Institute of Hydrology

Natural Environment Research Council

Natural Environment Research Council

Groundwater Storage in Chalk Aquifers
- estimation from hydrographs -

A.J. Wesselink and A. Gustard

/92

This report is an official document prepared under subcontract between the British Geological Survey and the Institute of Hydrology. It should not be quoted without permission of both the Institute of Hydrology and the British Geological Survey.

Report to
British Geological Survey
Hydrogeology Group
Wallingford

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxon
OX10 8BB

May 1992

Executive summary

In this study the volume of groundwater storage in two catchments on the Chalk aquifer is estimated using daily discharge data and two statistical analyses: the Base Flow Index separation method and the recession ratio. The results were aimed at the verification, in a separate study, of calculations of volumes of groundwater lost from storage using hydrogeological methods. The catchments are the Kennet (NRA Thames region) and the Itchen (NRA Southern region) and the periods of analysis were in 1975, 1976, 1988 and 1989. After assessment of the quality of the flow measurements and the degree of artificial influences on the river flows, three gauged subcatchments were retained for analysis, in addition to the main catchments.

Catchment decline of the hydrograph were selected and base flow separation was performed on the daily flow data, to estimate the reduction in storage of the chalk aquifer. The available base flow volume at the end of the 'no recharge' period was assessed by integration to infinity of the estimated base flow recession curve. The total base flow volume is the sum of the separated base flow volume and the volume under the base flow recession curve.

The values of the total base flow volume for the 8 catchments were compared by converting them to a depth of water by dividing by the estimated groundwater catchment area. It was concluded that:

1. The average volume of separated base flow in the Itchen was higher than in the Kennet, as a result of the higher annual rainfall in the Itchen.

2. The average volume of separated base flow was lowest in 1976. This was a result of the low rainfall, and therefore low recharge and low base flow, in the winter of 1975-1976.

3. The volume of recession curve base flow is generally estimated to be a third to half of the separated base flow volume.

4. The relative contribution of the recession curve base flow volume is smaller in the main catchments compared to the upstream subcatchments.

5. There is a wide range of calculated total base flow volume between the sub catchments although there is a consistent variation from year to year.

Contents

List of tables

List of Figures

Page

1 Introduction

The objective of this study was to estimate the volume of groundwater storage in Chalk aquifers. The following methods were used:

1 direct calculation of the change in volume of stored water in the aquifer, using hydrogeological data for the catchment, e.g. porosity and change in groundwater levels. These calculations are described in NRA R&D report 128/5/A: Groundwater storage in British Aquifers: Chalk.

2 calculation of volume of base flow during a period of no recharge to the groundwater reservoir, using daily discharge data and two statistical analyses: the Base Flow Index separation method (Institute of Hydrology, 1980) and the recession ratio (Gustard et al., 1989)

In a pre-study fifteen catchments in Lincolnshire and East Anglia covering the range of geographical and hydrogeological conditions were selected for investigation. They were chosen using the following criteria:

- Catchment wholly underlain by Chalk
- Catchment either drift-free or entirely drift-covered with exception of stream channels)
- Artificial influences on low flows minimal

It was originally decided to study the long streamflow recession between 1 May 1975 and 31 August 1976, assuming that recharge to the aquifer during the winter of 1975/76 was minimal. However both the well hydrographs and the baseflow separations indicated that some recharge did occur during this period, in most of the selected catchments. Therefore two shorter periods corresponding to the summer recessions were studied instead.

Five of the fifteen catchments then had to be discarded due to artificial influences on riverflow (34010, 36008, 36011, 36012) and in one case no data being available for the relevant period (33067). Preliminary streamflow analysis was carried out on the remaining catchments. However more detailed study of the catchments meant that five more were considered unsuitable because 'drift-free' catchments were overlain in part by boulder clay (19002, 29003), groundwater abstractions were significant in relation to streamflow (33029, 38003) or there were artificial influences on riverflow (33049). The remaining five 'drift-covered' catchments were all suitable for streamflow analysis, however none had sufficient water level information such that accurate groundwater contours could be constructed. No further work was therefore carried out on these catchments.

The two series of catchments finally selected for detailed analysis (the Itchen and the Kennet) are both in the southern half of the country and virtually drift-free. They have both been investigated over a period of nearly 20 years, for schemes to abstract groundwater for river augmentation, and therefore contain a large number of observation boreholes with water level information. These river augmentation schemes were tested or operated in most years. The periods studied were therefore generally shortened by this pumping, and stopped at its commencement. This minimised artificial influences on the streamflows.

In this chapter, the methods and results of the hydrological, i.e. second, approach are described. First, the selection of catchments that are suitable for analysis is discussed. Following a summary of the data selection, the results of the calculations of volume of water in store are presented. The periods of analysis used were the summers of 1975, 1976, 1988 and 1989.

2 Data selection

2.1 INITIAL CRITERIA

The river Itchen, in NRA Southern region, and the river Kennet, in NRA Thames region, were selected for the analysis because of the good spatial and temporal coverage of hydrological and hydrogeological data. The flow in these rivers is gauged at 5 and 11 sites respectively, including the gauging stations on subcatchments (Figure 1).

Gauging stations were selected for analysis if they met the following criteria:

1 daily flow data available for 1975, 1976, 1988 and 1989

2 minimal artificial influences on low flows

Information on criterion 2 has been obtained from the 1992 Low Flow Study station assessment record (Gustard et al., 1992) where the quality of the flow record has been indicated with two codes, one for the flow measurement errors and one for the amount of artificial influences in the gauged catchment. The information necessary to make these assessments was obtained from the relevant NRA region, and the final code was verified with them. For the present study, initially only those catchments were retained for which both grades were either A or B (see Table 1 for a definition of these grades). The region of study is underlain by Chalk aquifer, and so no catchment is entirely free from groundwater abstraction. However, the choice of grade A or B stations implies a limited influence of groundwater pumping on the flows.

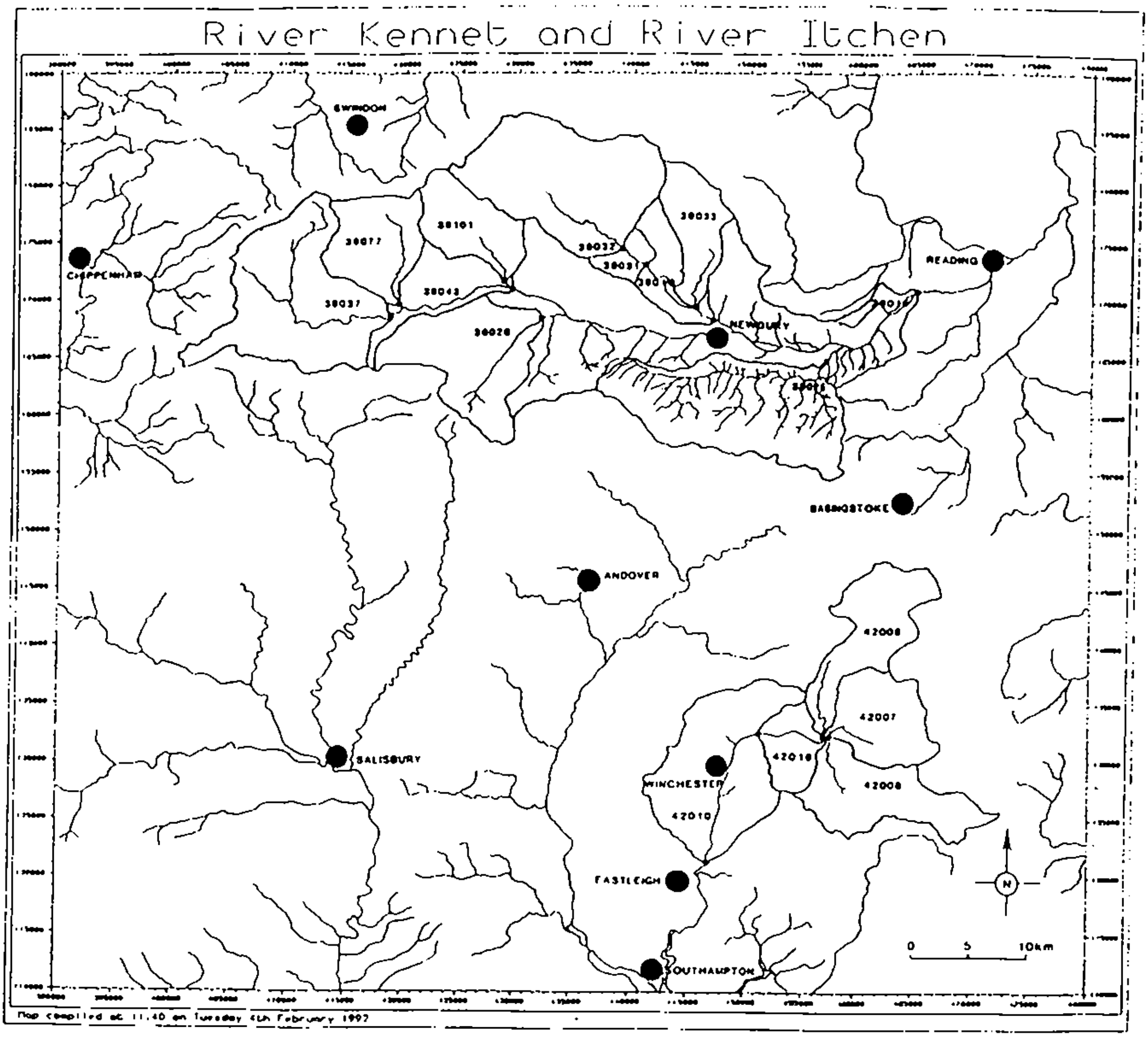


Figure 1 Gauged catchments in the River Kennet and River Itchen catchments scale approx. 1:1000,000

2.2 ANALYSIS OF ANNUAL HYDROGRAPHS

In addition to the initial selection described above, the station selection was verified by examination of hydrographs for the selected years (see Appendix A), which resulted in accepting one station (42008) where artificial influences are classified as C but some years were acceptable for analysis. It is important to note that the artificial influences grade only reports the degree of influence on the low flow statistic Q95 (the flow which is exceeded 95 percent of the time), whereas in the present analysis a wider flow range is of interest.

Table 2 lists all gauging stations in the Itchen and Kennet catchments and the reason for rejection, if applicable. Some more detailed comments on the hydrographs are presented in Appendix A. Information on the nature and extent of artificial influences was obtained from the 1981-1985 Hydrometric Register (Institute of Hydrology/British Geological Survey, 1988) and station files kept at the Institute of Hydrology, as well as from the relevant NRA regions.

Because of data processing limitations for the hydrogeological part of this study, it was necessary to select one period of analysis for a catchment and for a year, for example for all Kennet catchments the same period of analysis had to be used for 1989. This of course limited the possibility of analysis of over-year recessions.

Table 3a lists hydrological properties of the catchments that were retained for analysis. They were calculated for all catchments for the period 1970-1990 to make direct comparison of the figures possible. The flow statistics BFI (Base Flow Index) and Q95 are in a narrow band for all catchments, indicating that the catchment characteristics are very similar. The following figures of mean flow expressed as a depth over the catchment are presented for comparison only and are calculated using the surface water catchment. In practice some of these topographic catchment areas are very different from the groundwater catchment areas. In the Kennet catchment the mean flow expressed in mm/year is very similar at 230-290 mm/year. The higher mean flow from the whole Kennet catchment compared to the subcatchments may be attributed to groundwater flow from the upstream catchment, which is (partly) discharged into the stream below the upstream catchment and above the downstream gauging station. The results of the mean flow calculations using groundwater catchment areas are wider apart than using surface water catchment areas, the most notable outlier being the Dun (Table 3b).

In the Itchen catchment the rainfall is similar in the subcatchments, with all catchment average figures between 820 and 883 mm/year. Using the topographic catchment area, the runoff in mm/year gives a wide range of figures: the Alre catchment (42007) 869 mm/year, the downstream Itchen catchment (42010) 451 mm/year and the Candover (42009) and Cheriton Stream (42008) approximately 250 mm/year. However, using the average groundwater catchment areas (Table 3b) the mean flow figures are more similar, ranging from 384 mm/year in the Alre to 252 in the Candover.

The flows in the Alre and the Candover (42007 resp. 42009) are occasionally influenced by groundwater augmentation. In both the Kennet and the Itchen catchments, the effects of the artificial influences in the upstream catchments (groundwater augmentation, water management in cress beds) are relatively small at the gauging stations further downstream. Details of the effect of the operation of the groundwater augmentation schemes are described in Appendix A.

3 Calculations of base flow volume

3.1 INTRODUCTION

Runoff from a catchment is often considered as being composed of a rapid response component and a slow flow or base flow component which is derived from groundwater sources. Separating the base flow from the total hydrograph therefore enables an approximation of the groundwater hydrograph to be derived. Many different methods of separation exist (e.g. Ineson & Downing, 1964) ranging from purely statistical to those based on water-chemistry. In this analysis a numerical base flow separation algorithm has been used (Gustard et al., 1989). The advantages of this method are:

1. automated and quick derivation from observed daily flows
2. the result is not influenced by the user, resulting in a unique solution for a given hydrograph

In a period of no recharge to groundwater, the volume of base flow over the period (V_B in Figure 2) gives the volume of change in storage of the groundwater reservoir. If at the end of the period the storage, and therefore the base flow, are negligible, the calculated volume represents the total base flow volume present at the beginning of the period. In practice, zero storage hardly ever occurs, and the available base flow volume at the end of the period has to be estimated (V_R in Figure 2). This has been done by integration of the estimated base flow recession curve, starting at the end of the period over which the base flow separation was performed.

In order to reduce the errors in estimation of the base flow it is desirable to perform these calculation over as long a period as possible, and to use periods when the discharge at the end of the period is low. The periods that were chosen were the summers of 1975, 1976, 1988 and 1989. It was not possible to select periods including a winter season, because the separated base flows indicated that recharge occurred in most catchments.

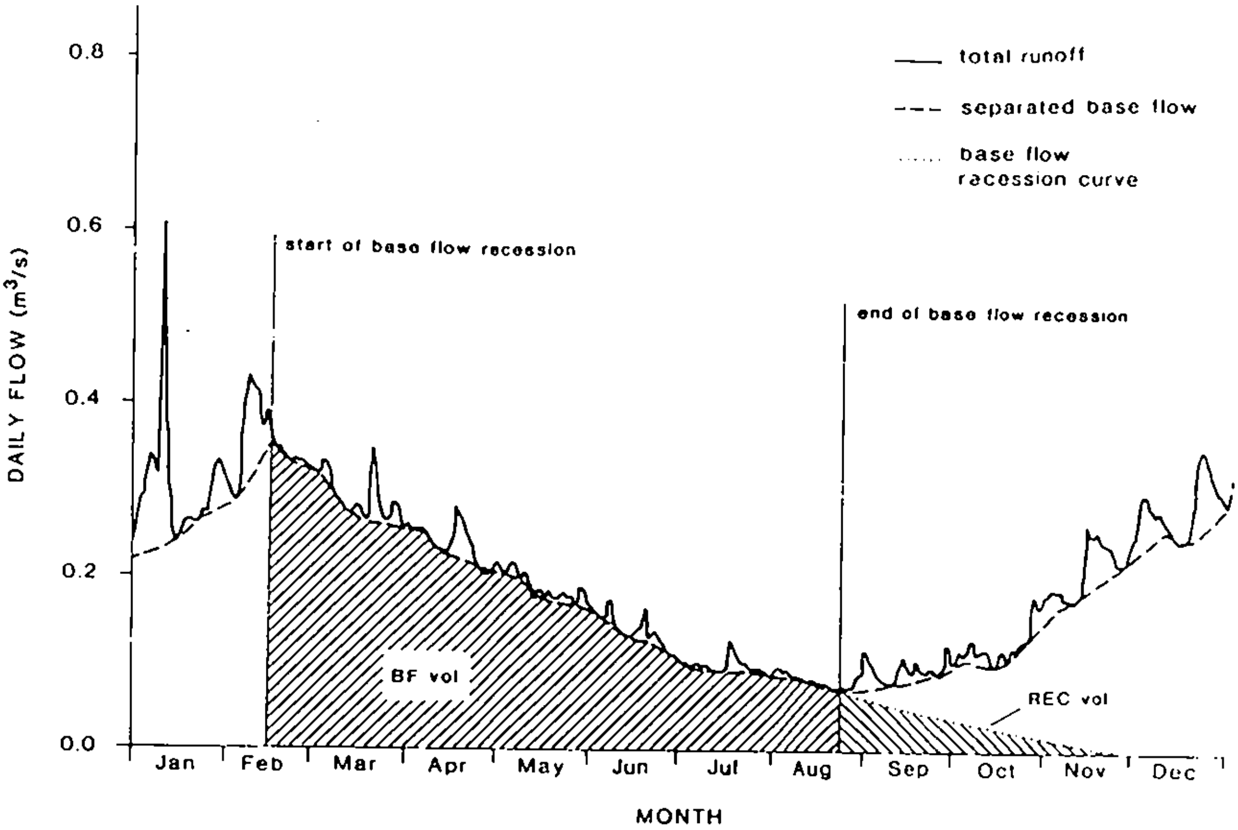


Figure 2 Hydrograph with separated base flow and calculated base flow recession curve

3.2 CALCULATION OF BASE FLOW VOLUME BY HYDROGRAPH SEPARATION

The start and end dates of the periods of analysis (Tables 5a to 5d) have been chosen by inspection of the hydrograph and the separated base flow line for the selected catchments and are defined by the periods without apparent significant recharge. For every year one common period has been chosen for each river basin. However, in some catchments a year had to be rejected due to artificial influences on the hydrograph.

Base flow was separated (Figure 2) from gauged daily flow by a standard Institute of Hydrology algorithm (see Section 3.1). The algorithm follows a stepwise approach:

1. divide the daily flow data into five day non-overlapping blocks and calculate the minimum for each of these blocks

2. determine turning points of the five-day minimum values

3. connect the turning points to give the separated base flow line

Table 5a to 5d give the results of the calculations of base flow runoff volume for all catchments (columns 3 and 4). The value which is most easily comparable is the base flow volume expressed as a depth over the catchment area (in mm), calculated using the average value of the estimated groundwater catchment area for the appropriate season (see Table 4).

3.3 CALCULATION OF BASE FLOW VOLUME BY RECESSION ANALYSIS

The base flow recession curve is given by (Ineson & Downing, 1964):

$$Q(t) = Q_T * K^t \qquad (3)$$

where Q_T is the flow at the start of the recession and K the recession constant. Alternatively this can be expressed as:

$$K^t = Q(t)/Q_T \qquad (4)$$

The recession constant K in Equation (4) has been calculated using a standard Institute of Hydrology algorithm (Gustard et al., 1989). According to this algorithm, all 2-day recession pairs with a starting point less than the mean flow are extracted from the flow record, and their individual 2-day K value (or ratio of the flows) is calculated with Equation (4). The 1-day K is the square root of the 2-day K. The algorithm then proceeds to calculate the distribution of the K values. The 90-percentile K was selected as the catchment recession 'constant' to calculate the base flow volume under the recession curve using the following formula:

$$\text{REC vol} = \int_0^{\infty} Q_T * K^t \, dt = -(Q_T/\ln K) * 86400 \qquad (in\ m^3) \qquad (5)$$

where the constant converts from seconds to days. The solution of the integral assumes that the groundwater reservoir decays exponentially. Tables 5a to 5d present the results of these calculations (columns 5 to 8). The base flow volume under the recession curve in mm was calculated using the estimated groundwater catchment area for the appropriate season (see Table 4).

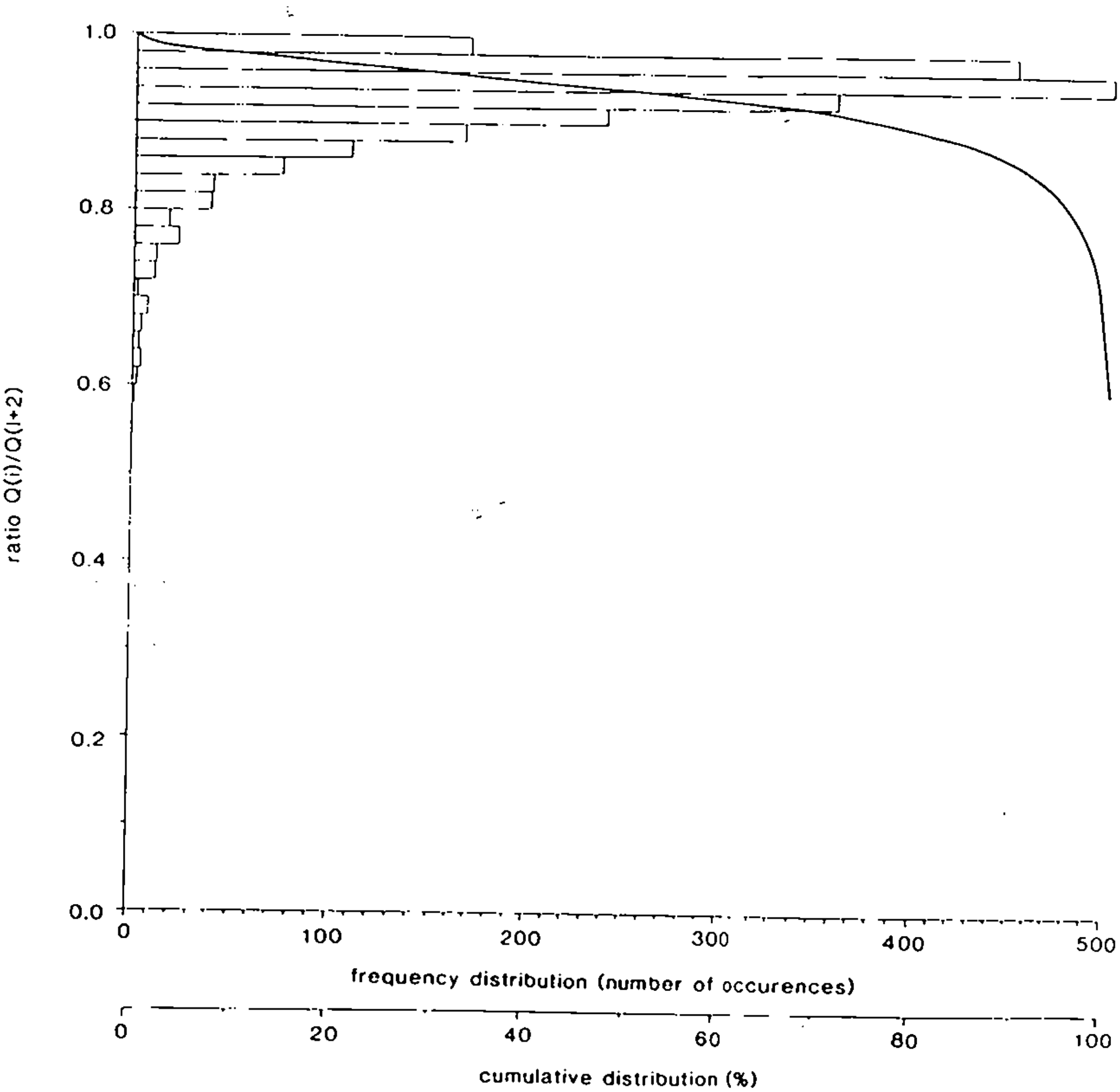


Figure 3 Example frequency distribution and cumulative frequency of 2-day recession pairs

3.4 CALCULATION OF TOTAL BASE FLOW VOLUME

The estimated total base flow volume at the start of the analysed period is the sum of the results of the calculations presented in Sections 3.2 and 3.3. The results are presented in Tables 5a to 5d (columns 9 and 10). The formula used is:

TOTAL = BF vol + REC vol (in m^3 or mm)

A second approach to comparing the results from hydrogeological and hydrological calculations has been to calculate the depletion of the groundwater reservoir over a specified period, not taking into account the base flow volume water that may have remained at the end of the 'no recharge' period. In this case, the base flow volume under the recession curve has not been considered, and the calculations are confined to those described in Section 3.2.

