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Reconstructed river flow series from 1860s to present

Updating previously reconstructed series to 2002

Science Report SC040052/SR

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EXECUTIVE SUMMARY

Riverflow records in the UK are generally relatively short in length, many beginning in the late-1950s. Rainfall records, in contrast, are numerous with many extending back into the early decades of the 19th century. In the early-1980s, work began to extend riverflow records for a number of catchments using a simple rainfall-runoff model. The earliest work was funded by the Natural Environment Research Council and updated in the 1990s for the National Rivers Authority (NRA) and the Environment Agency (EA). The principal results indicated that long and reliable reconstructions could be achieved provided the catchment rainfall averages were homogeneous. The present report extends the reconstructions to 2002. Comparisons with observed flows for 1980-2002 imply that land-use changes are having little effect on flows, at least at the monthly timestep. Such reconstructions should prove useful in updating naturalised flow series on some catchments.

The principal difficulty with undertaking the updating of the monthly flow records has been in obtaining the necessary monthly rainfall and flow records for the last 8-10 years. Our initial expectation was that these data would be available from the various EA regions. Responses to initial enquiries soon revealed that, for many catchments, the required data were not readily available. This was particularly the case for rainfall. For riverflow, naturalised as well as measured monthly averages were required but some of the naturalised series were either no longer available or new (and different from those available in the mid-1990s) ones had been introduced. In addition, some difficulty was experienced in trying to get hold of relevant metadata to complement the flow series (naturalised and measured) that were supplied.

To complete the project on schedule we had to consider alternatives. We obtained a daily gridded (at 5km resolution) rainfall dataset, recently developed at the Met Office (MetO). This covers the period 1958-2002 and includes all of the standard meteorological variables. Whether the dataset will be regularly updated is not known, but the entire dataset would seem extremely useful for many EA activities and research projects. We also obtained monthly catchment rainfall series from the Centre for Ecology and Hydrology (CEH, Wallingford). For riverflow, CEH also supplied monthly observed (and where available naturalised) series. This report, therefore, additionally includes comparisons of the series obtained from the various sources for monthly rainfall totals (NRA/EA from the original work, CEH and MetO) and monthly riverflow averages (earlier NRA/EA, CEH and new EA). A clear recommendation from this study is for an extensive review of the EA's data archiving, involving discussions with the Met Office and CEH.

The value of long homogeneous riverflow series is illustrated by example; with reference to the flows produced by the extreme wet period during the autumn of 2000. The hydrological extremes experienced during 2000 and 2001 are put into the context of the flow-period 1865-2002. In addition, for some of the catchments, the inadequacy of flow gauging installations under such extreme flow conditions is illustrated.

Low flows, during the 1980-2002 period, were not as unusual as the high flows. The years 1984, 1989 and especially 1995 rank in the five lowest flows since 1865 on more than one catchment, but low flows during 1870, 1887, 1921, 1933/4 and 1976 were more spatially extensive.

The principal cost in extending the work to additional catchments would involve the development of long monthly catchment rainfall series before 1958. The Met Office has extensive archives of hand-written monthly and daily rainfall data, but many series are not digitised for periods prior to 1961. Many monthly series would need to be digitised from the hand-written 10-year books held by the Met Office and then assessed for long-term homogeneity. Finally, with the newly constructed MetO daily gridded rainfall dataset, a software package could be developed to update the monthly flow series at annual intervals, provided the Met Office routinely update the high-resolution gridded rainfall dataset.

1. INTRODUCTION

The purpose of this work is to update the earlier river flow reconstructions for 15 catchments in England and Wales (Jones and Lister, 1995 and 1997). The reconstructions were developed using a statistical catchment model developed by Wright (1978). More details of the model are given in Section 2. The earlier reconstructions covered the period *c.a.* 1860 to the early/mid-1990s. The long series are also extensively discussed in Jones and Lister (1998). Some discussion of earlier extremes (cold/warm summers/winters and periods of high/low flows) is given Jones et al (1984) based on documentary sources extending back to 1556.

Most observed flow records only go back to the 1950s and these tend to suffer from problems of inhomogeneity (with regard to flow behaviour in response to rainfall events), due to increased use of water resources and the resultant increase in flow modifying activities. The production/maintenance of long homogeneous flow records is, therefore, essential to the planning of effective long-term water resource and water quality management strategies.

