0364 SWC#24 + 0.000613 SWC#24*RAIN	
30017	0.529	1.01	0.064 + 0.000596 SWC#22	12
	0.844	0.61	-0.37 + 0.230 RAIN - 0.00159 RAIN*MORECS	

It has already been noted, and shown in Figure 3.6, that estimation of flow volumes via PR was very good on catchment 29002; the equations in Table 3.5 are very slightly better. On the other two catchments the quality of the two variable equations presented in Table 3.5 is shown in Figure 3.8.

While the fit of these equations is good, confidence in using them would be low. Each is based on a small set of events that fails to sample adequately the possible combinations of event and catchment parameters that will occur on the catchment. In addition the terms in the equations vary between catchments giving no confidence in any particular model. The conclusion must be that, based on these data sets, it is not practical to develop a different form of equation to estimate runoff volumes.

It had been hoped at the outset of this study to also examine using these soil moisture data to develop models that represent variations in response during events. Since large variations between events are not better explained using the soil water content data, the possibility of examining within event variations has not been pursued.

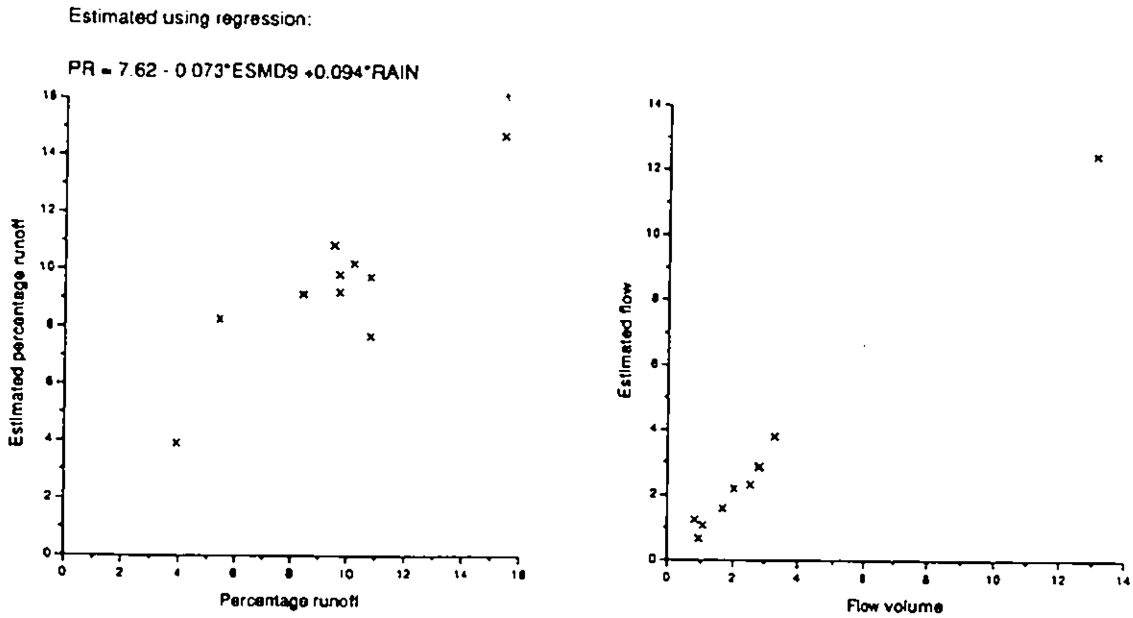


Figure 3.5 *Estimated PR and flow volume for the Great Eau catchment*

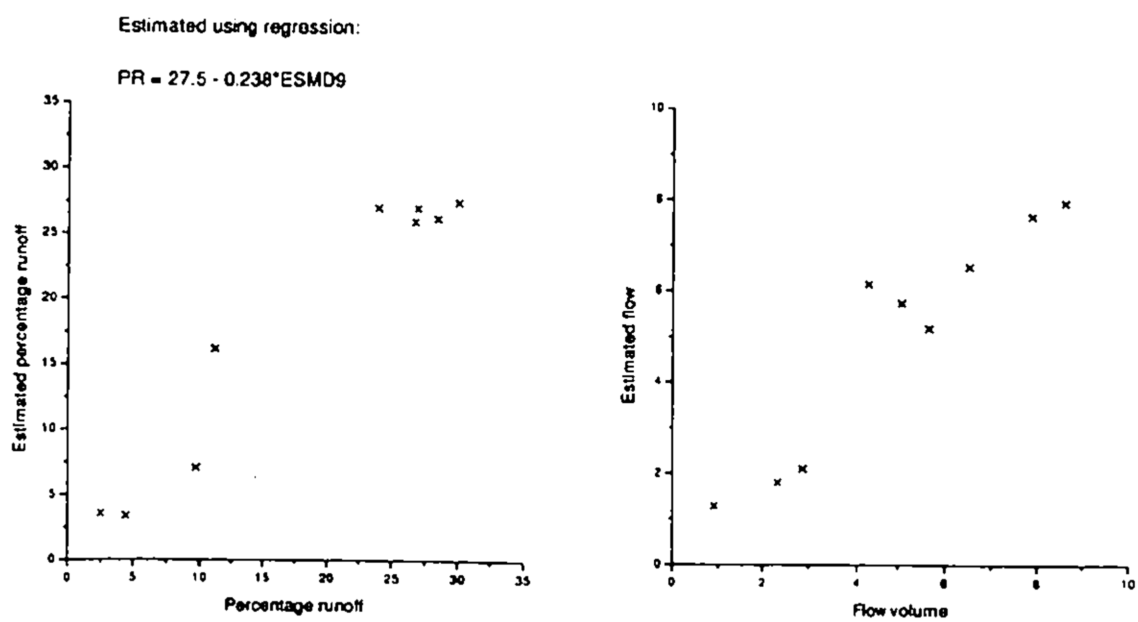


Figure 3.6 *Estimated PR and flow volume for the Partney Lymn catchment*