4 Discussion of results

4.1 THE VOLUME OF SEPARATED BASE FLOW

Intercomparison of values of the volumes of water that were calculated for the 8 catchments is only possible if the volumes are converted to a depth of water, for example expressed in mm. A summary of all figures is given in Table 6. Apart from the differences in catchment area, the length of the period analysed has to be taken into account when comparing the volume of separated base flow (BF vol). The following observations can be made:

1. In all years except 1989 the average volume of separated base flow in the Itchen (42010) was higher than in the Kennet (39016). This may be explained by higher annual rainfall in the Itchen (Table 3a). The exception in 1989 is a result of a much shorter period of analysis in the Itchen; a similar length of period would have given more base flow in the Itchen than in the Kennet.

2. In the Itchen and the Kennet the average volume of separated base flow was lowest in 1976. This was a result of the low rainfall, and therefore low recharge and low runoff, in the winter of 1975-1976.

3. In general the pattern of variation in the separated base flow in the subcatchments within the main catchments is consistent from year to year. However, there is a wide spread of figures amongst the subcatchments within the main Itchen catchment (42007, 42008 and 42009). Three reasons may be identified: 1. variation in recharge, 2. variations in the hydraulic relation between the aquifer and the stream, 3. the groundwater catchments do represent the actual contributing catchment.

It may be assumed that the results for the main catchments are more accurate than for the small subcatchments because of the smaller relative errors in flow and groundwater catchment area calculations.

In the Kennet the calculated volume of separated base flow (in mm) is consistently higher in the subcatchments Lambourn (39019) and Dun (39028), compared with the Kennet as a whole (39016). The differences in catchment average rainfall do not explain this. It is possible that the groundwater catchments in the two subcatchments have been underestimated. Alternatively, there may be more water draining into the stream in the analysis period in the upstream catchments because of higher recharge rates and a greater hydraulic gradient in the groundwater table. The calculated volume in the upstream Kennet (39043) is very close to the volume calculated for the whole Kennet (39016), apart from 1976. A possible explanation for the different behaviour in this very dry year is that a severe lowering of the groundwater table caused the effective contributing groundwater catchment to be reduced significantly.

In the Itchen the calculated volume in the Alre (42007) is much higher than from the total catchment (42010), and that in the Candover (42008) is much lower. A possible explanation for this would be a groundwater divide which makes the Candover catchment too big at the expense of the Alre. The calculated volume in the Cheriton Stream (42009) agrees with the figure for the whole Itchen.

4.2 THE VOLUME OF RECESSION CURVE BASE FLOW

The base flow volumes under the recession curve (REC vol) were converted to a depth of water, expressed in mm. A summary of all calculations is given in Table 6. The following observations can be made:

1. In all years the average volume of recession curve base flow was higher in the Itchen (42010) than in the Kennet (39016). This may be explained by higher annual rainfall and hence recharge in the Itchen (Table 3a). The volume of recession curve base flow in 1976 was similar in both catchments, and very low.

2. In general the pattern of variation in the volume of recession curve base flow in the subcatchments within the main catchments is consistent from year to year. However, there is a wide spread of figures amongst the subcatchments within both main catchments. In addition to the three reasons for this variation identified above (Section 4.1), the calculated volume REC vol is very sensitive to the estimated K. For example, an addition of 0.001 to the K value of the Kennet at Knighton (0.9904) would change the calculated volume in 1975 from 37 to 41 mm.

The latter problem is illustrated by the consistently high figures in the Alre catchment. In all seasons the volume of recession curve base flow is estimated to be equal to the volume of separated base flow, and higher than or equal to the total base flow volume in the other catchments. In the other catchments the volume of recession curve base flow is generally estimated to be a third to half of the separated base flow volume. However, the high K value for the Alre, the highest of all K values, is supported by the highest Q95 and the highest Base Flow Index.

4.3 THE TOTAL BASE FLOW VOLUME

The total base flow volume over the analysed periods is the sum of the volumes discussed above (Sections 4.1 and 4.2). The same pattern of variation between the years and between the catchments can be observed in the total base flow volumes, and the same comments therefore apply to these figures.

The proportion of this total base flow volume contributed by the volume of recession curve base flow (Table 6) depends, amongst other things, on the catchment's recession constant K: the proportion of water that is estimated to remain in store is consistently higher in the Itchen catchments. Excluding the extremely dry year 1976, which shows different behaviour to the other years, in the Itchen the fraction of the total volume which is taken by the recession curve base flow varies from 0.54 to 0.31 with an average of 0.44, while in the Kennet it varies from 0.41 to 0.21 with an average of 0.32. In general, the relative contribution of the recession curve base flow volume is smaller in the main catchments (39016 and 42010) compared to the upstream subcatchments.

The total volumes will have to be compared with the volumes of drainable water calculated using hydrogeological data.

References

Gustard, A., Roald, L.A., Demuth, S., Lumadjeng, H.S. and Gross, R. (1989) Flow Regimes form Experimental and Network Data (FREND) Volume I Hydrological Studies, Institute of Hydrology

Gustard, A., Bullock, A. and Dixon, J.M. (1992) Low Flow Estimation in the United Kingdom. Institute of Hydrology Report 108. (In press)

Ineson, J. & Downing, R.A. (1964) The ground-water component of river discharge and its relationship to hydrology. In: J.Inst.Water Engineers, vol.18 no.7, November 1964

Institute of Hydrology (1980) Low Flow Studies Report

Institute of Hydrology/British Geological Survey (1988) Hydrometric Register and Statistics 1981-5

Southern Water Authority (1979) Itchen groundwater regulation scheme. Final report on the Candover pilot scheme.

Southern Science (1991) Report on the 1989 test pumping of the Alre scheme. Report number 91/R/160

Table 1 Classification scheme for low flow suitability

CLASSIFICATION OF HYDROMETRIC QUALITY

GRADE A

Accurate low flow measurement over a sensitive control (S.I. less than 20%) with the scatter of spot gaugings about the rating curve at the Q95 discharge having a factorial standard error of estimate of less than 1.1, and no obvious deterioration of the gauging station due to siltation, weed growth or vandalism.

GRADE B

Less accurate low flow measurement with either a less sensitive control (S.I. between 20% and 50%) or a factorial standard error of estimate of between 1.1 and 1.2, and/or observed periodic deterioration of the gauging station due to siltation, weed growth or vandalism.

GRADE C

Station with low accuracy of low flow measurement due to either an insensitive control (S.I. in excess of 50%), and/or with the scatter of gaugings about the rating curve at the Q95 discharge having a factorial standard error of estimate in excess of 1.2, and/or observation of sustained deterioration of the gauging station due to siltation, weed growth or vandalism.

CLASSIFICATION OF DEGREE OF ARTIFICIAL INFLUENCE

GRADE A

The gauged Q95/mean flow ratio differs by less than 20% from the estimated natural Q95/mean flow ratio.

GRADE B

The gauged Q95/mean flow ratio differs by more than 20% but less than 50% from the estimated Q95/mean flow ratio.

GRADE C

The gauged Q95/mean flow ratio differs by more than 50% from the estimated Q95/mean flow ratio.

Table 2 Gauging stations in the study area

Station	Selected/reason for rejection
RIVER KENNET	
39016 Kennet at Theale	selected
39019 Lambourn at Shaw	selected
39025 Enbourne at Brimpton	rejected: clay catchment
39028 Dun at Hungerford	selected
39031 Lambourn at Welford	rejected: incomplete record (1962-1983)
39032 Lambourn at East Shefford	rejected: incomplete record (1966-1983)
39033 Winterbourne at Bagnor	rejected: catchment area too small
39037 Kennet at Marlborough	rejected: grading BC
39043 Kennet at Knighton	selected
39077 Og at Marlborough	rejected: incomplete record (1980-)
39101 Aldbourne at Ramsbury	rejected: incomplete record (1982-)
RIVER ITCHEN	
42007 Alre at Drove Lane, Alresford	selected
42008 Cheriton St at Sewards Bridge	selected
42009 Candover St at Borough Bridge	selected
42010 Itchen at Highbridge+Allbrook	selected
42016 Itchen at Easton	rejected: incomplete record (1975-1983)

Table 3a Statistics of the selected catchments, calculated for the period 1970-1990 using surface water catchment areas

Station Location	Catchment area (km^2)	Grade	Record length	MF ($m^3 s^{-1}$)	MF ($mm y^{-1}$)	Rainfall ($mm y^{-1}$)	BFI (-)	Q95 (% MF)
RIVER KENNET								
39016 Kennet at Theale	1033.4	AA	1961-	9.516	291	761	0.875	39.7
39019 Lambourn at Shaw	234.1	AB	1962-	1.696	227	724	0.967	47.7
39028 Dun at Hungerford	101.3	AA	1968-	0.735	229	770	0.950	37.3
39043 Kennet at Knighton	295.0	BA	1962-	2.462	263	782	0.950	20.4
RIVER ITCHEN								
42007 Alre at Drove Lane, Alresford	57.0	AA	1970-	1.570	869	851	0.980	65.1
42008 Cheriton Stream at Sewards Bridge	75.1	AC	1970-	0.622	261	883	0.969	43.5
42009 Candover Stream at Borough Bridge	71.2	AB	1970-	0 540	239	821	0.964	55.7
42010 Itchen at Highbridge + Allbrook	360 0	AA	1958-	5.148	451	833	0.962	55.9

Notes:
grade = result of station quality assessment during 1991 Low Flow Study.
AA = high quality flow measurements, few artificial influences
AB = high quality flow measurements, some artificial influences
BA = moderate quality flow measurements, few artificial influences
AC = high quality flow measurements, considerable artificial influences
(see Table 1 for full definitions)

MF = mean flow for 1970-1990
BFI = Base Flow Index for whole period of record, in fraction of mean flow (see section 3 for a further description)
Q95 = 1-day mean flow that was exceeded or equalled for 95% of the time during the whole period of record, in % of mean flow

Table 3b Statistics of the selected catchments, calculated for the period 1970-1990 using average groundwater catchment areas

Station Location	Catchment area (km^2)	MF ($m^3 s^{-1}$)	MF ($mm y^{-1}$)	Rainfall ($mm y^{-1}$)
RIVER KENNET				
39016 Kennet at Theale	957	9.516	314	761
39019 Lambourn at Shaw	172	1.696	311	724
39028 Dun at Hungerford	51.9	0.735	447	770
39043 Kennet at Knighton	276	2.462	281	782
RIVER ITCHEN				
42007 Alre at Drove Lane, Alresford	129	1.570	384	851
42008 Cheriton Stream at Sewards Bridge	71.9	0.622	273	883
42009 Candover Stream at Borough Bridge	88.0	0.540	252	821
42010 Itchen at Highbridge + Allbrook	472	5.148	344	833

Notes: MF = mean flow for 1970-1990
BFI = Base Flow Index for whole period of record, in fraction of mean flow (see section 3 for a further description)
Q95 = 1-day mean flow that was exceeded or equalled for 95% of the time during the whole period of record, in % of mean flow

Table 4 Mean groundwater catchment areas for the period of analysis

Station Location	Catchment area (km^2)				
	1975	1976	1988	1989	average
RIVER KENNET					
39016 Kennet at Theale	950	927	1000	974	957
39019 Lambourn at Shaw	179	177	168	167	172
39028 Dun at Hungerford	69.3	40.7	63.7	62.4	51.9
39043 Kennet at Knighton	287	272	273	274	276
RIVER ITCHEN					
42007 Alre at Drove Lane, Alresford	133	129	127	125	129
42008 Cheriton Stream at Sewards Bridge	69.7	66.8	79.2	72.2	71.9
42009 Candover Stream at Borough Bridge	82.7	90.0	89.2	90.0	88.0
42010 Itchen at Highbridge + Allbrook	465	468	471	479	472

Table 5a Calculated base flow volumes in Spring 1975

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 1 4 1975 to 31 8 1975 (153 days)									
39016 Kennet	0.953	8.94	112.6	118	0.9884	4.57	33.8	36	146.4	154
39019 Lambourn	0.988	2.19	28.6	160	0.9918	1.15	12.0	67	40.6	227
39028 Dun	0.959	0.76	9.60	139	0.9909	0.417	3.94	57	13.5	196
39043 Kennet	0.870	2.96	34.1	119	0.9904	1.14	10.2	37	44.3	155
RIVER ITCHEN catchment	period of analysis. 12 3 1975 to 31 8 1975 (173 days)									
42007 Alre	0.982	1.96	28.8	217	0.9960	1.43	30.8	232	59.6	449
42008 Cheriton Str	0.992	0.70	10.5	151	0.9940	0.820	5.59	80	16.1	231
42009 Candover	0.975	0.64	9.34	113	0.9937	1.42	6.21	75	15.6	188
42010 Itchen	0.982	5.52	81.0	174	0.9921	3.37	36.7	79	117.7	253

Notes for Table 5

(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve base flow, i.e. $-Q_T$ * 86400/ln K, in $10^6 m^6$
(8) Volume of recession curve base flow as in (7), in mm, calculated using groundwater catchment area
(9) Total base flow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total base flow volume water in mm, i.e. (4) + (8)

Table 5b Calculated base flow volumes in Spring 1976

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 3 1976 to 15 8 1976 (154 days)									
39016 Kennet	0.904	2.53	30.4	33	0.9884	1.31	9.70	10	40.1	43
39019 Lambourn	0.984	0 607	7.95	45	0.9918	0.426	4.47	25	12.4	70
39028 Dun	0.967	0 279	3.59	88	0.9909	0.201	1.90	47	5.49	135
39043 Kennet	0.886	0.345	4 07	15	0.9904	0 132	1.18	4	5.25	19
RIVER ITCHEN catchment	period of analysis: 2 4 1976 to 31 7 1976 (121 days)									
42007 Alre	0.982	0.978	10.0	78	0.9960	0.820	17.7	137	27.7	215
42008 Cheriton Str	0.970	0.247	2.50	37	0.9940	0.174	2.50	37	5.00	74
42009 Candover	not suitable (groundwater augmentation)									
42010 Itchen	0.969	2.83	28 7	61	0.9921	2.46	5 81	12	34.5	73

Notes for Table 5

(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve base flow, i.e. $-Q_T$ * 86400/ln K, in $10^6 m^6$
(8) Volume of recession curve base flow as in (7), in mm, calculated using groundwater catchment area
(9) Total base flow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total base flow volume water in mm, i.e. (4) + (8)

Table 5c Calculated base flow volumes in Spring 1988

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 4 1988 to 31 8 1988 (138 days)									
39016 Kennet	0.964	7.45	86.3	86	0.9884	6.65	49.2	49	135.5	135
39019 Lambourn	0.965	1.69	19.6	117	0.9918	1.21	12.7	76	32.5	193
39028 Dun	0.971	0.582	6.78	106	0.9909	0.381	3.60	57	10.4	163
39043 Kennet	0.985	1.94	22.9	84	0.9904	1.08	9 67	35	32.6	119
RIVER ITCHEN catchment	period of analysis: 17 3 1988 to 31 8 1988 (168 days)									
42007 Alre	0.987	1.79	25.6	202	0.9960	1.42	30.6	241	56.2	443
42008 Cheriton Str	0.984	0.638	9.11	115	0.9940	0.432	6.20	78	15.3	193
42009 Candover	0.981	0.568	8.09	91	0.9937	0.425	5.81	65	13.9	156
42010 Itchen	0.978	5 15	73.1	155	0.9921	2.62	41.5	88	114.6	243

Notes for Table 5

(1) Base Flow Index over specified period, in fraction of mean flow (column 2)
(2) Mean Flow over specified period, in $m^3 s^{-1}$
(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$
(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area
(5) Recession constant
(6) Flow at the end of the 'no recharge' period
(7) Volume of recession curve base flow, i.e. $-Q_T$ * 86400/ln K, in $10^6 m^3$
(8) Volume of recession curve base flow as in (7), in mm, calculated using groundwater catchment area
(9) Total base flow volume in $10^6 m^3/s$, i.e. (3) + (7)
(10) Total base flow volume water in mm, i.e. (4) + (8)

Table 5d Calculated base flow volumes in Spring 1989

	BFI (-) (1)	MF ($m^3 s^{-1}$) (2)	BF vol ($10^6 m^3$) (3)	BF vol (mm) (4)	K (-) (5)	Q_T ($m^3 s^{-1}$) (6)	REC vol ($10^6 m^3$) (7)	REC vol (mm) (8)	TOTAL ($10^6 m^3$) (9)	TOTAL (mm) (10)
RIVER KENNET catchment	period of analysis: 15 4 1989 to 15 9 1989 (154 days)									
39016 Kennet	0.959	6.21	79.2	81	0.9884	4.45	33.0	34	112.2	115
39019 Lambourn	0.982	1.35	17.6	105	0.9918	0.896*	12.1	72	29.7	177
39028 Dun	0.970	0.470	6.07	97	0.9909	0.275	3.94	63	10.0	160
39043 Kennet	0.997	1.82	24.2	88	0.9904	0.792	10.2	37	34.4	125
RIVER ITCHEN catchment	period of analysis: 24 4 1989 to 31 7 1989 (99 days)									
42007 Alre	not suitable (groundwater augmentation)									
42008 Cheriton Str	0.994	0.486	4.13	57	0.9940	0.284	4.08	57	8.21	114
42009 Candover	0.982	0.416	3.49	39	0.9937	0.282	3.85	43	7.34	82
42010 Itchen	0.955	3.96	32.3	67	0.9921	2.62	28.5	59	60.8	126

Notes for Table 5

* Because the gauge was drowned from 10.9.89, the flow on 9.9.89 has been taken to represent the correct value

(1) Base Flow Index over specified period, in fraction of mean flow (column 2)

(2) Mean Flow over specified period, in $m^3 s^{-1}$

(3) Base Flow volume, i.e. BFI * MF * length of specified period, in $10^6 m^3$

(4) Base Flow volume as in (3), in mm, calculated using groundwater catchment area

(5) Recession constant

(6) Flow at the end of the 'no recharge' period

(7) Volume of recession curve base flow, i.e -Q_T * 86400/ln K, in $10^6 m^3$

(8) Volume of recession curve base flow as in (7), in mm, calculated using groundwater catchment area

(9) Total base flow volume in $10^6 m^3/s$, i.e. (3) + (7)

(10) Total base flow volume water in mm, i.e. (4) + (8)

Table 6 Summary of base flow volume calculations

	1975			1976			1988			1989		
	BF vol (mm)	REC vol (mm)	TOTA L (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)	BF vol (mm)	REC vol (mm)	TOTAL (mm)
RIVER KENNET catchment												
39016 Kennet	118	36	154	33	10	43	86	49	135	81	34	115
39019 Lambourn	160	67	227	45	25	70	117	76	193	105	72	177
39028 Dun	139	57	196	88	47	135	106	57	163	97	63	160
39043 Kennet	119	37	155	15	4	19	84	35	119	88	37	125
RIVER ITCHEN catchment												
42007 Alre	217	232	449	78	137	215	202	241	443	-	-	-
42008 Cheriton Str	151	80	231	37	37	74	115	78	193	57	57	114
42009 Candover	113	75	188	-	-	-	91	65	156	39	43	82
42010 Itchen	174	79	253	61	12	73	155	88	243	67	59	126

Annex A Annual hydrographs of daily flows for the selected years

INTRODUCTION

Below, hydrographs of daily flow during a calendar year are presented for the catchments and years that were analyzed: 1975, 1976, 1988 and 1989. The maximum of the discharge scale is the same for all years for one station, and determined by the maximum flow on record for that station. Apart from the time plot of daily flows, the graphs also display the base flow line which was separated from the daily flows by a standard Institute of Hydrology algorithm (Section 3.1). On the graphs the period of analysis is indicated by two bold vertical lines. The graphs are grouped by year to facilitate the comparison of runoff patterns in the catchments. Some features of the presented graphs are commented on below.

COMMENTS

River Kennet (catchments 39016, 39019, 39028, 39043)

General: The flows recorded in the Kennet at Theale (39016) are not solely derived from Chalk; approximately 10% of the catchment, i.e. the Enbourne catchment, has a predominantly impervious geology of Eocene clays. The responsiveness of the Enbourne catchment results in some high runoff peaks at Theale, higher than expected from a pure Chalk catchment. The different response to precipitation is also reflected in a lower BFI, 0.54 instead of 0.95 in the upstream Chalk catchments (39019, 39028 and 39043), indicating that baseflow comprises a lower fraction of the total runoff than in the other catchments.

A groundwater augmentation scheme has been in operation, pumping water into the River Lambourn when flows were low. This discharge into the river is easily recognisable on the hydrographs, but dates may be verified with the following list of dates when the scheme was operated (provided by Thames NRA):

1 September - 5 December 1975
23 August - 17 November 1976
5 September - 27 September 1989
18 October - 24 November 1990

Apart from groundwater abstraction, there are artificial influences on river flows by mills (in the upper Kennet, 39043) and flows in and out of the Kennet and Avon Canal (in the Dun, 39028). These practises influence more the distribution during a day or week than the total volume of water, and will therefore not have much influence on the volume of base flow which has been calculated.

1975: The hydrograph of the Kennet at Knighton shows some prolonged and relatively high peaks (two to three times the flow recorded during the rest of the summer, and lasting several weeks). These peaks do not occur at the upstream gauging station at Marlborough (39037). Furthermore, the station description mentions occurrences of drowning due to weed growth and a very flat gradient. It was therefore assumed that drowning took place. These peaks do not influence the total volume of base flow to a sufficiently large extent to reject the data for analysis, because the over-estimation balances out the under-estimation.

1976: The only remarkable feature of the 1976 hydrographs, apart from the very low flows, is the sudden increase in flows towards the end of August in the Lambourn at Shaw (39019). This is a result of the operation of the Lambourn groundwater augmentation scheme. The period of analysis therefore has an end date of 15 August.

1988: The hydrographs of this year present a good example of the general statement made above, with short, high runoff peaks in the Kennet at Theale (39016) which are hardly repeated in the other catchments. The sudden dip in the flow record of the Lambourn at Shaw (39019) at the beginning of May is not a data error and probably due to a large but short-term abstraction upstream of the gauging station. The resulting loss in baseflow volume was measured and amounts to 2% of total baseflow during the period that was analysed.

1989: Although the natural recession as derived from the hydrographs continued until October, the operation of the groundwater augmentation scheme from the beginning of September, with a marked impact on the flows in the Lambourn, resulted in a shorter season of analysis. The recession did not start until mid-April.

River Itchen (42007, 42008, 42009, 42010)

General: The irregularity of daily flows as they appear on the hydrographs, is mainly a result of the water management performed for the benefit of the extensive watercress beds and fish farms in the upstream part of the Itchen catchment. The irregularity does not significantly affect the calculated base flow volume.

The operation of the Candover and Alre groundwater augmentation schemes do have an impact on the calculated volume of base flow. The Candover scheme affects riverflow mainly in the Candover Stream and to a small extent in the other rivers in the Itchen catchment (Southern Water Authority, 1979, p.84). The Alre scheme affects flows mainly in the River Alre and to a lesser extend the flow gauged in the other rivers in the Itchen catchment (Southern Science, 1991, p.18). When the schemes were operated, only the directly affected catchments were not analysed. The relevant dates are:

Candover scheme
8 May - 10 November 1975 (a few short pumping tests)
3 May - 22 December 1976
9 August - 8 December 1989

Alre scheme
8 May 1989 - 8 February 1990 (severe test pumping)

1975: The flow in all catchments is in recession from the beginning of April until the end of July, when the gauged flows start to increase. The test pumping in the Candover catchment has taken place for 15 days from 8 May, for 10 days from 1 August and for 5 days from 17 August. The total volume pumped was estimated at 0.9×10^6 m^3 (Southern Water Authority, 1979, p.34-35), which is 10% of the estimated total baseflow runoff volume from the Candover catchment(Table 5a). The pumping tests have not visibly altered the hydrographs in the Candover, and the flow data have not been rejected for analysis. However, caution has to be taken in interpreting the resulting baseflow volume. Because of the limited impact on Candover flows itself, the baseflow from peripheral catchments may be assumed unaltered by the pumping tests.

1976: The Candover groundwater augmentation scheme has been in operation for most of the summer (from the beginning of May until the end of August), which means that the measured flows in the Candover catchment are unsuitable for analysis. The depletion of Alre streamflow was estimated at 0.1×10^6 m^3, which is 1% of the calculated baseflow runoff and therefore negligible. The depletion of Itchen flows was estimated at 0.2×10^6 m^3, less than 1% of the calculated baseflow volume, and this can therefore equally be ignored (after Southern Water Authority, 1979, p.83).

1988: The flows in all but one catchment were in recession from mid-February, whereas the recession started one month later in the Alre. This difference could be attributed to a difference in the physical characteristics of the Chalk that underlies the catchments. A sustained peak in groundwater levels has been observed in the Northern boundary of the catchment, probably due to extremely impermeable nature of the Chalk (Southern Science, 1991, p.3). This phenomenon would explain a slow release of the stored water and a delayed start of the recession. Towards the end of August flows start to increase again.

1989: Flows are very irregular in the Alre due to the operation of the groundwater augmentation scheme. The effect of the pumping has been analysed elsewhere (Southern Science, 1991). As a result the 1989 data for the Alre catchment have not been analysed. The groundwater augmentation scheme in the Candover catchment has been in operation from the beginning of August, which limited the period that was analysed.

Figure A.1a Kennet at Theale (39016): Hydrograph with separated baseflow for 1975

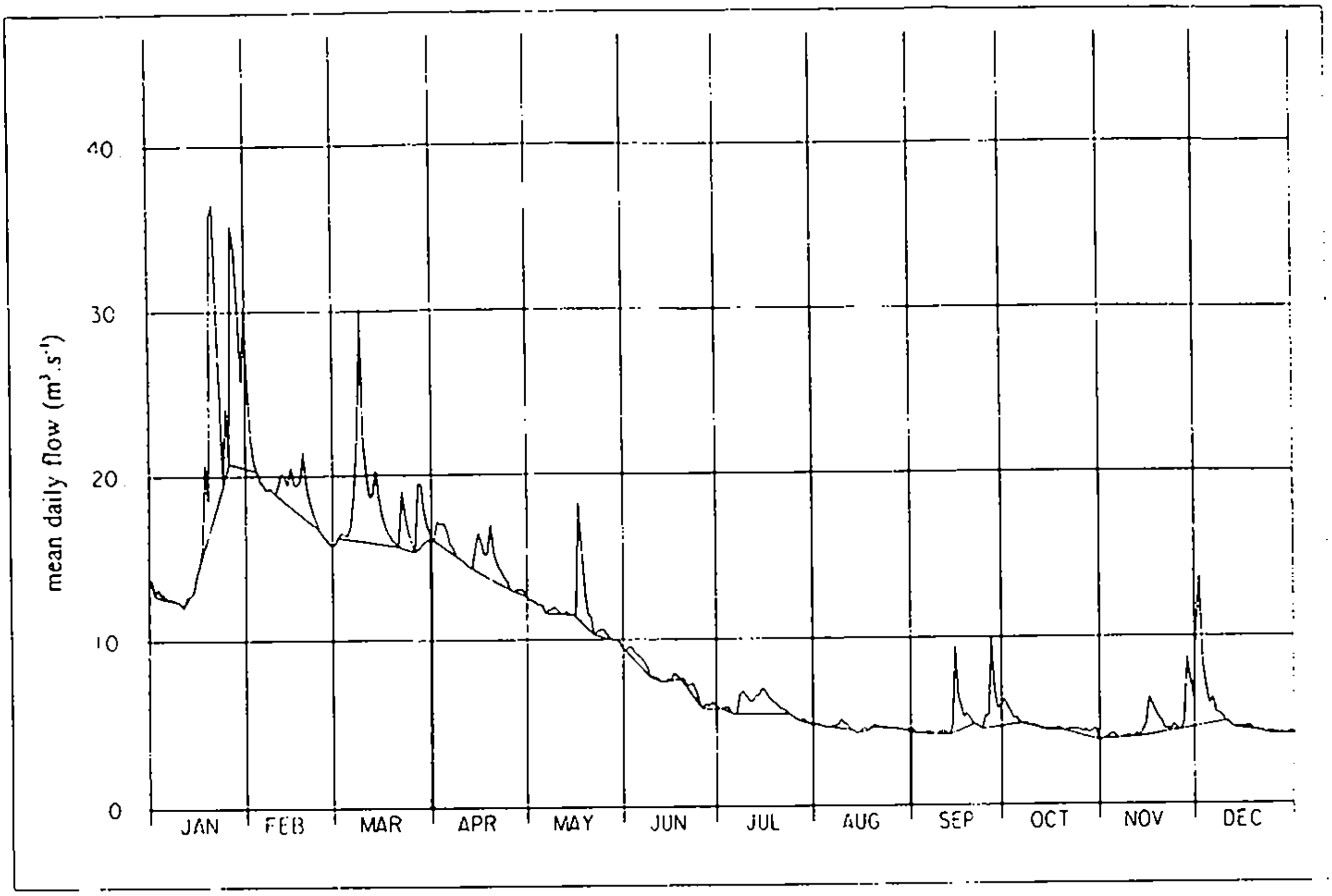


Figure A.1b Lambourn at Shaw (39019): Hydrograph with separated baseflow for 1975

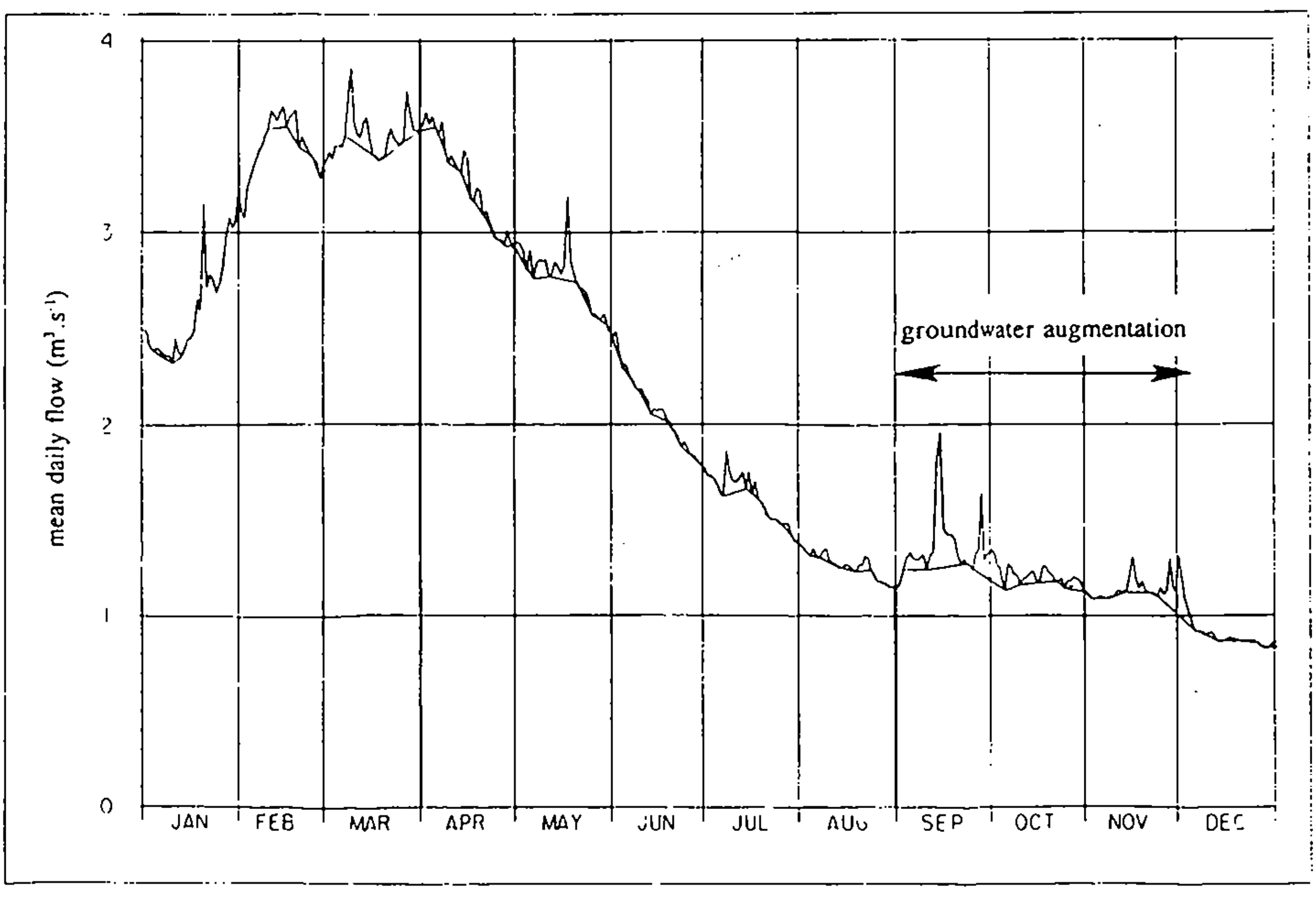


Figure A.1c Dun at Hungerford (39028): Hydrograph with separated baseflow for 1975

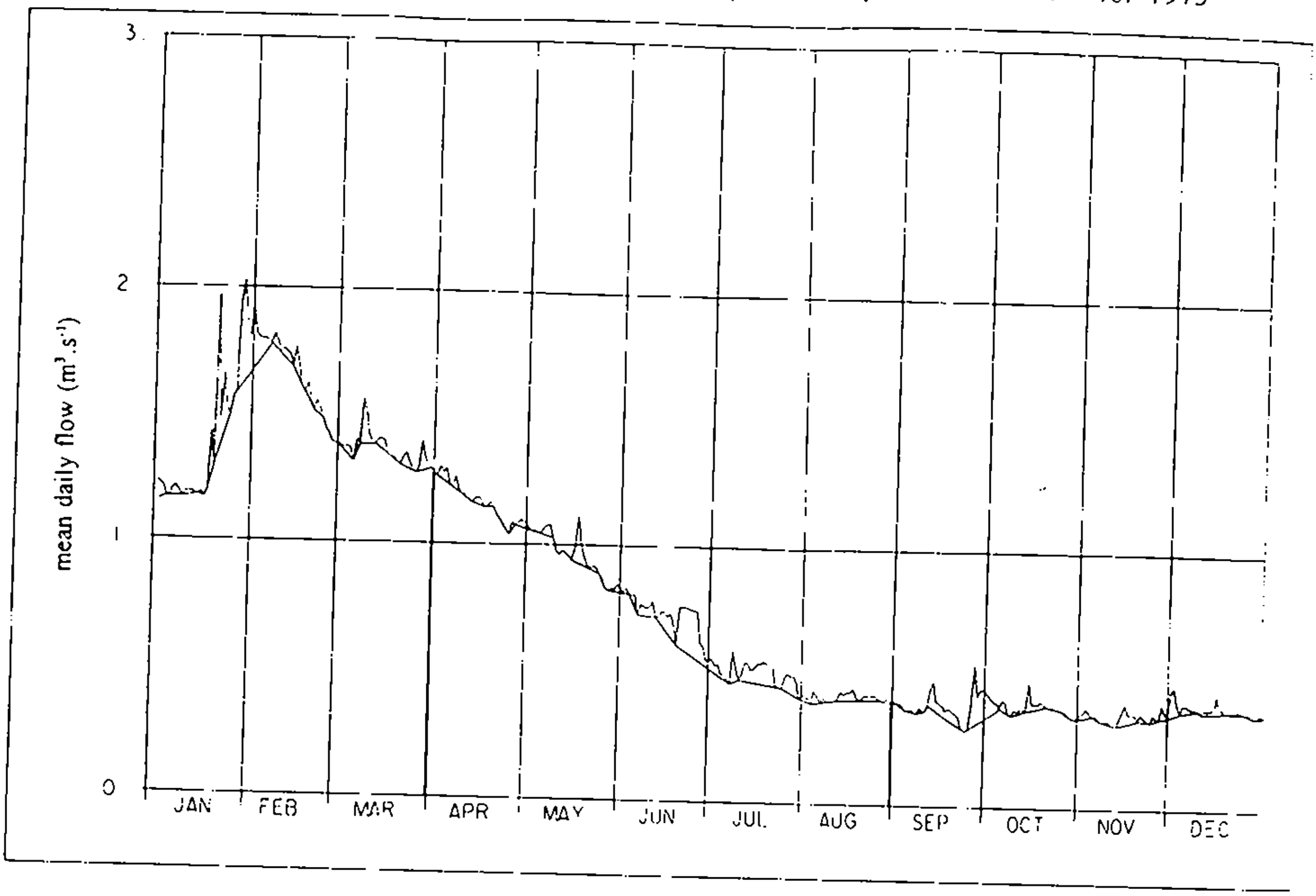


Figure A.1d Kennet at Knighton (39043): Hydrograph with separated baseflow for 1975

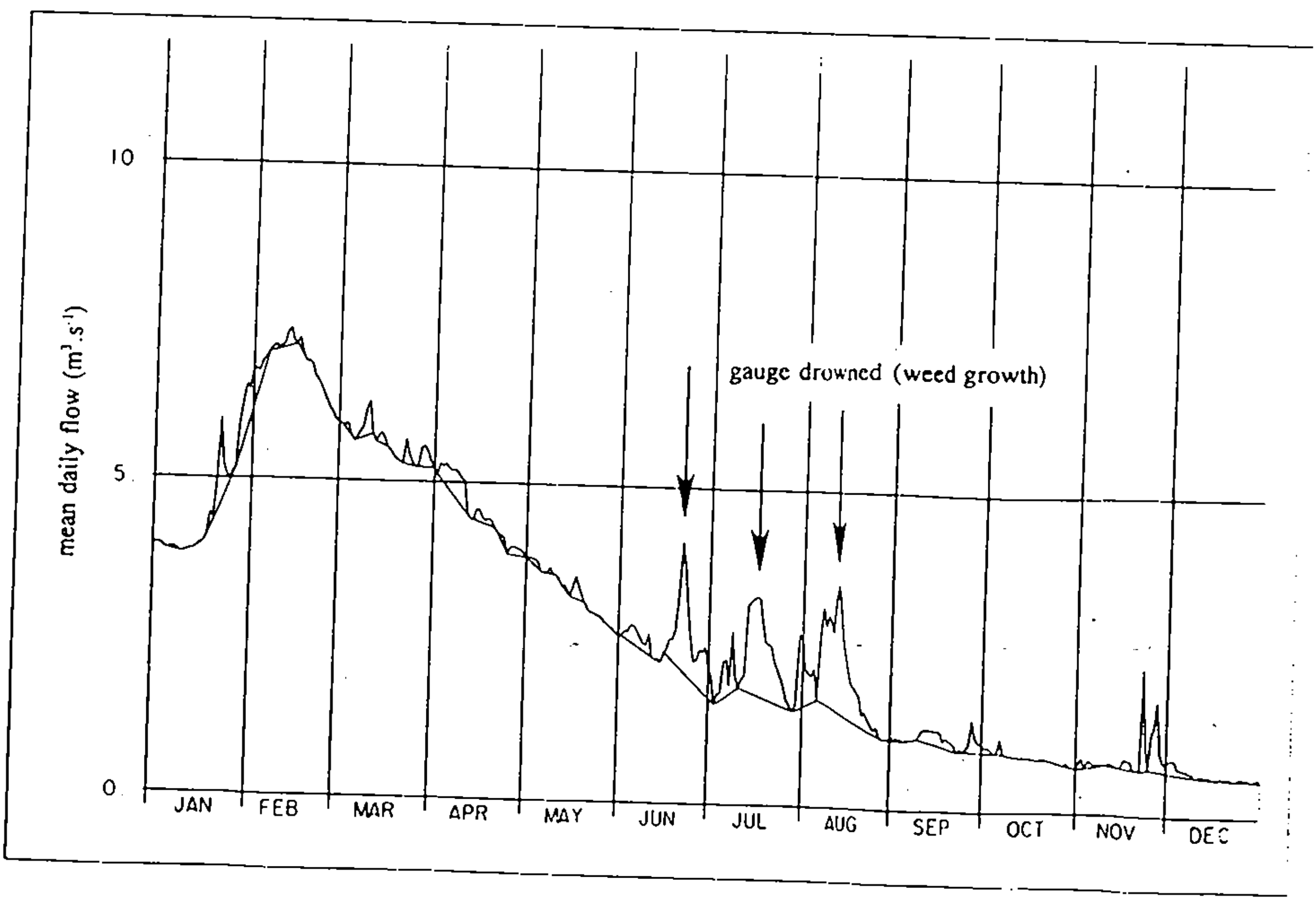


Figure A.2a Kennet at Theale (39016): Hydrograph with separated baseflow for 1976

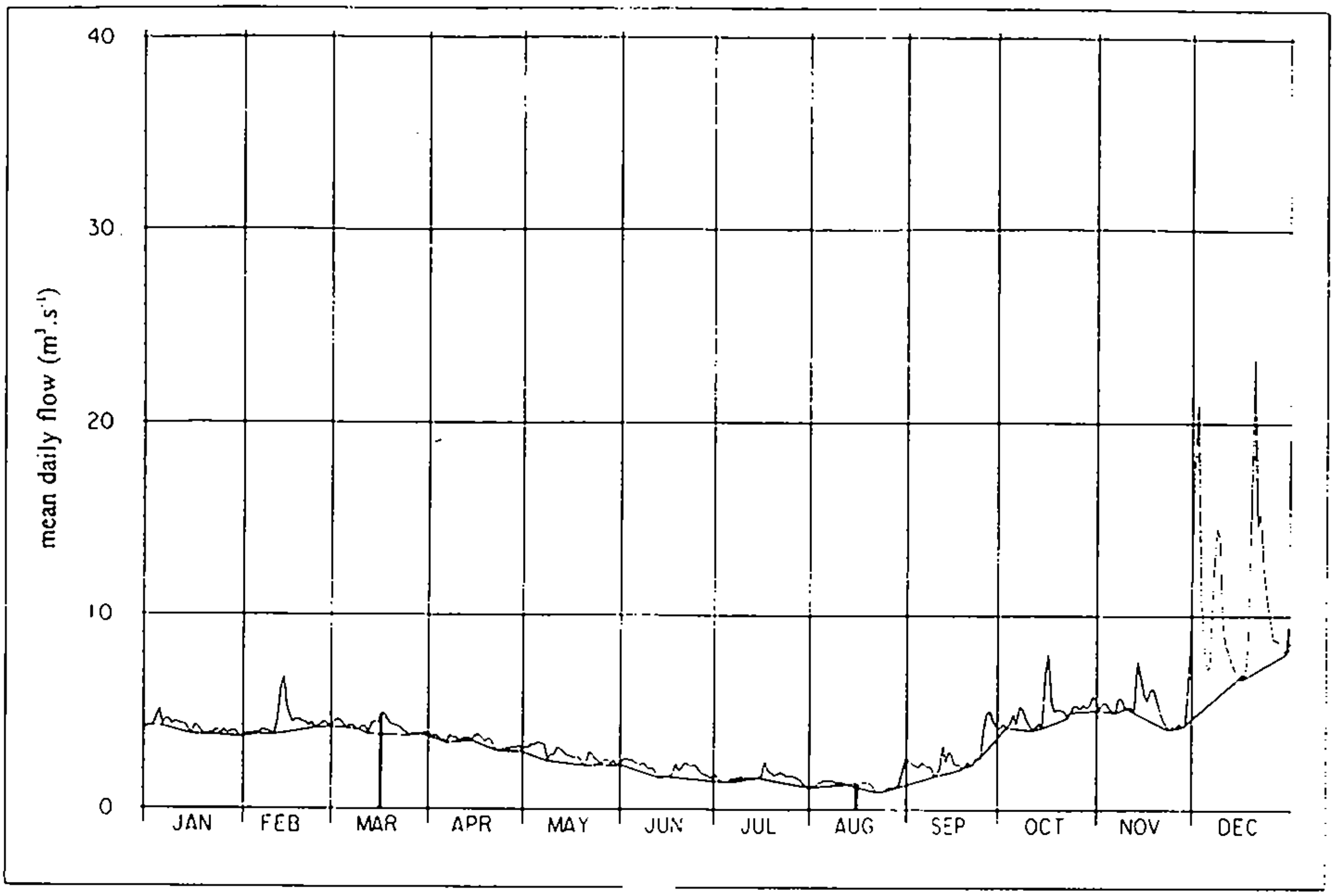


Figure A.2b Lambourn at Shaw (39019): Hydrograph with separated baseflow for 1976