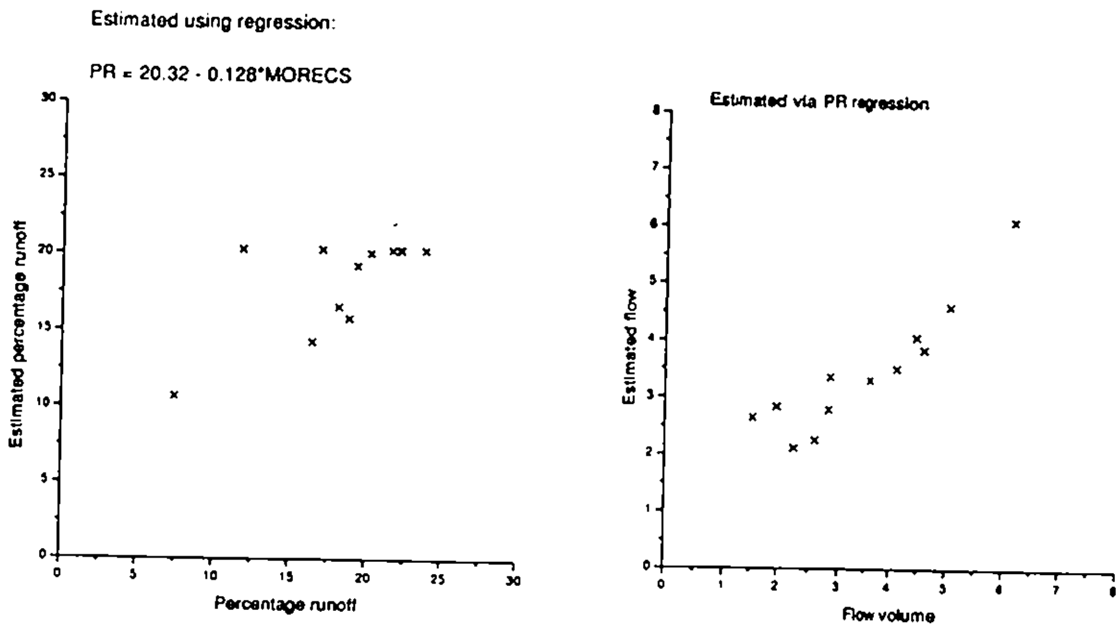


Figure 3.7 *Estimated PR and flow volume for the Witham catchment*

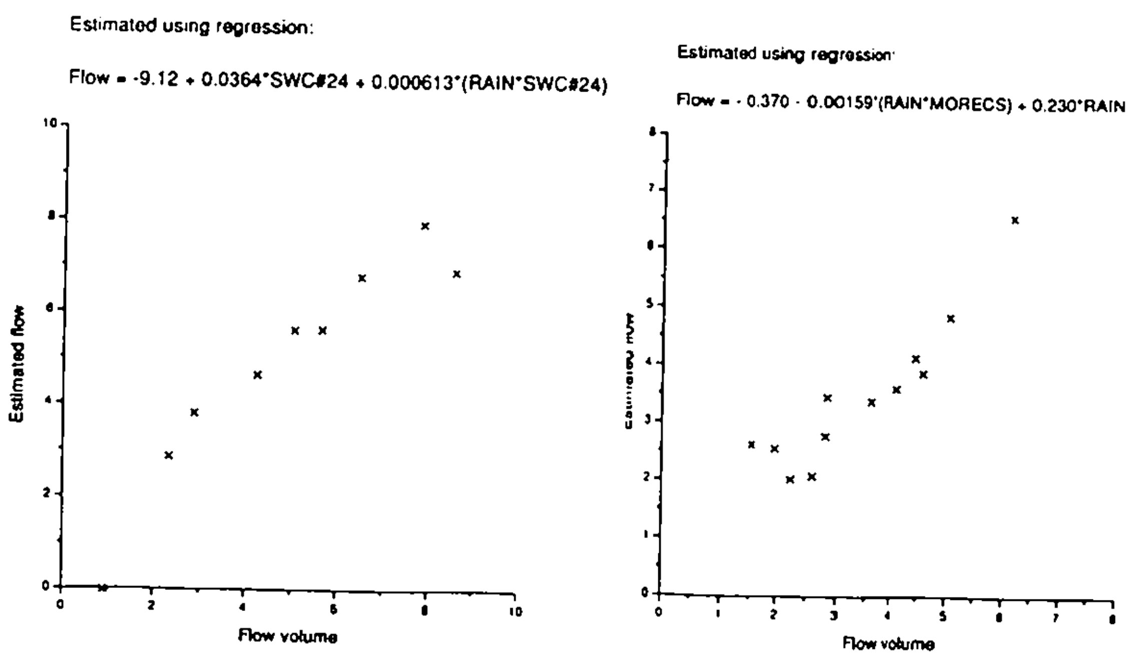


Figure 3.8 *Regression equations fitted to flow for the Partney Lymn (left) and Witham (right)*

4. Conclusions

The objective of the study was to examine the usefulness of the recorded soil water data collected by Lincoln NRA for flood modelling. Three Lincolnshire catchments were selected as being able to provide event data and being close to sites at which soil water measurements were made. When data from the catchments and the soil water sites were collated it was found that very few events (9, 10 and 12) with soil water data were available.

These events were used to derive regression equations to estimate percentage runoff of a similar form to equations previously developed in the FSR and FSSR16, which are in widespread use in the UK. Equations were developed based on the measured soil water content, the ESMD from the Met. Office Penman-based calculation and SMD from MORECS. The resulting equations would lead to better estimates of runoff volumes for events similar to those available for study. Since the form of the equations and the values of the coefficients are similar to those in the national equations, some confidence in limited extrapolation to more extreme events would be justified. However, no one index of soil moisture was found to be the best in estimating PR.

Other types of model were also examined in which the volume of response flow was estimated directly. While very good estimation equations were derived, because of the unusual form of these equations little confidence would be attached to the use of them for types of event not represented in the data sets.

Overall, based on the analysis of very limited data, it is not possible to say that the recorded soil moisture data are of greater usefulness for flood modelling than other measures of soil moisture, such as the SMD values contained in MORECS.

This is a surprising and disappointing conclusion since, intuitively, soil moisture data recorded on or close to the catchment would be more useful that data that comes from a soil water model using sparse or remote climatological data. It remains an interesting question as to why this is so, but not one that can be resolved using such small data sets.

Recent technical developments now enable soil moisture changes to be continuously monitored and logged in the field. This offers a means of obtaining considerably more accurate estimates of initial soil contiditions at the start of storm events, and, therefore, the potential to develop improved estimates of runoff volumes. Work at IH in this area is supported by both the Ministry of Agriculture, Fisheries and Food, and the National Rivers Authority. A report to MAFF is in preparation by Robinson.

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