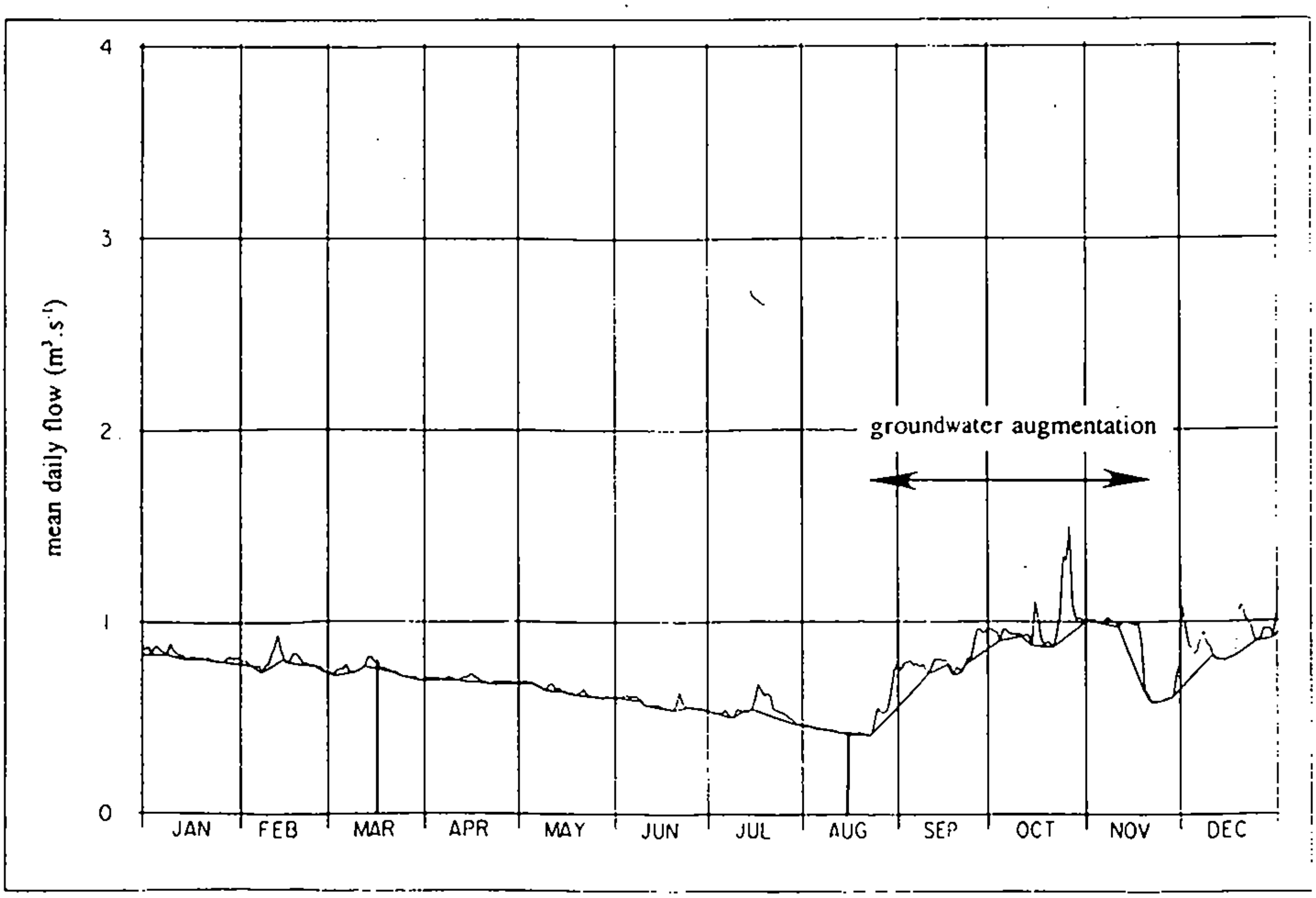


Figure A.2c Dun at Hungerford (39028): Hydrograph with separated baseflow for 1976

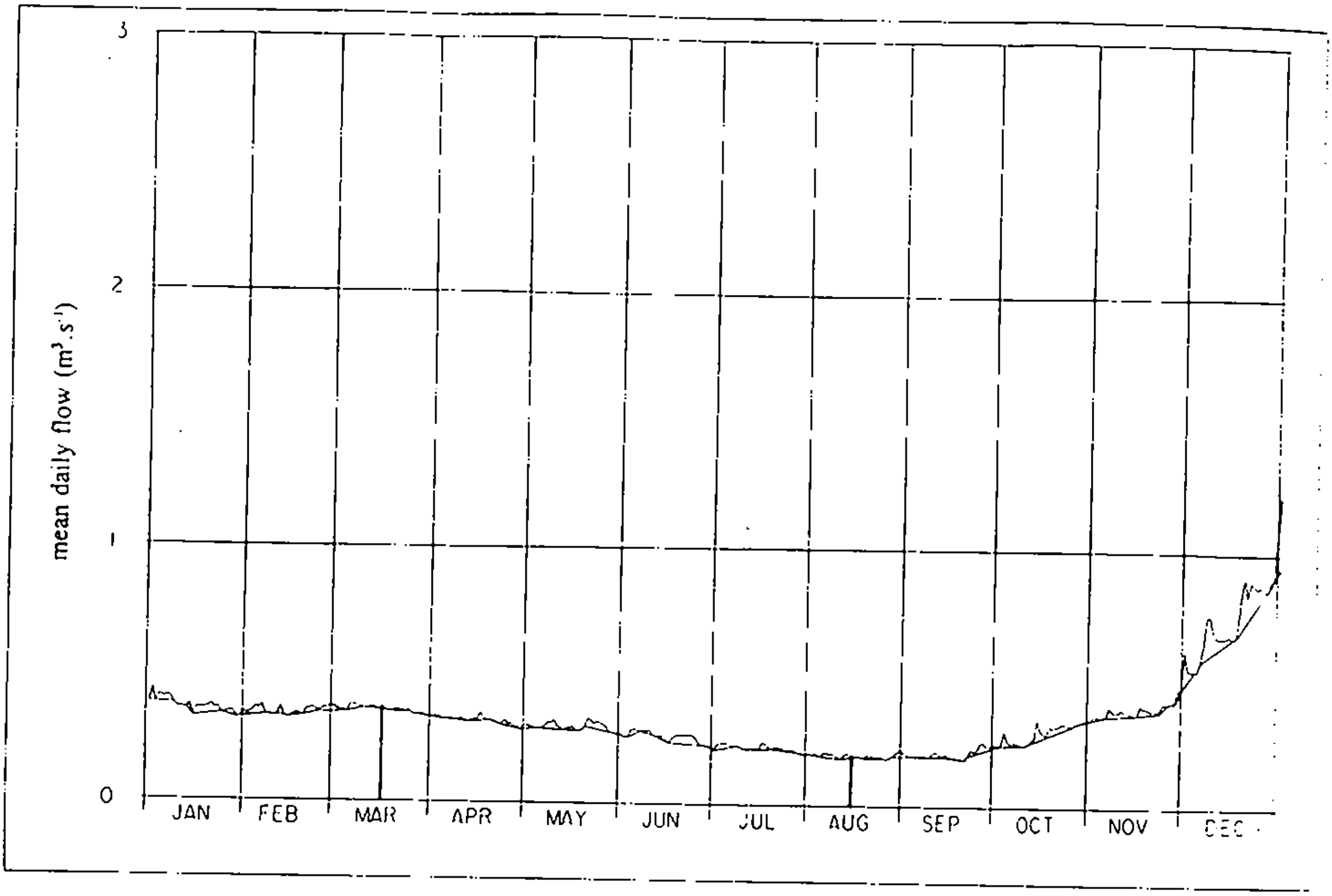


Figure A.2d Kennet at Knighton (39043): Hydrograph with separated baseflow for 1976

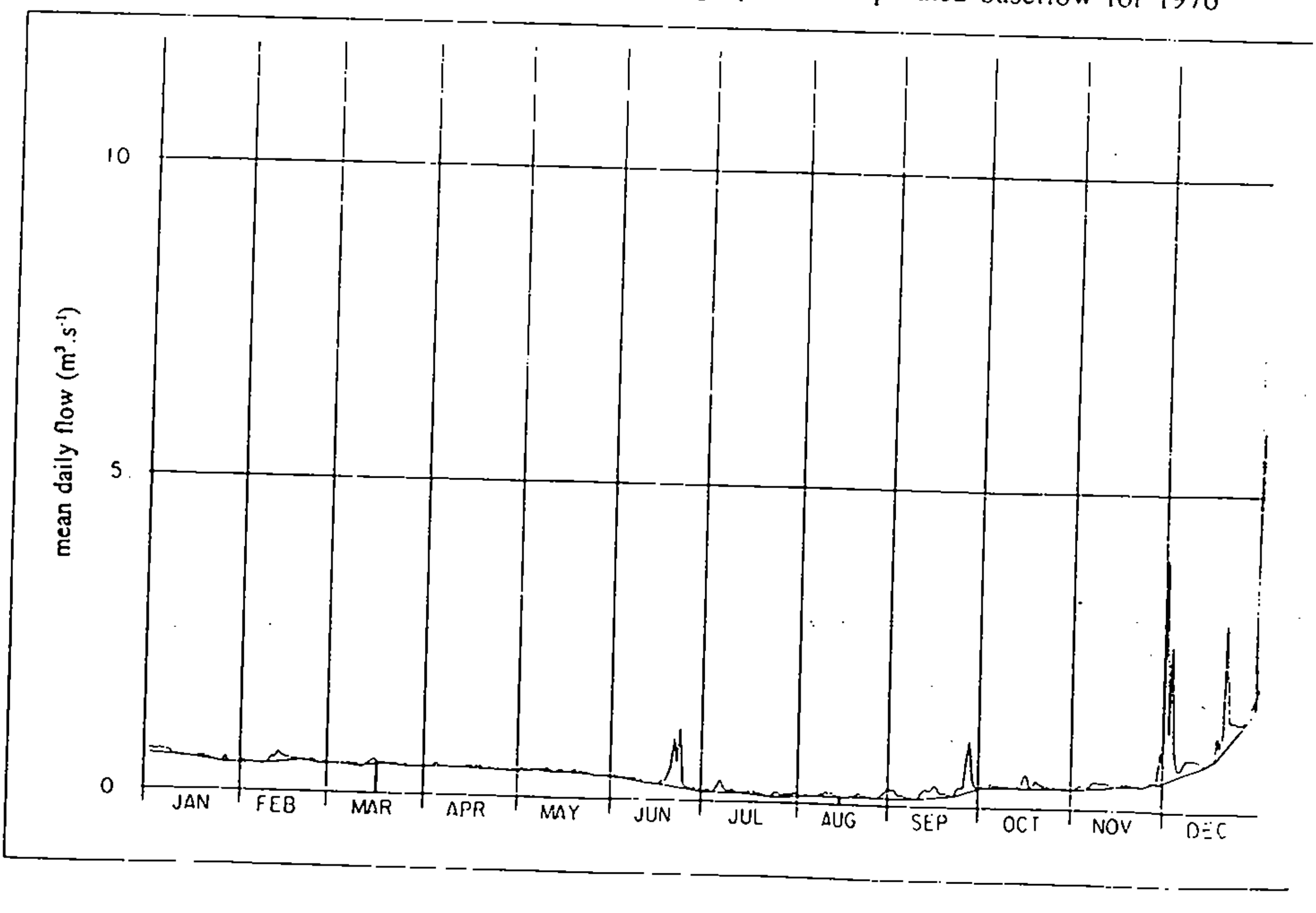


Figure A.3a Kennet at Theale (39016): Hydrograph with separated baseflow for 1988

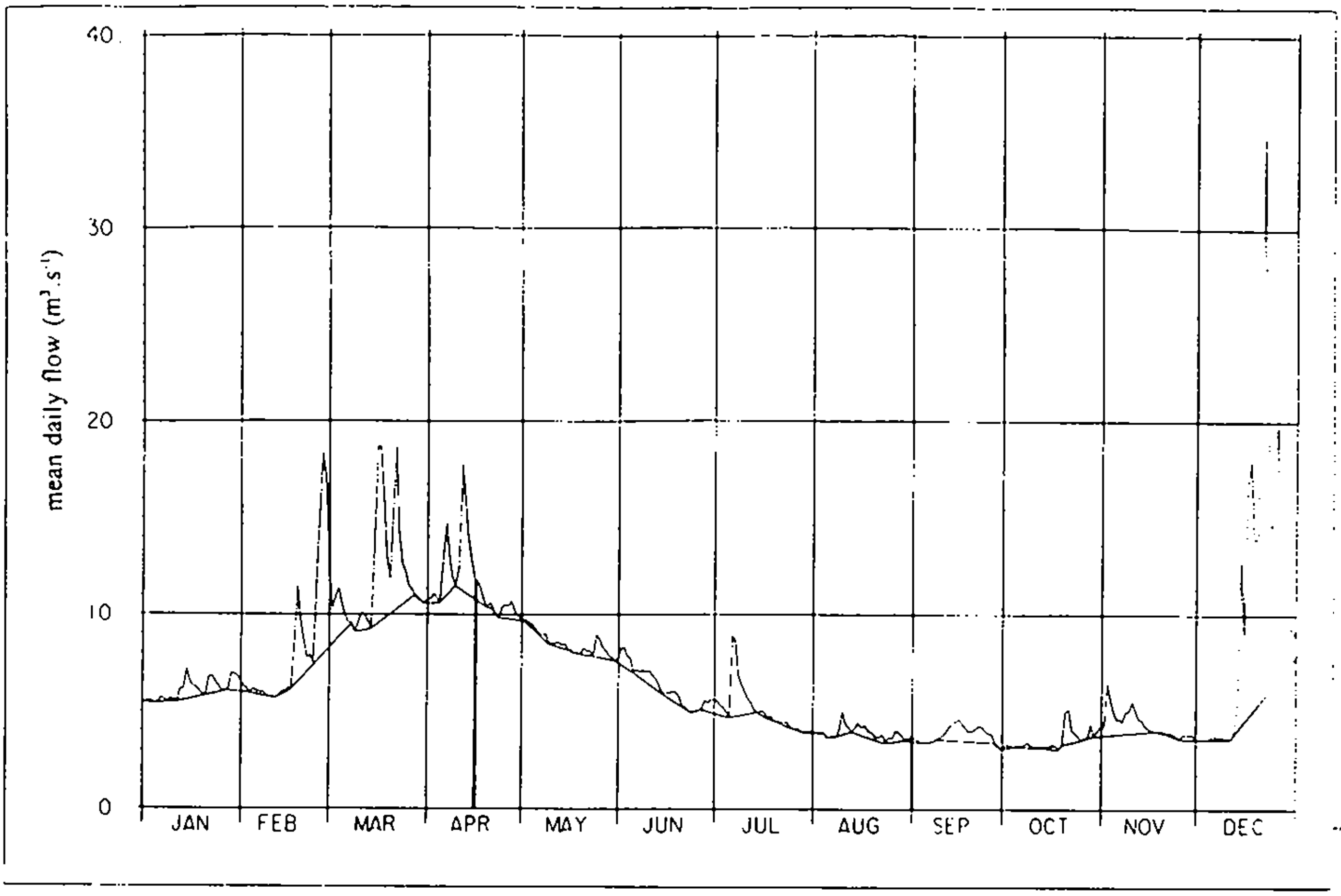


Figure A.3b Lambourn at Shaw (39019): Hydrograph with separated baseflow for 1988

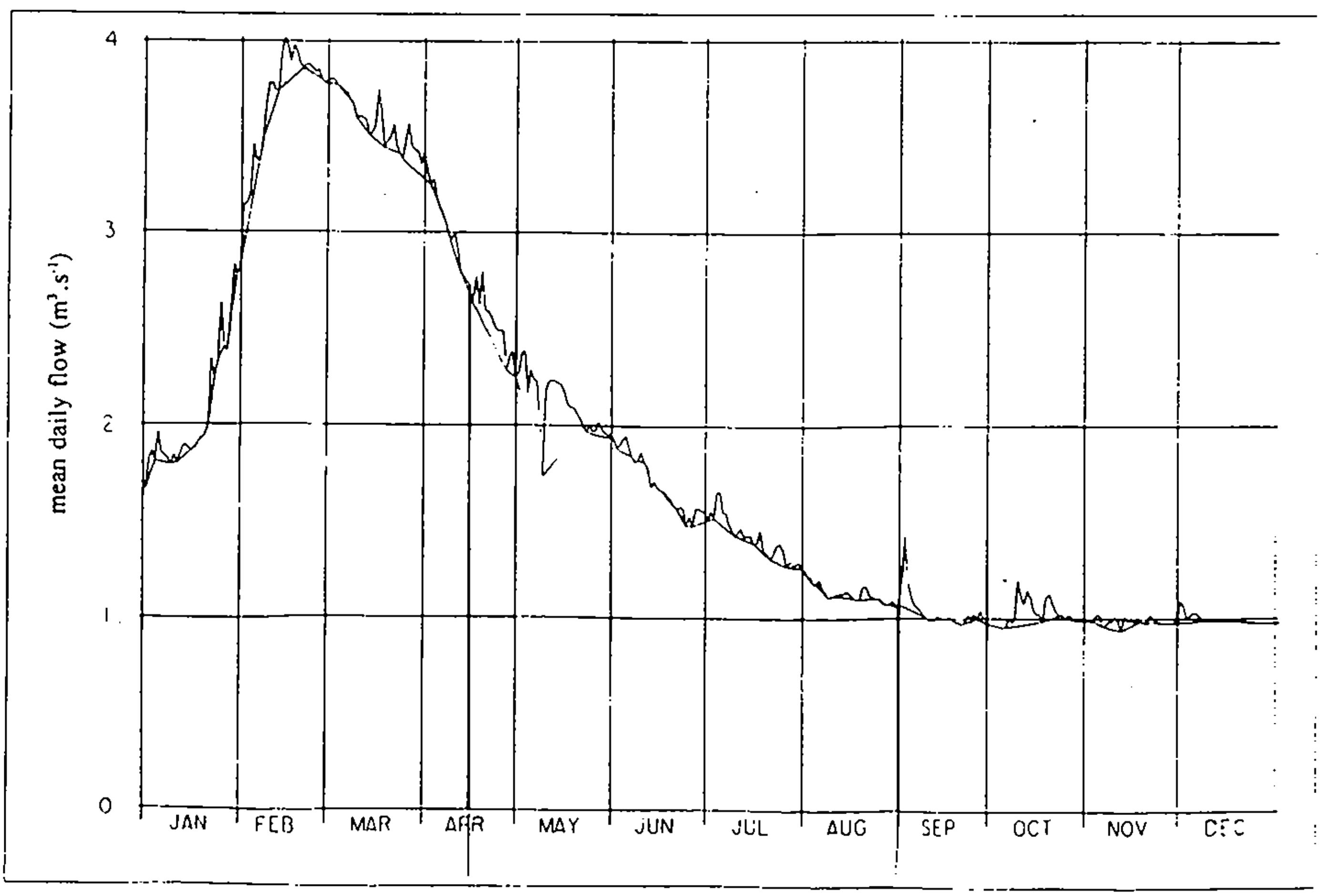


Figure A.3c Dun at Hungerford (39028): Hydrograph with separated baseflow for 1988

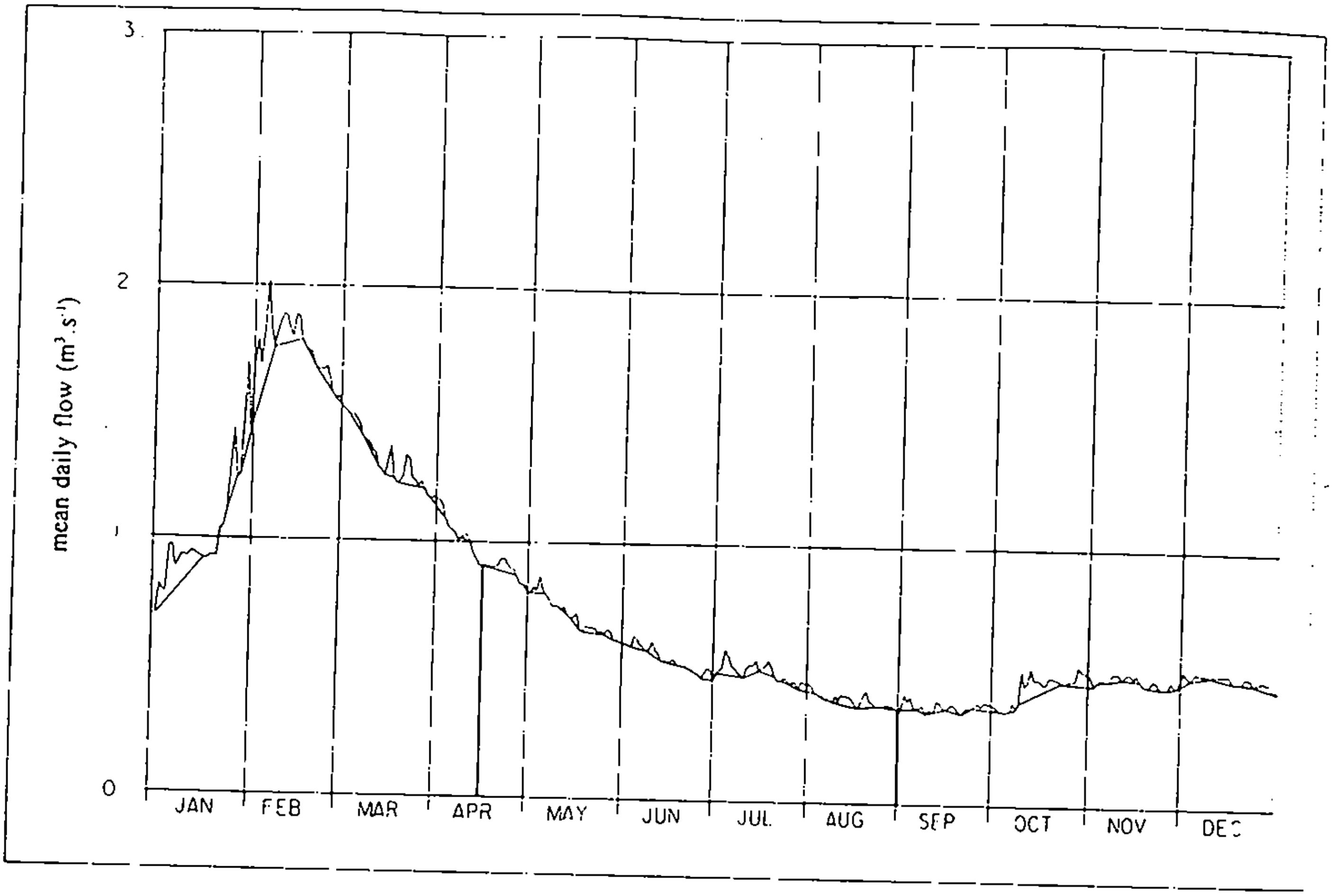


Figure A.3d Kennet at Knighton (39043): Hydrograph with separated baseflow for 1988

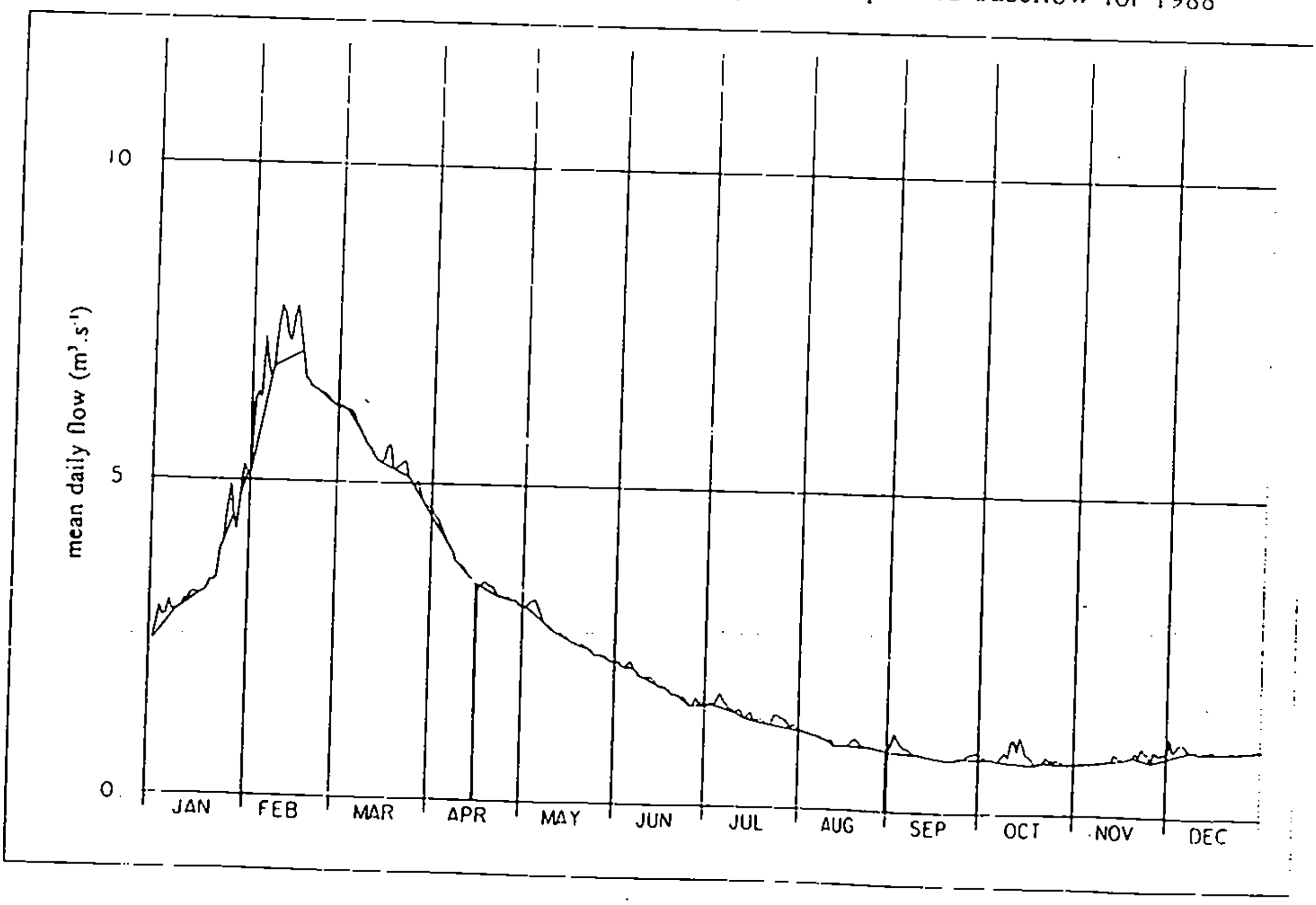


Figure A.4a Kennet at Theale (39016): Hydrograph with separated baseflow for 1989

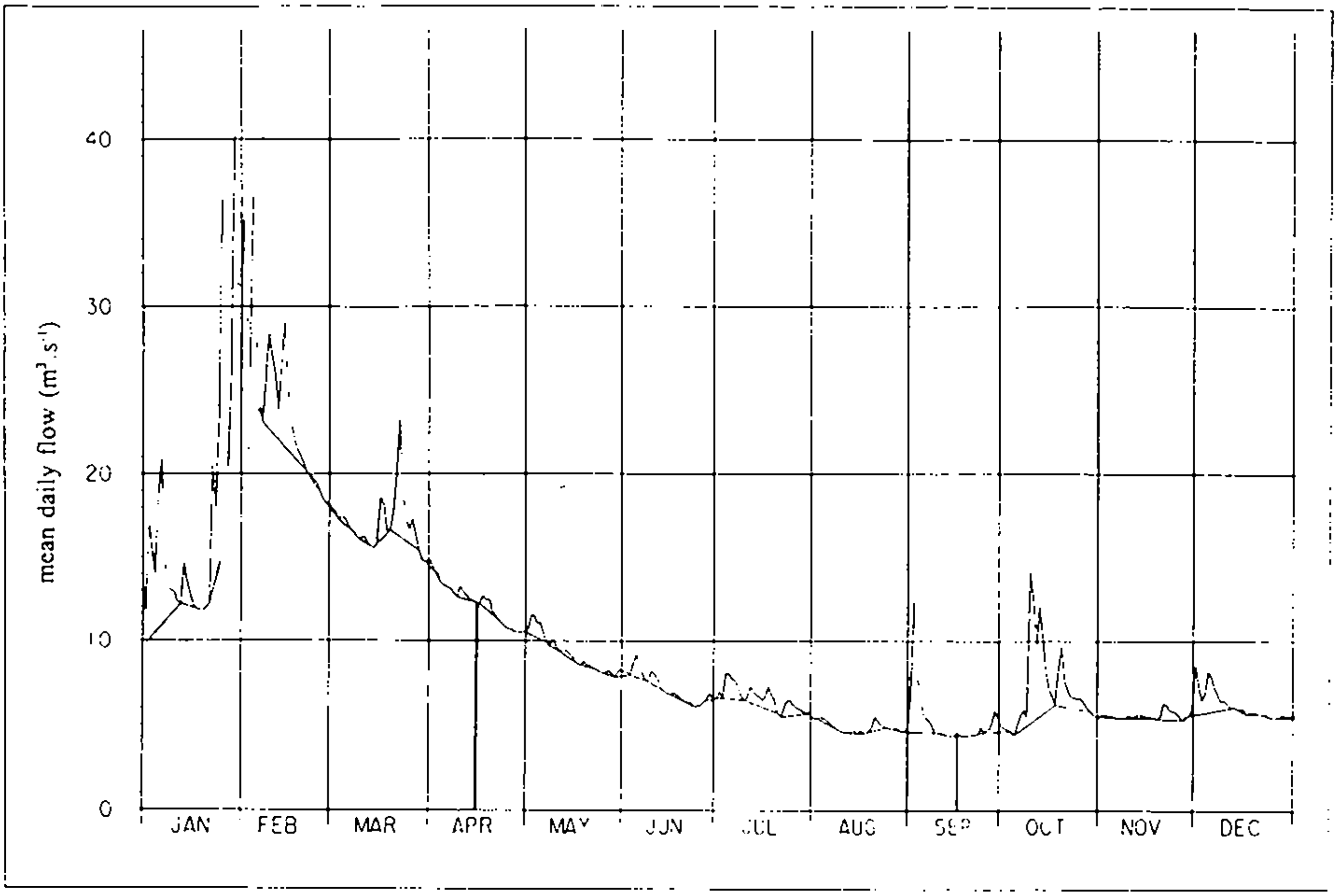


Figure A.4b Lambourn at Shaw (39019): Hydrograph with separated baseflow for 1989

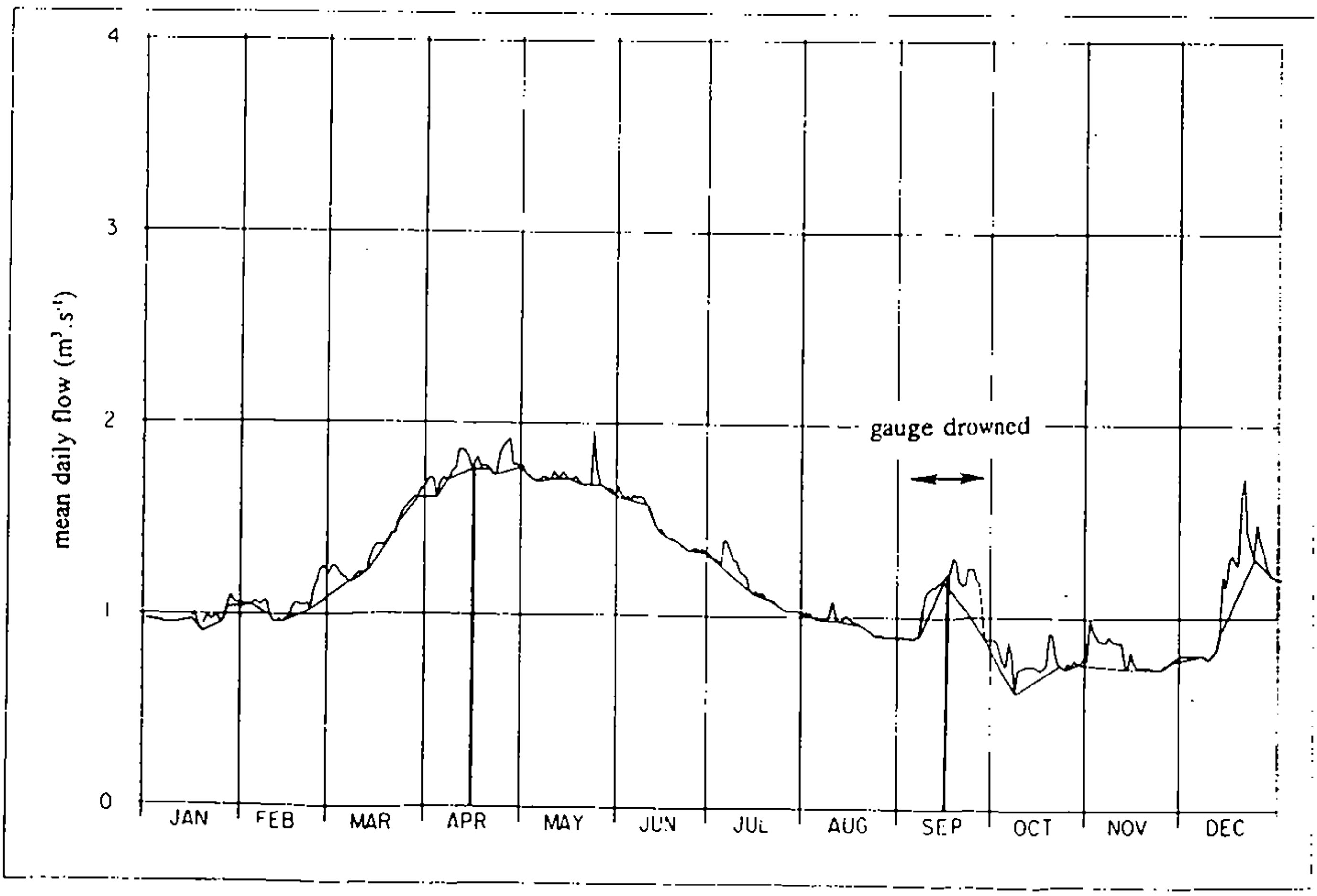


Figure A.4c Dun at Hungerford (39028): Hydrograph with separated baseflow for 1989

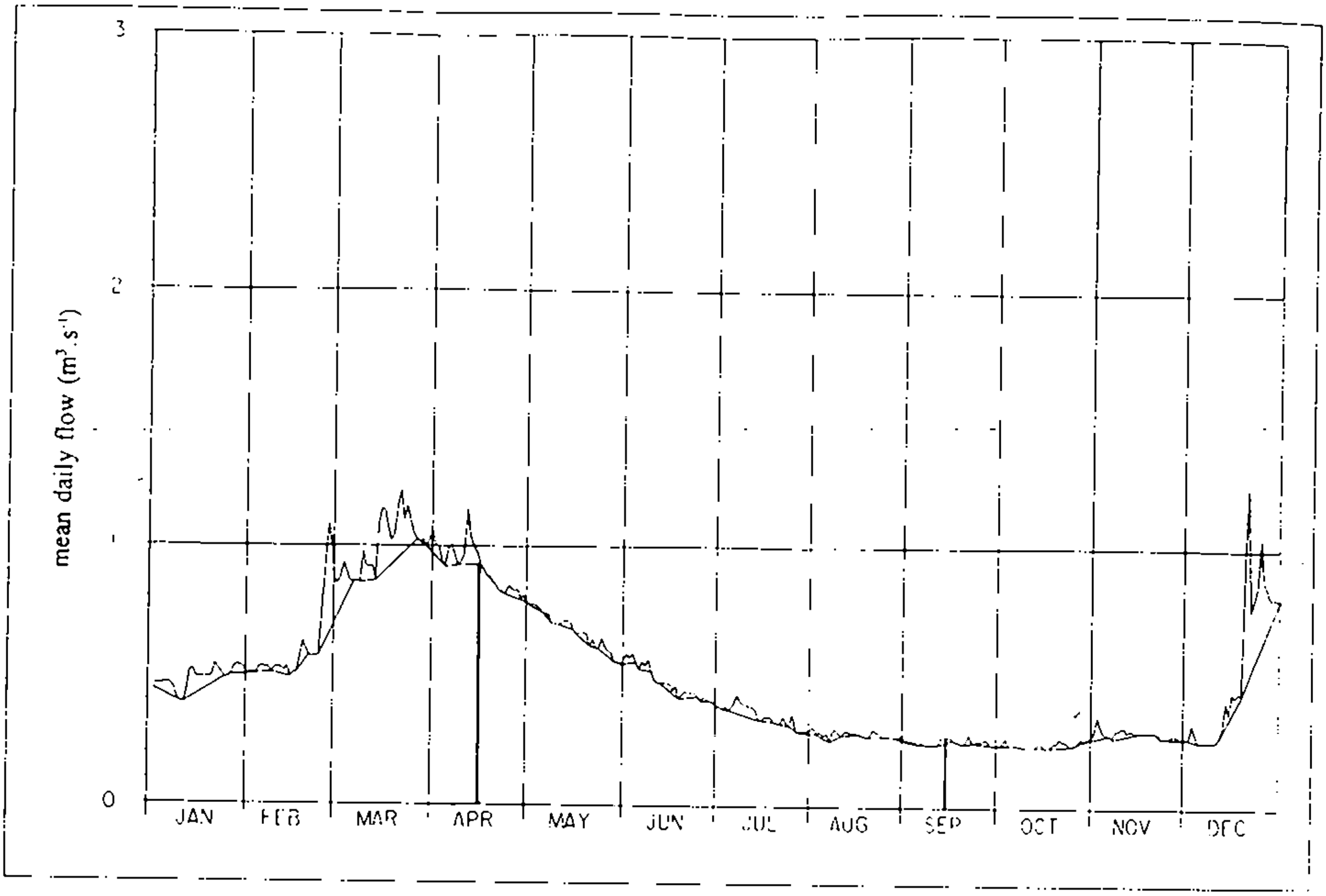


Figure A.4d Kennet at Knighton (39043): Hydrograph with separated baseflow for 1989

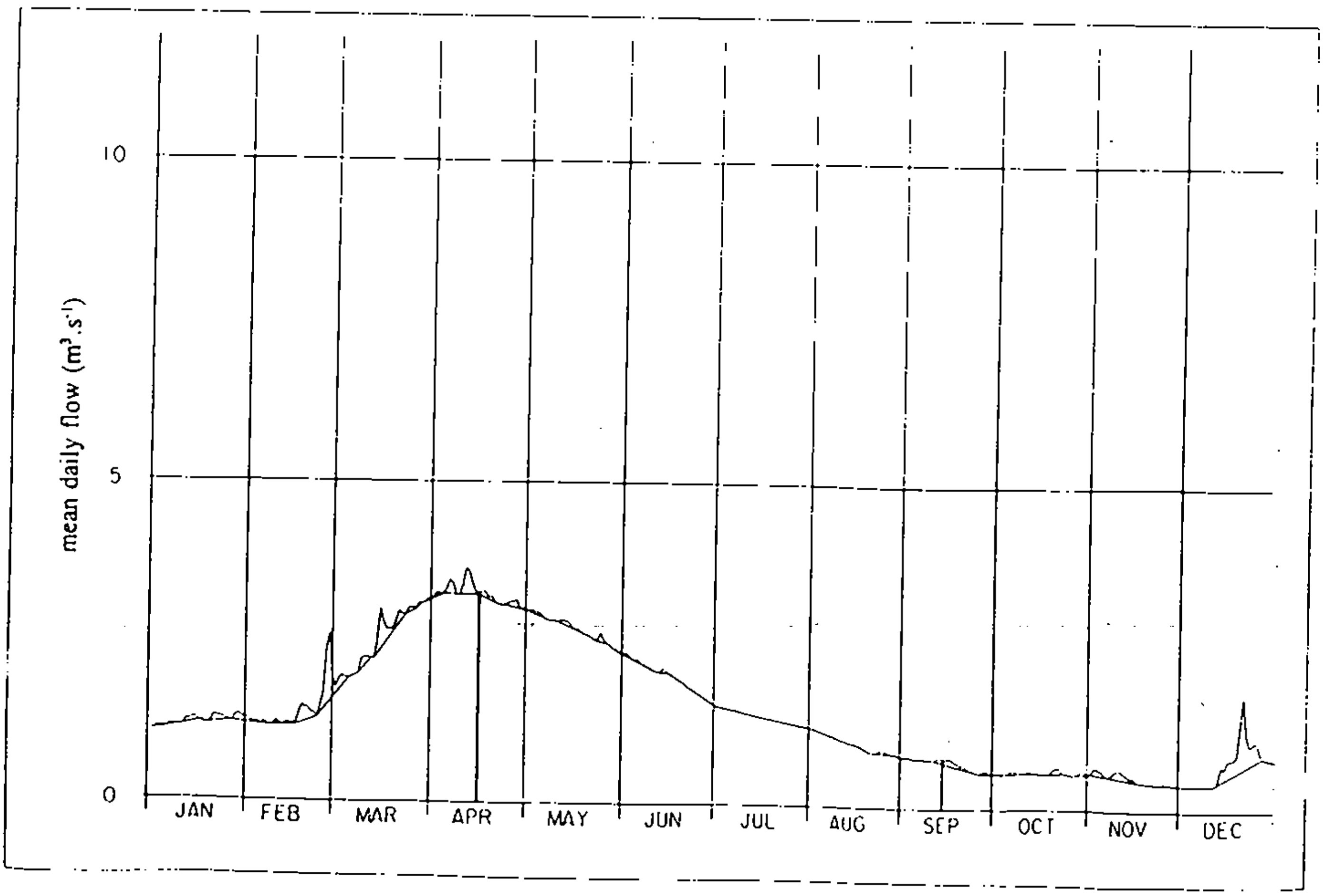


Figure A.5a Alre at Drove Lane, Alresford (42007): Hydrograph with separated flow for 1975

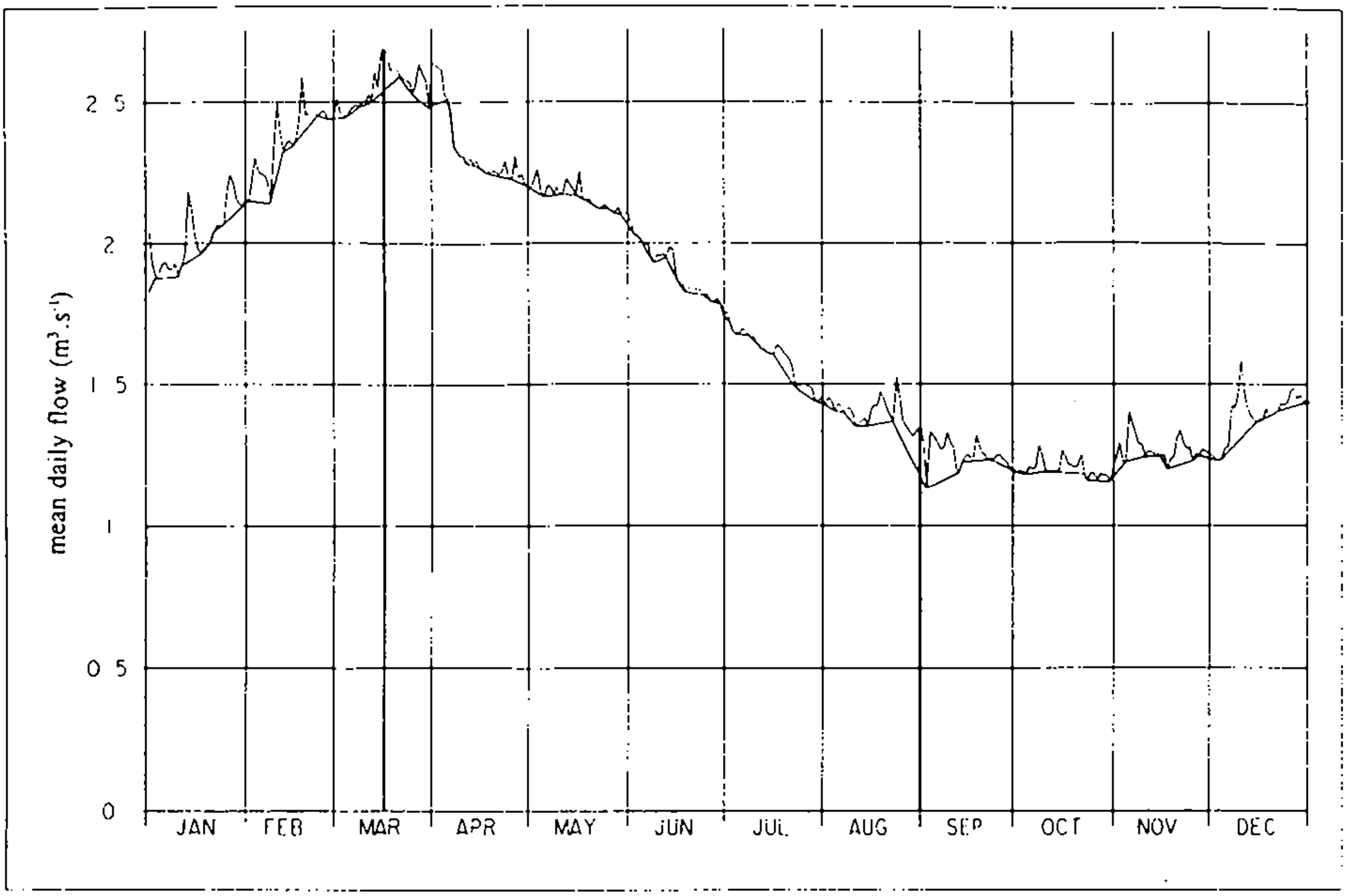


Figure A.5b Cheriton Stream at Sewards Bridge (42008): Hydrograph with separated flow for 1975

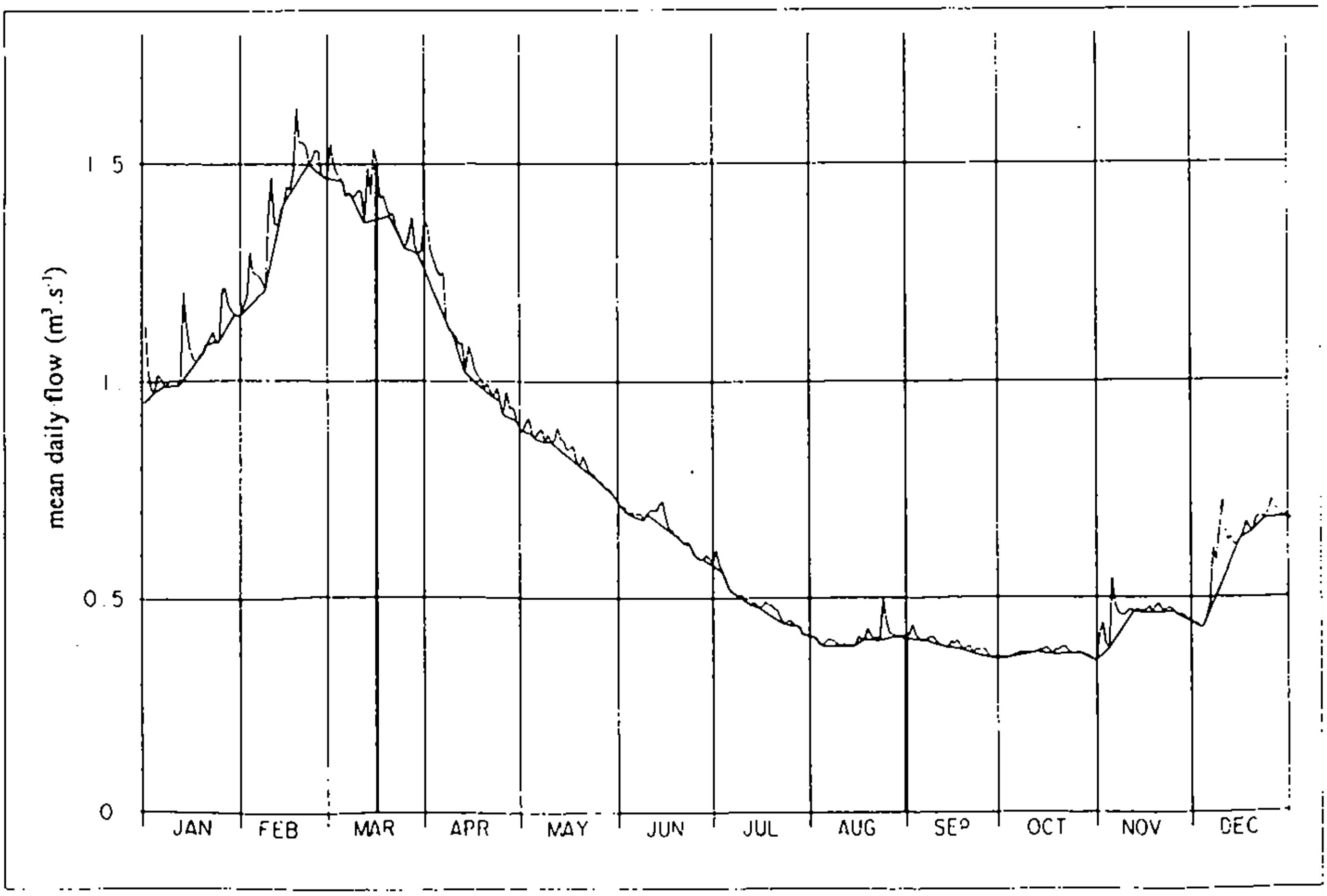


Figure A.5c Candover Stream at Borough Bridge (42009): Hydrograph with separated flow for 1975

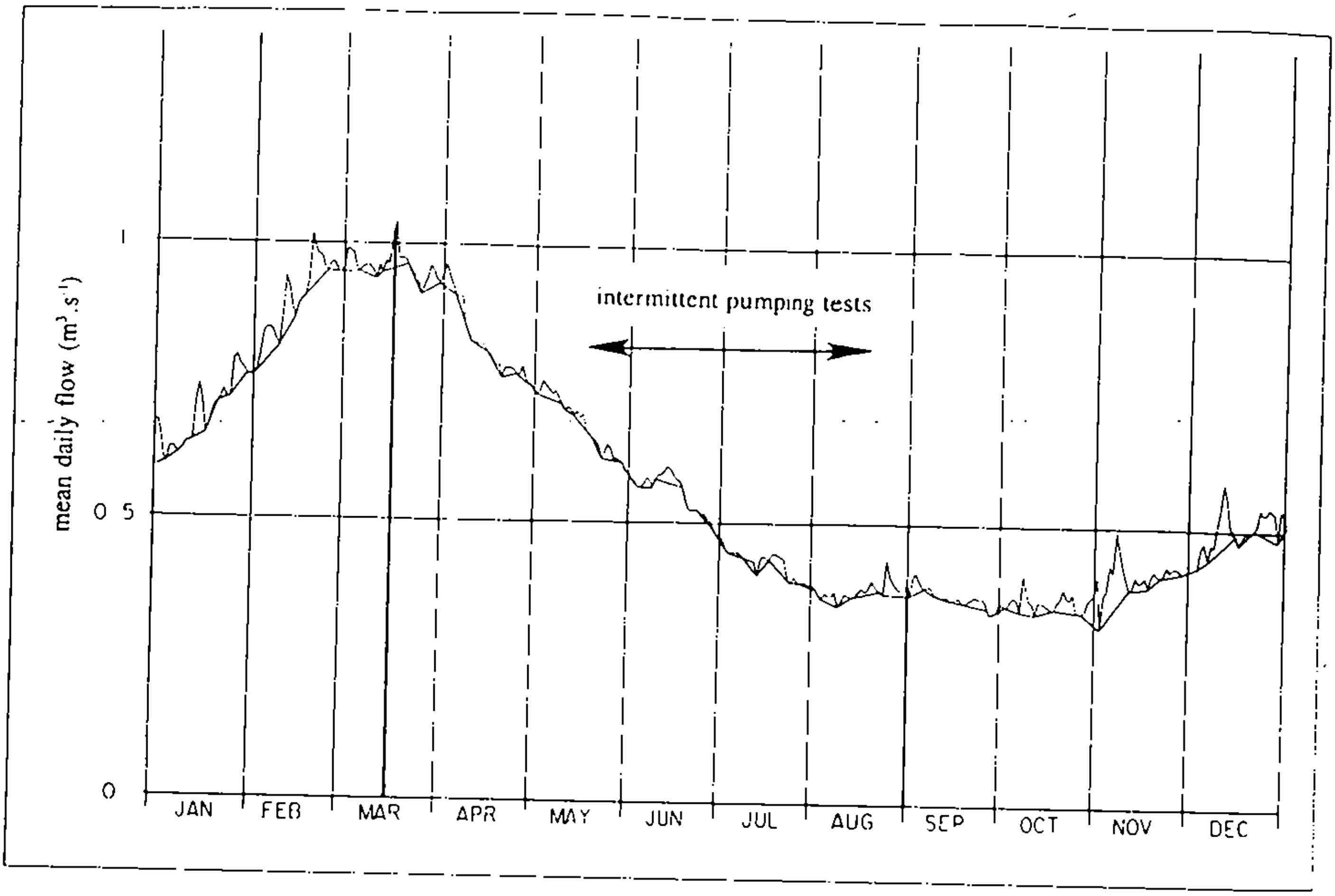


Figure A.5d Itchen at Highbridge + Allbrook (42010): Hydrograph with separated flow for 1975

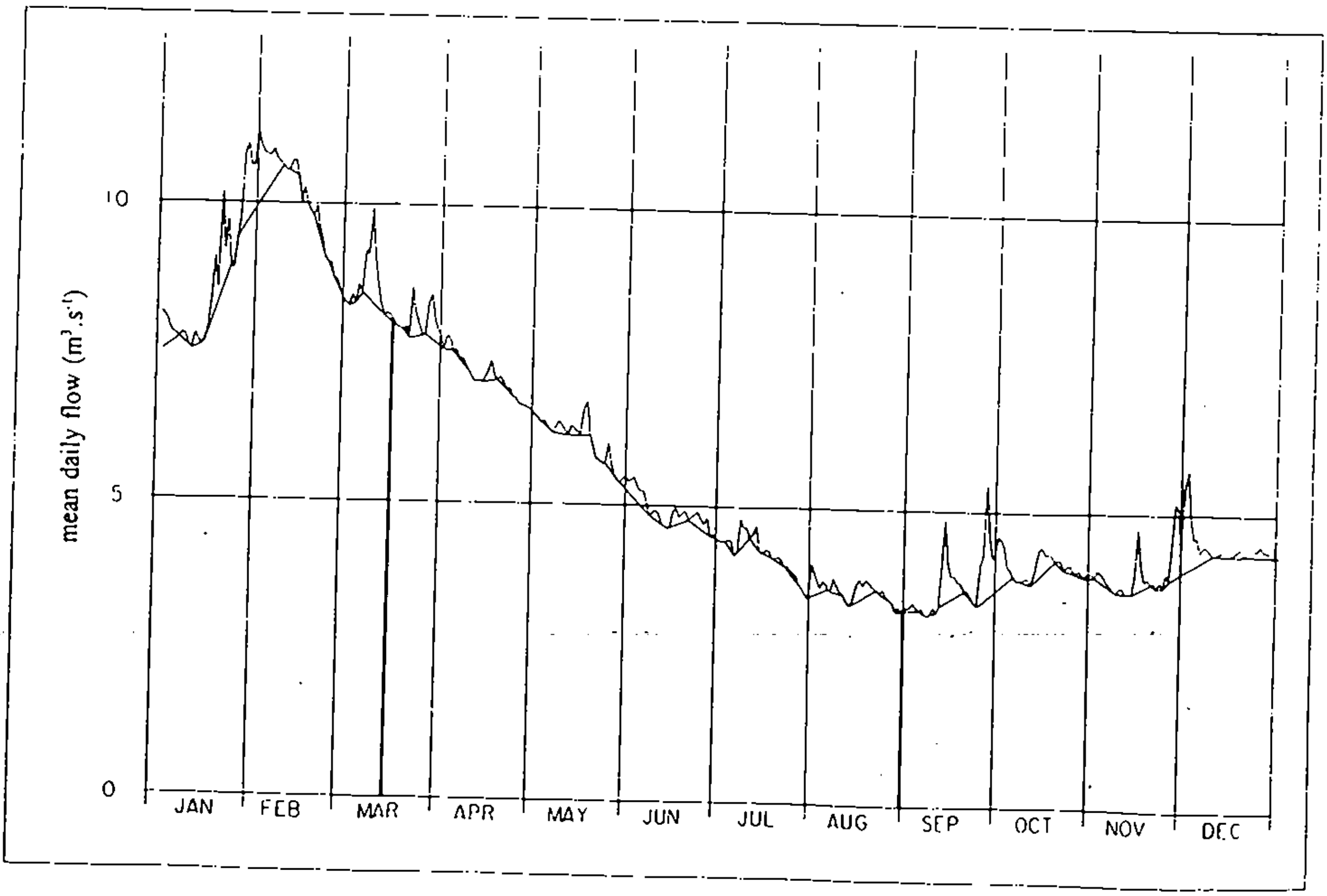


Figure A.6a Alre at Drove Lane, Alresford (42007): Hydrograph with separated flow for 1976

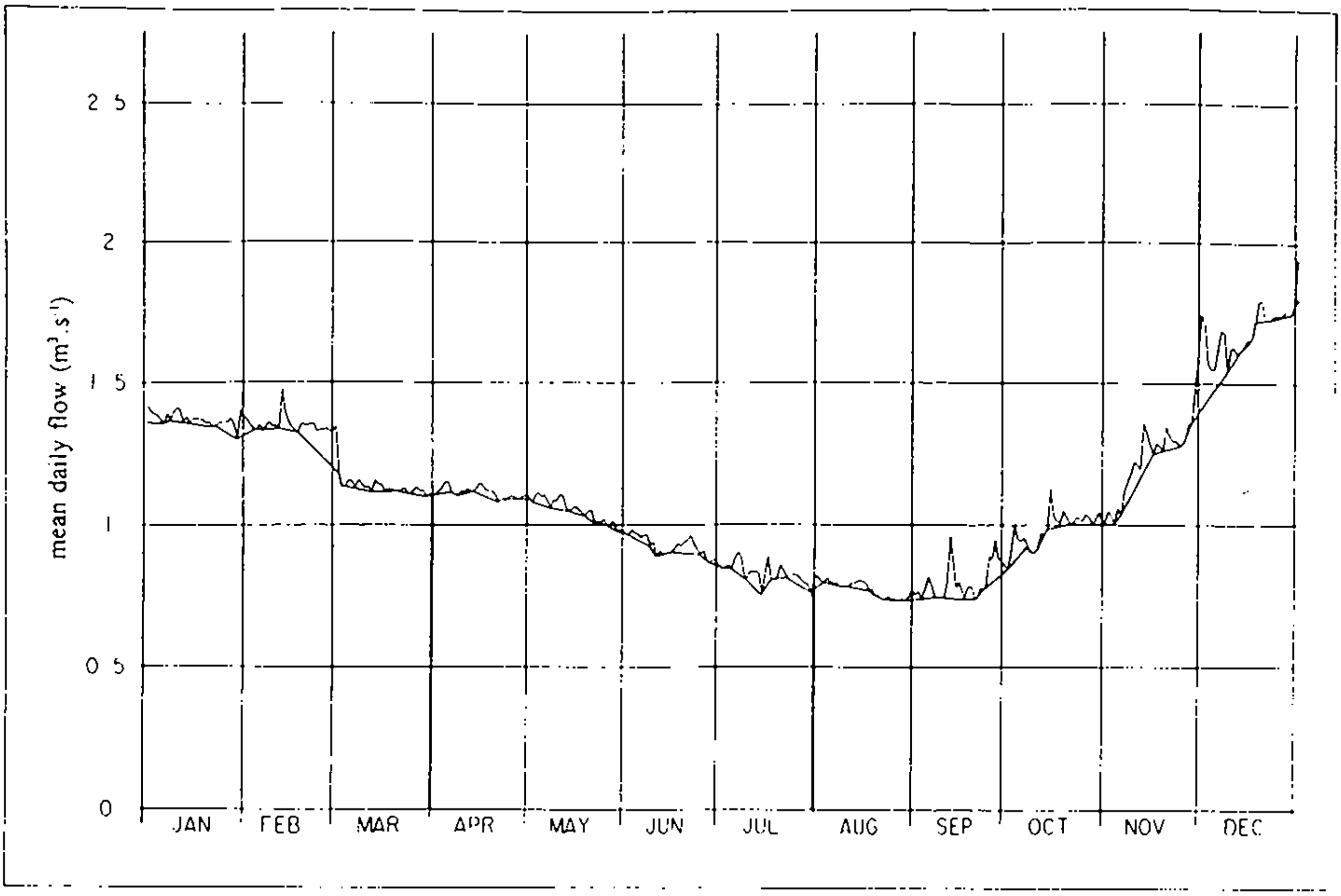


Figure A.6b Cheriton Stream at Sewards Bridge (42008): Hydrograph with separated flow for 1976

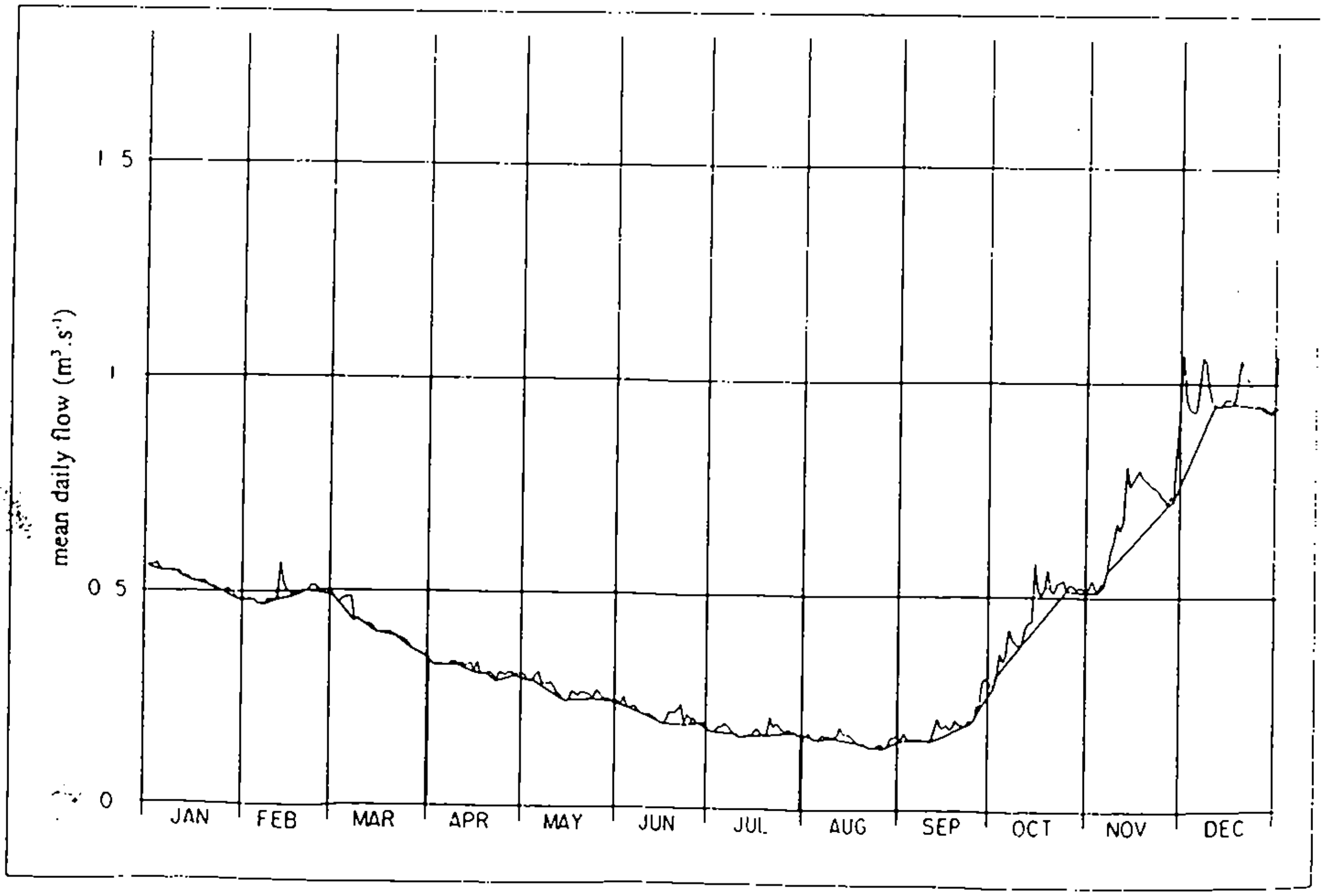


Figure A.6c Candover Stream at Borough Bridge (42009): Hydrograph with separated flow for 1976

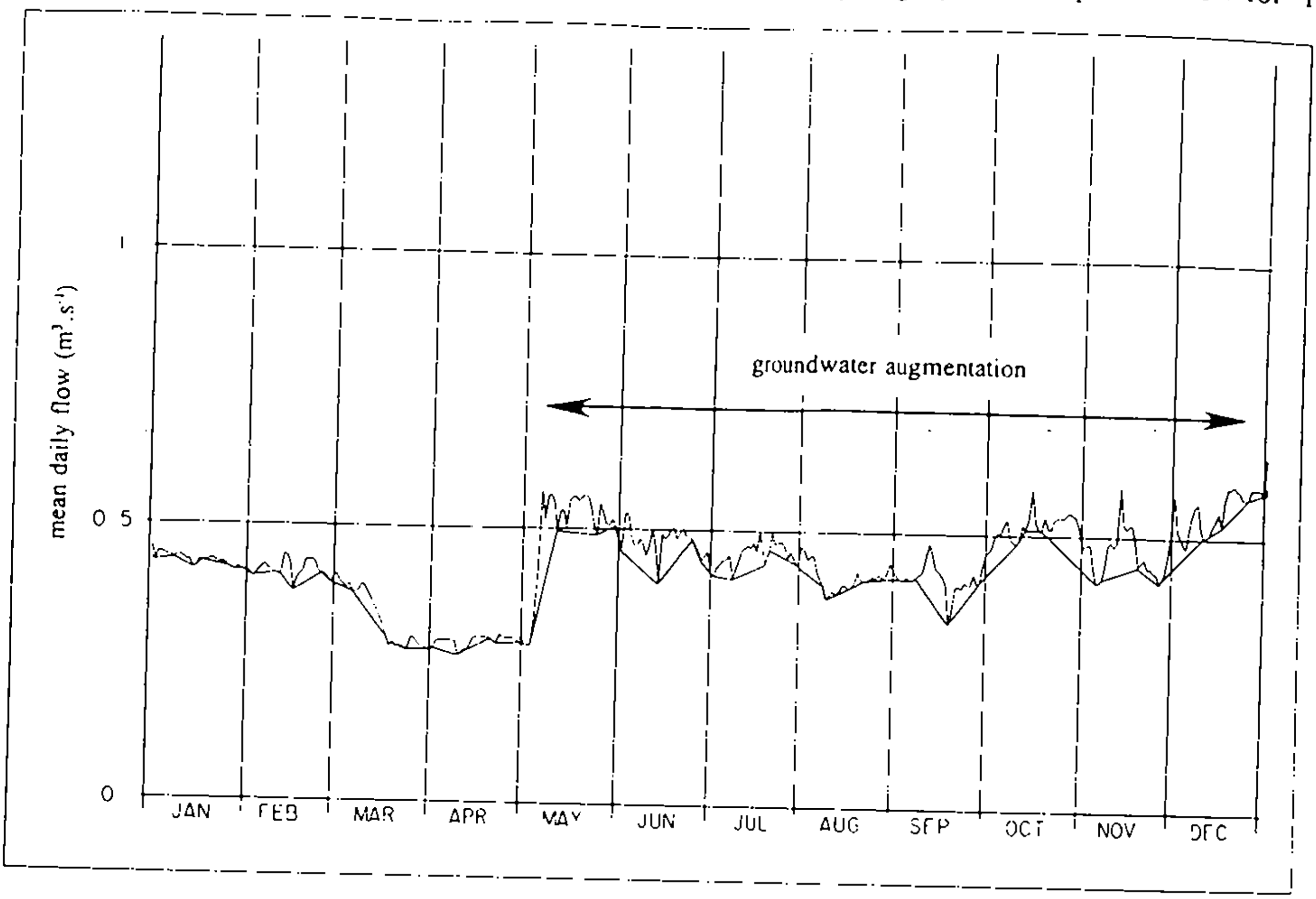


Figure A.6d Itchen at Highbridge + Allbrook (42010): Hydrograph with separated flow for 1976

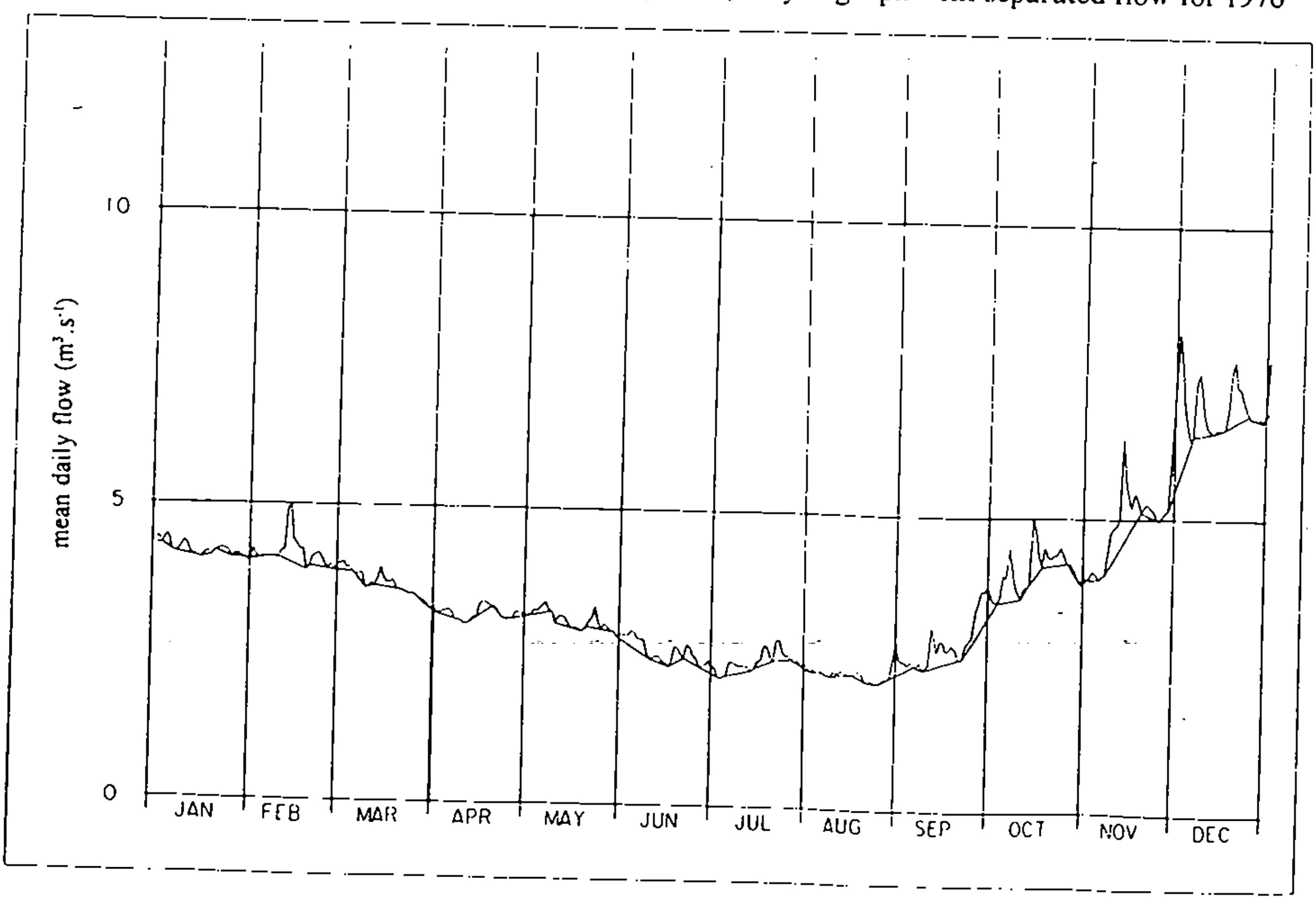


Figure A.7a Alre at Drove Lane, Alresford (42007): Hydrograph with separated flow for 1988

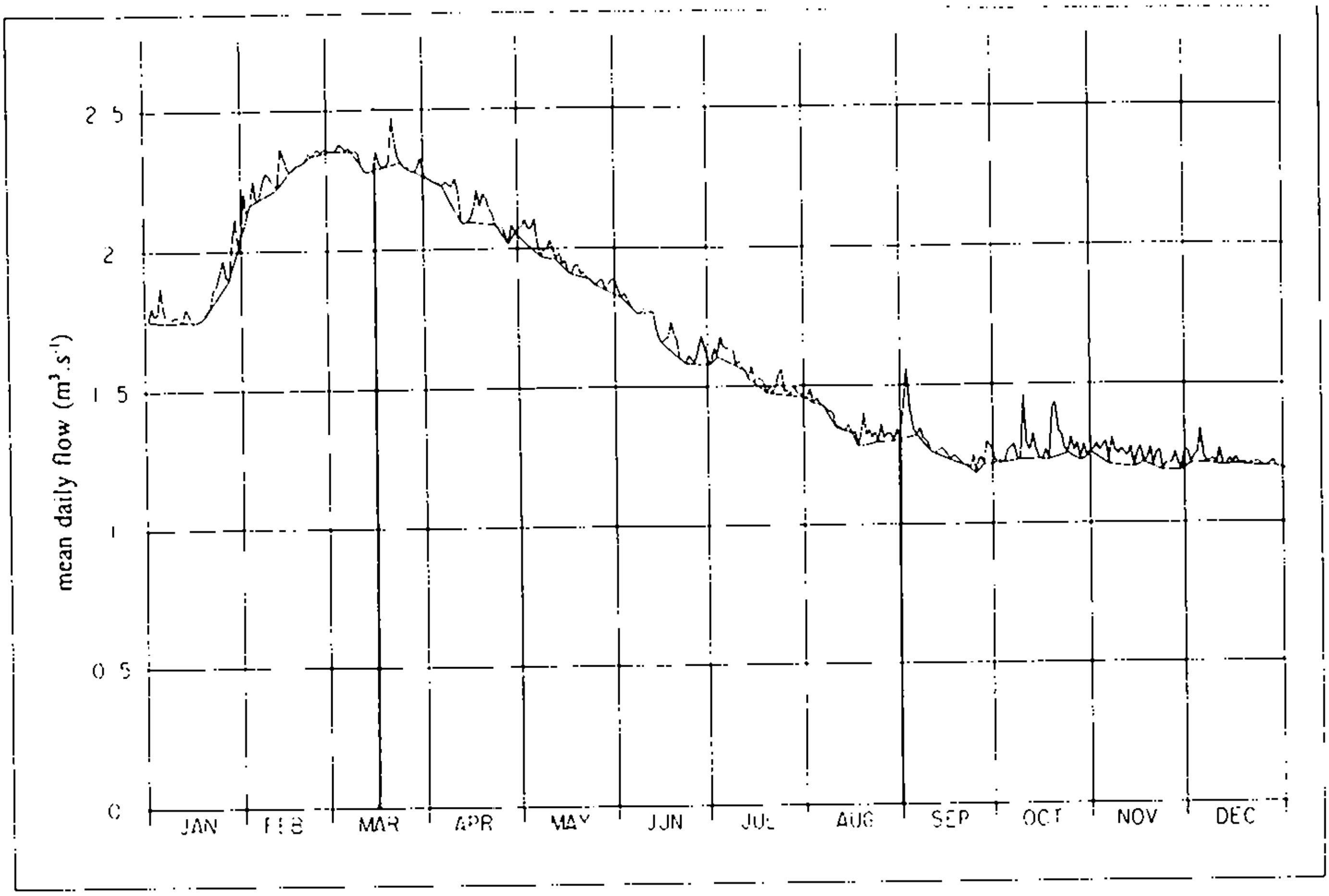


Figure A.7b Cheriton Stream at Sewards Bridge (42008): Hydrograph with separated flow for 1988

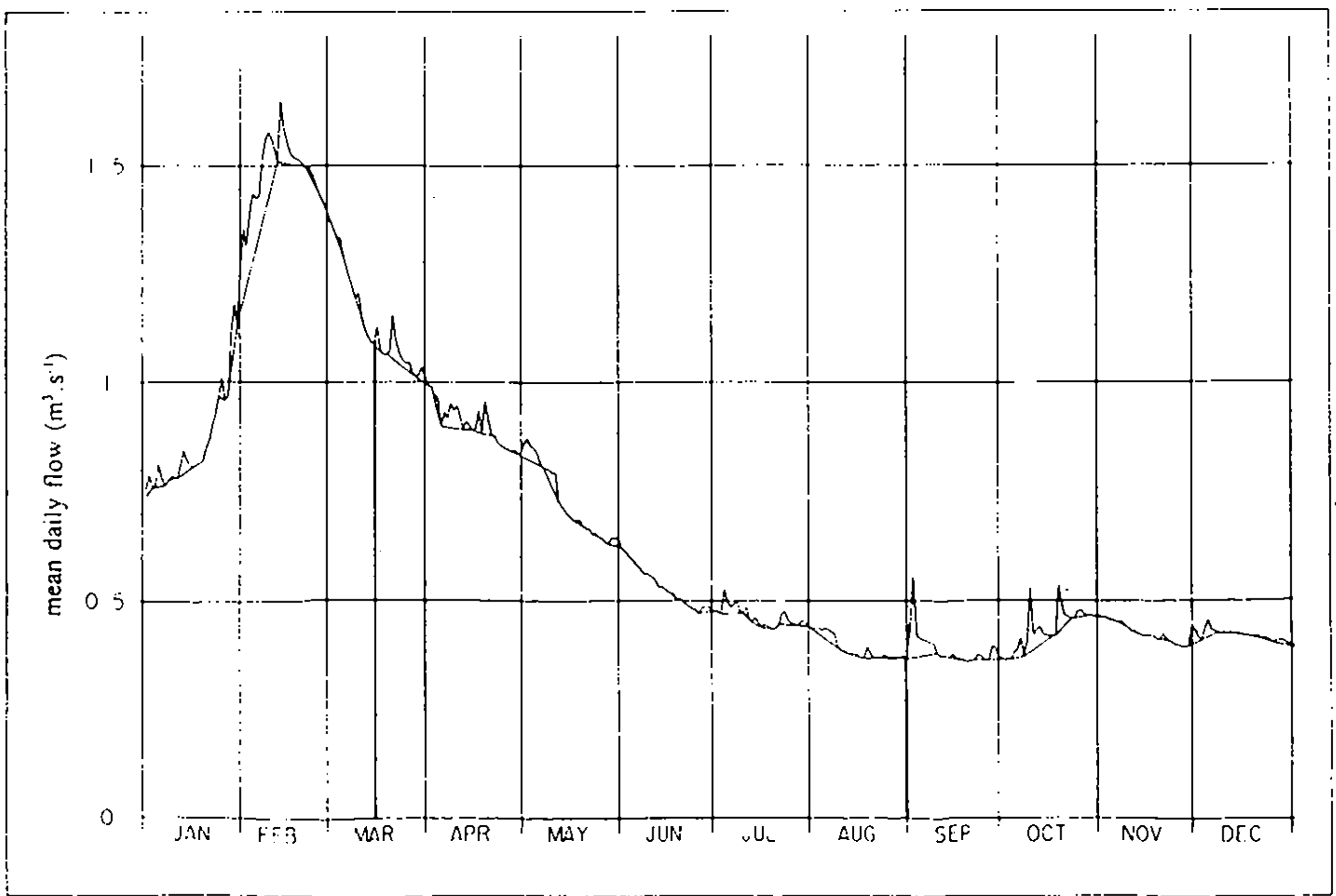


Figure A.7c Candover Stream at Borough Bridge (42009): Hydrograph with separated flow for 1988

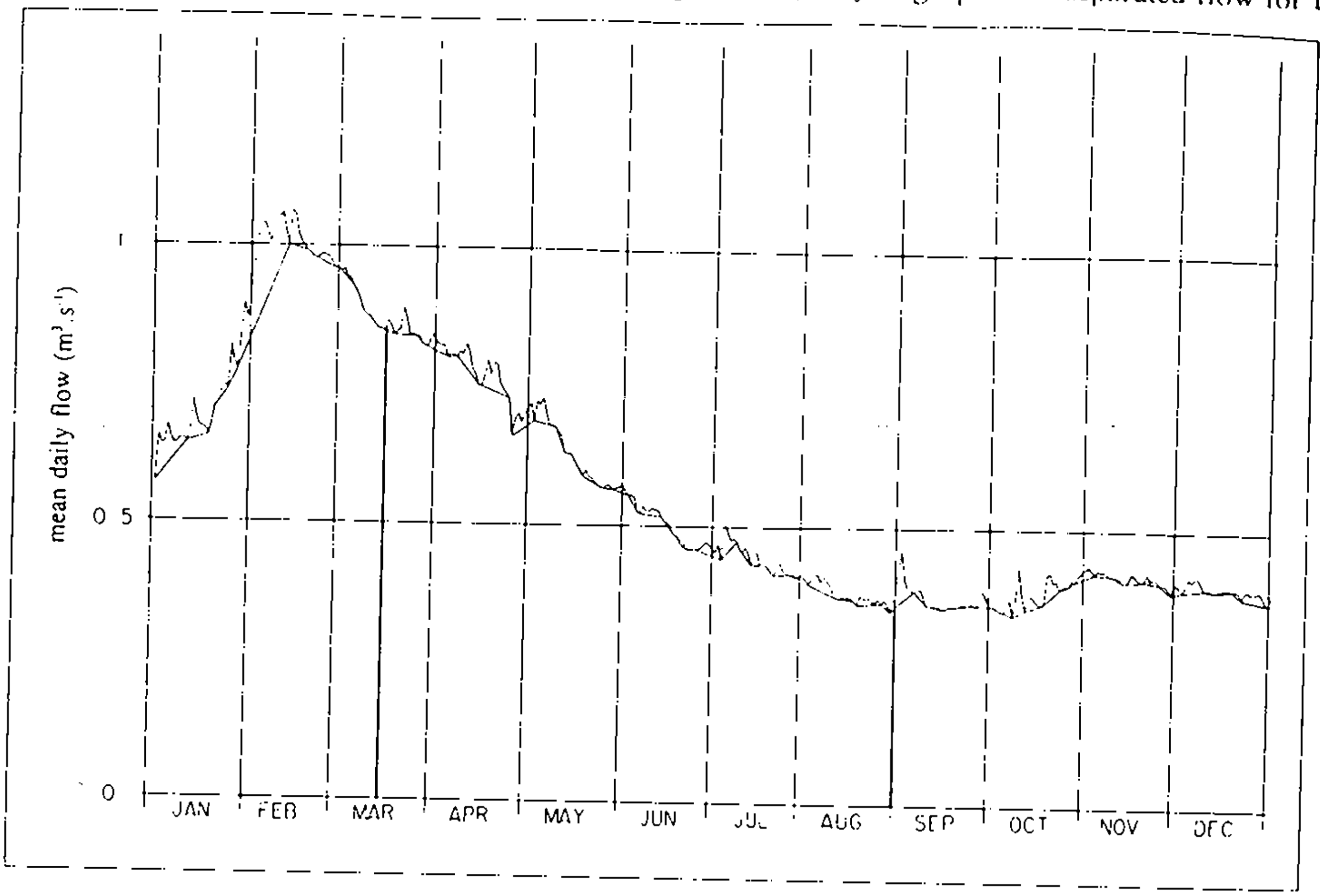


Figure A.7d Itchen at Highbridge + Allbrook (42010): Hydrograph with separated flow for 1988

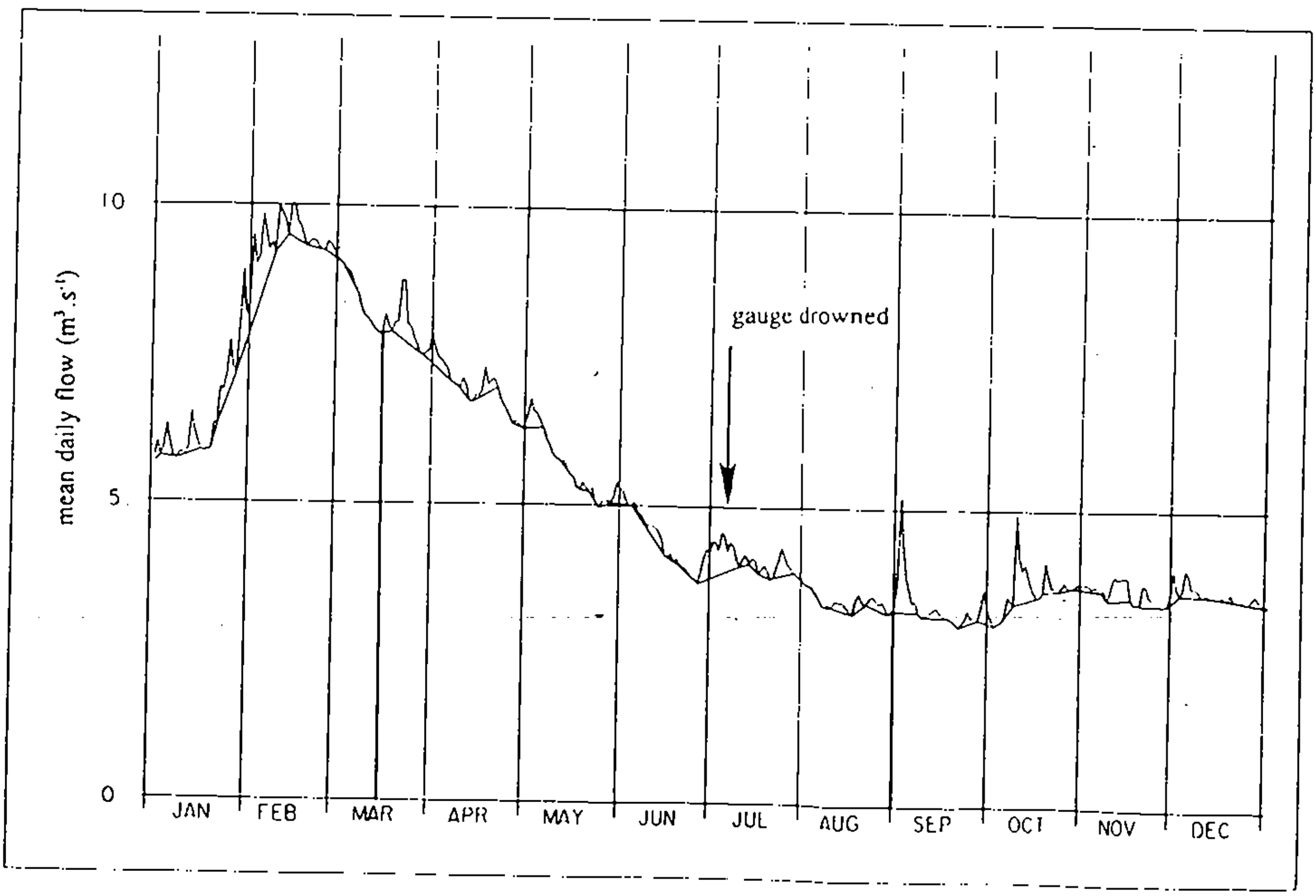


Figure A.8a Alre at Drove Lane, Alresford (42007): Hydrograph with separated flow for 1989

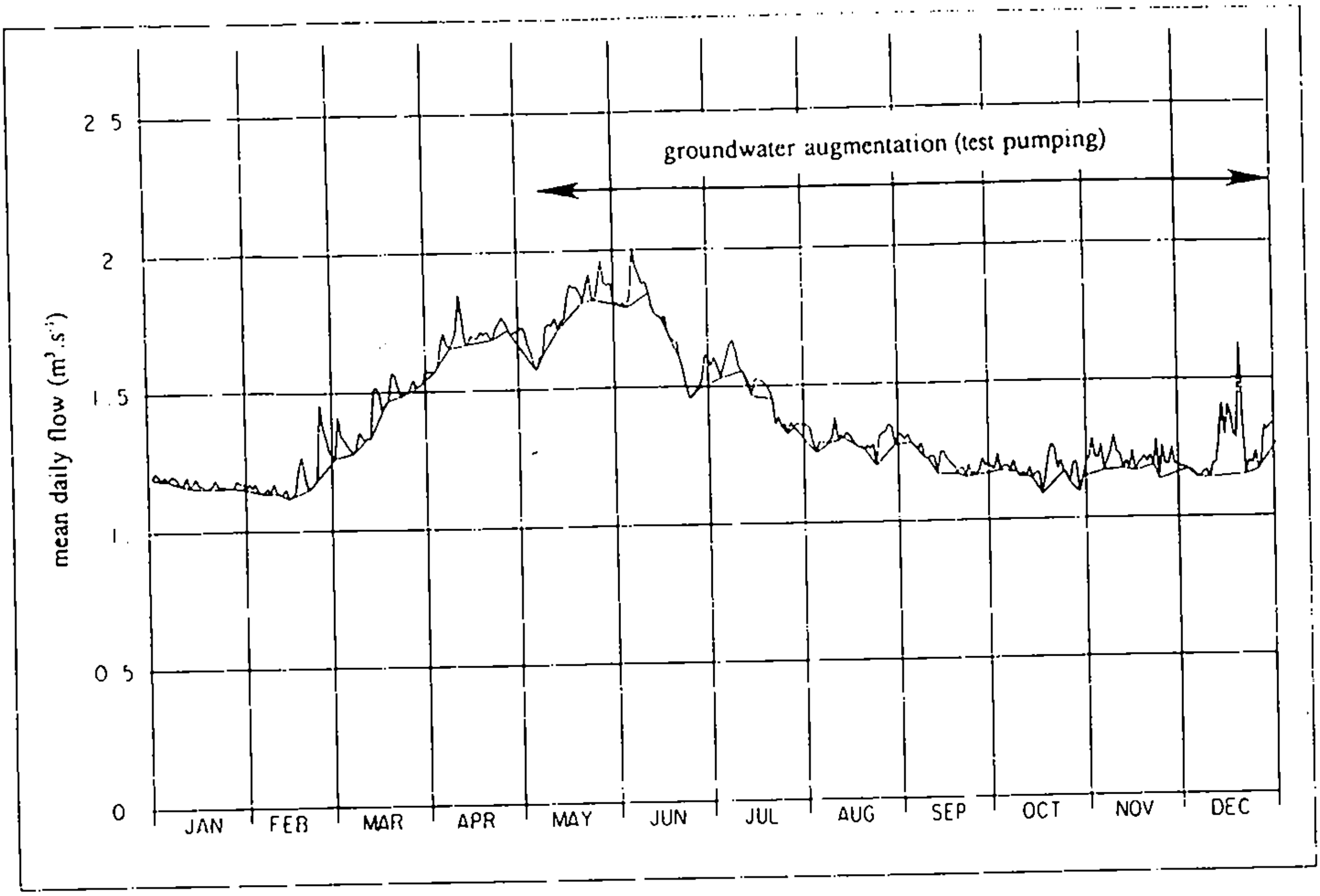


Figure A.8b Cheriton Stream at Sewards Bridge (42008): Hydrograph with separated flow for 1989

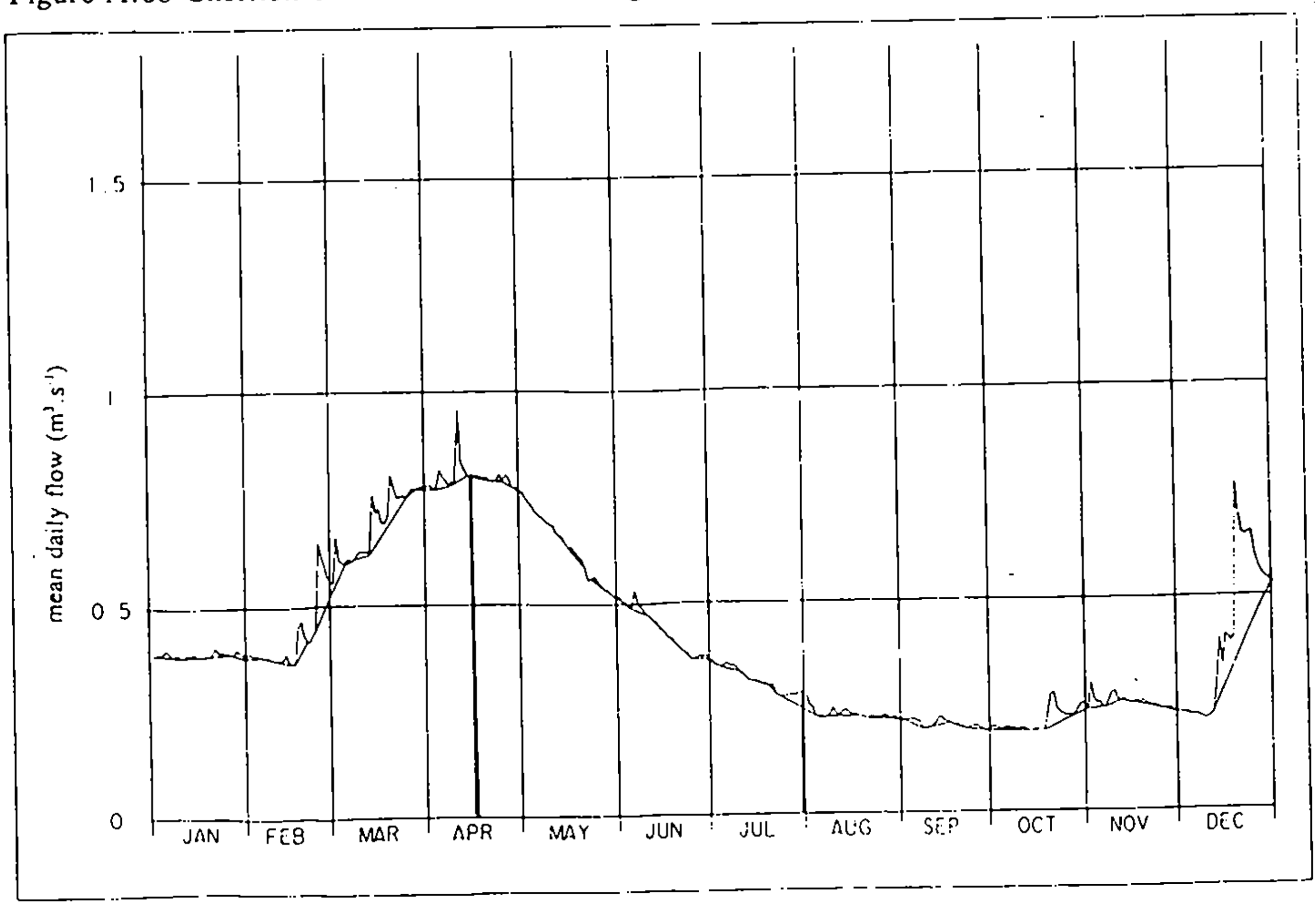


Figure A.8c Candover Stream at Borough Bridge (42009): Hydrograph with separated flow for 1[illegible]

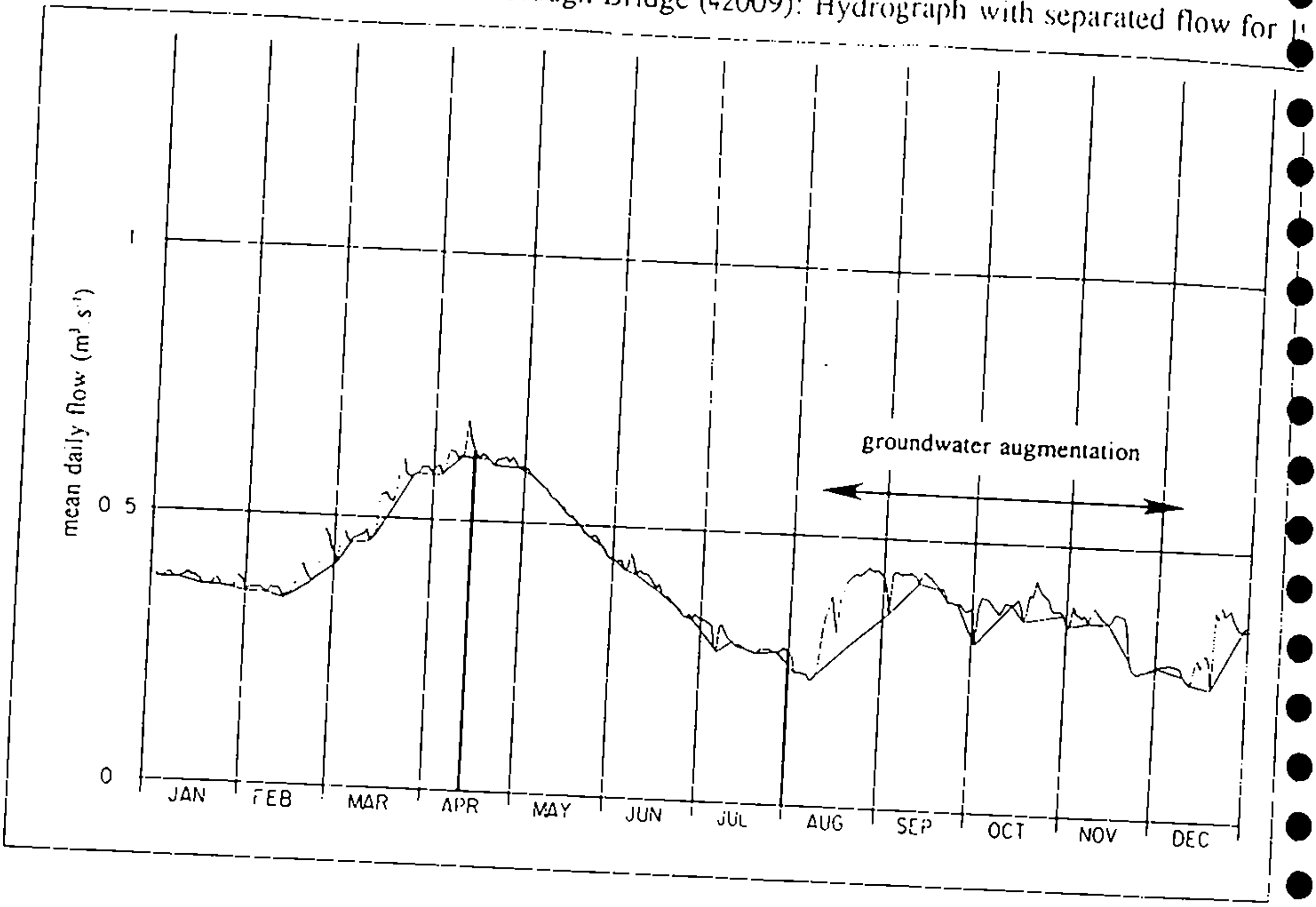
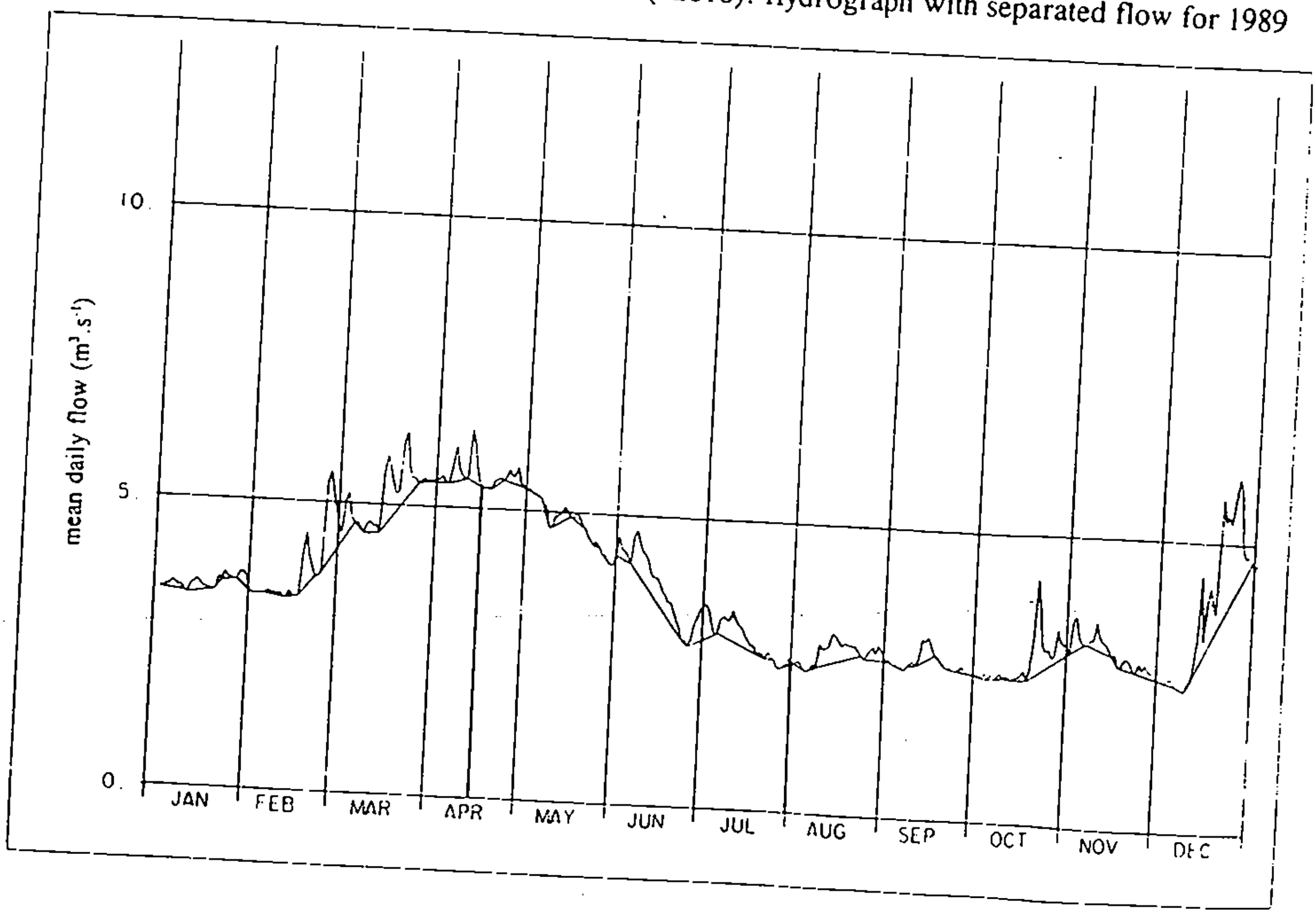
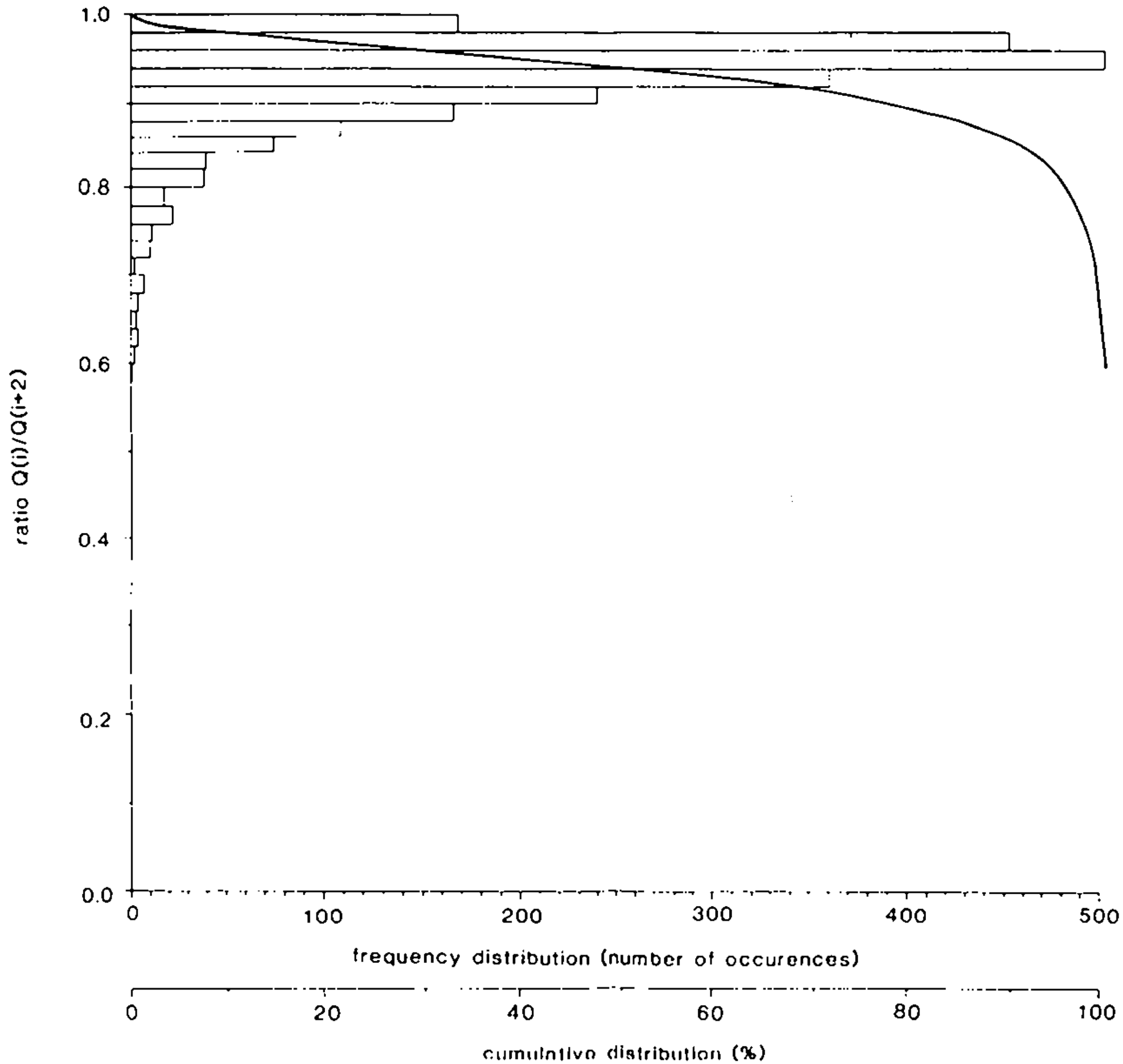
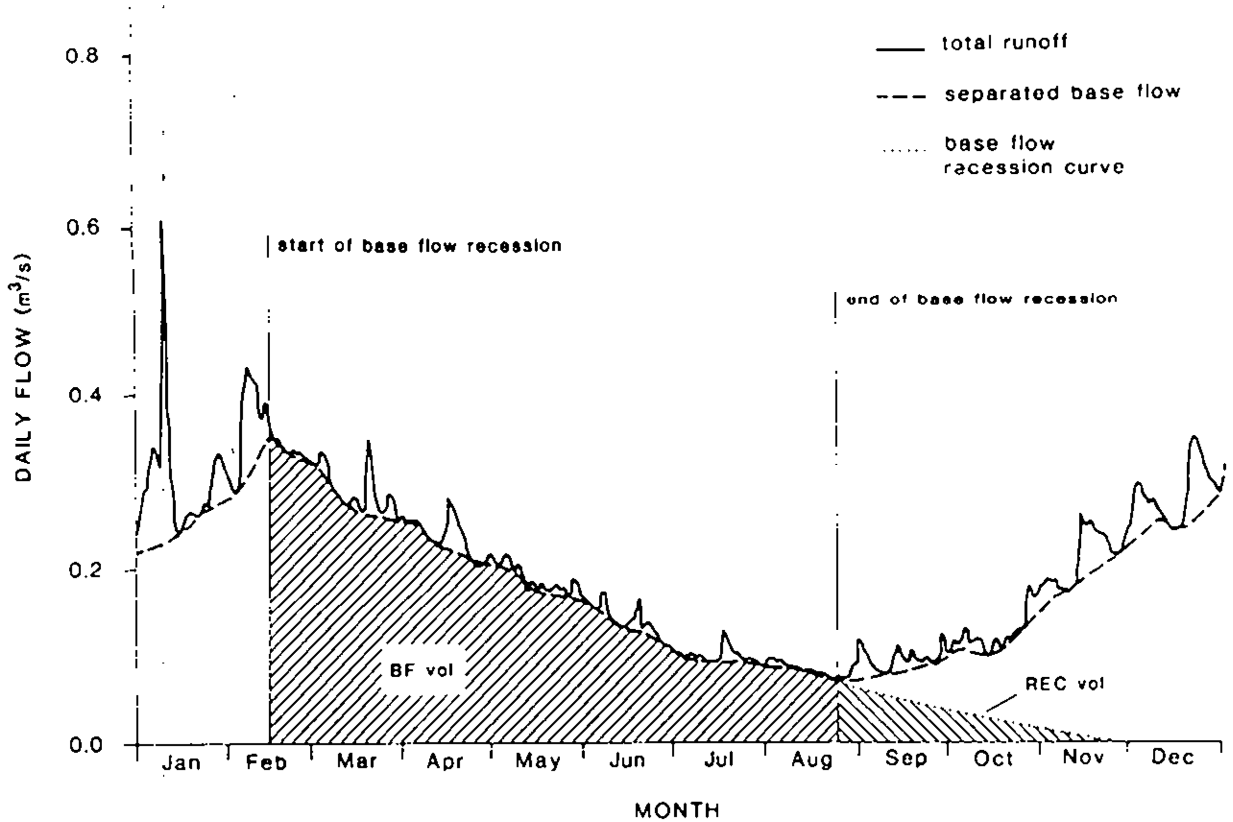


Figure A.8d Itchen at Highbridge+Allbrook (42010): Hydrograph with separated flow for 1989




ratio Q(i)/Q(i+2)
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
frequency distribution (number of occurences)
0
20
40
60
80
100
cumulative distribution (%)


total runoff
separated base flow
base flow recession curve
start of base flow recession
end of base flow recession
DAILY FLOW (m³/s)
0.8
0.6
0.4
0.2
0.0
BF vol
REC vol
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
MONTH