The homogeneity of reconstructed flow series depends upon the quality of rainfall/runoff models, their calibrations and the maintenance of homogeneous catchment rainfall series. An important component of this study is an extended evaluation of the rainfall/runoff model performance (by reference to observed flow series). Good model performance over a longer time-frame and thus potentially more varied climatic regime, will add confidence to the flow reconstruction technique and so to the resultant reconstructed flow series.

The original 15 catchments, for which reconstructed flow series were produced in the mid-1990s, were chosen to be representative of the catchments of England and Wales. It was intended that basic flow behaviour, based on statistics from the long reconstructed series, could be “transferred” to other “similar” catchments on a regional basis. The 15 catchments, along with some of their important characteristics, are shown in Figure 1.1 and Table 1.1. Table 1.2 lists the availability of naturalised records on all 15 catchments, together with the calibration periods (as used by Jones and Lister, 1995 and 1997) for the statistically-based catchment model. Of the original 15, ten catchments were chosen in the mid-1980s, with the additional five chosen in the mid-1990s. At the time, they were chosen based on the availability of long rainfall records and at least 30 years of monthly measured (and naturalised, where necessary) riverflow data, based on advice from the National Rivers Authority (NRA) regions in terms of hydrometric practice and to achieve a fairly representative coverage of England and Wales. These criteria were relaxed a little in the mid-1990s flow reconstruction work when calibration and verification periods were shorter for the five catchments concerned (see Table 1.2). As will become apparent in this report, some are now no longer as appropriate (in terms of accuracy, or availability of naturalised flow measurements) as they were.

Table 1.1 The 15 catchments with their basic characteristics

River	Flow gauge	Gauge No	NGR of gauge	Catchment area (km^2)	61-90 av. precip. (mm)	Max. elevation (m)	Mean flow (m^{3}s^{-1})	Q95 (m^{3}s^{-1})	Q10 (m^{3}s^{-1})	Comments
Tyne	Bywell	23001	45 (NZ) 038 617	2176	1015	893	45.2	6.1	102	Mainly upland
Tees	Broken Scar	25001	45 (NZ) 259 137	818	1141	893	16.9	1.8	41	Mainly upland
Wharfe	Addingham	27043	44 (SE) 092 494	427	1383	704	14.1	1.6	36	Mainly upland
Derwent	Longbridge/St. Mary's Bridge	28010 #	43 (SK) 356 363	1054	1012	636	17.8	5	37	Significant upland influence
Ely Ouse	Denver Complex	33035	53 (TF) 588 010	3430	587	167	11.8	0	29	Lowland with some g.w. input
Wensum	Costessey Mill	34004	63 (TG) 177 128	571	672	94	4	1.3	7.4	Lowland with sig. g.w. input
Thames	Eynsham	39008	42 (SP) 445 087	1616	730	330	13.8	1.1	33	Mainly lowland
Medway	Teston	40003	51 (TQ) 708 530	1256	744	267	11.2	1.5	25	Lowland
Itchen	Highbridge + Allbrook	42010	41 (SU) 467 213	360	833	208	5.4	2.9	7.9	Major g.w. input
Exe	Thorverton	45001	21 (SS) 936 016	601	1248	519	16.3	2	39	Mainly upland
Wye	Redbrook	55023	32 (SO) 528 110	4010	1011	752	74.3	11.6	175	Mainly upland
Teifi	Glan Teifi	62001	22 (SN) 244 416	894	1382	593	28.9	3	67	Mainly upland
Dee	Erbistock/Manley Hall	67015 #	33 (SJ) 348 415	1019	1369	884	31.2	5.8	71	Mainly upland
Eden	Warwick Bridge/ Great Corby	76002 #	35 (NY) 470 567	1367	1272	950	34	6.9	73	Mainly upland
Eden	Temple Sowerby	76005	35 (NY) 605 283	616	1146	950	14.4	1.9	33.4	Mainly upland

Notes: All data in Table 1.1 come from CEH's Concise Register of Gauging stations (see www.nwl.ac.uk/ih/nrfa/station_summaries/crg.html) Some values are period specific and will differ slightly from statistics given elsewhere in this Report.

These observed flow series are composite records combining the named gauges. The latter gauge is the one in current use. In the case of the Eden to Warwick Bridge/Great Corby, catchment statistics relate to Warwick Bridge.

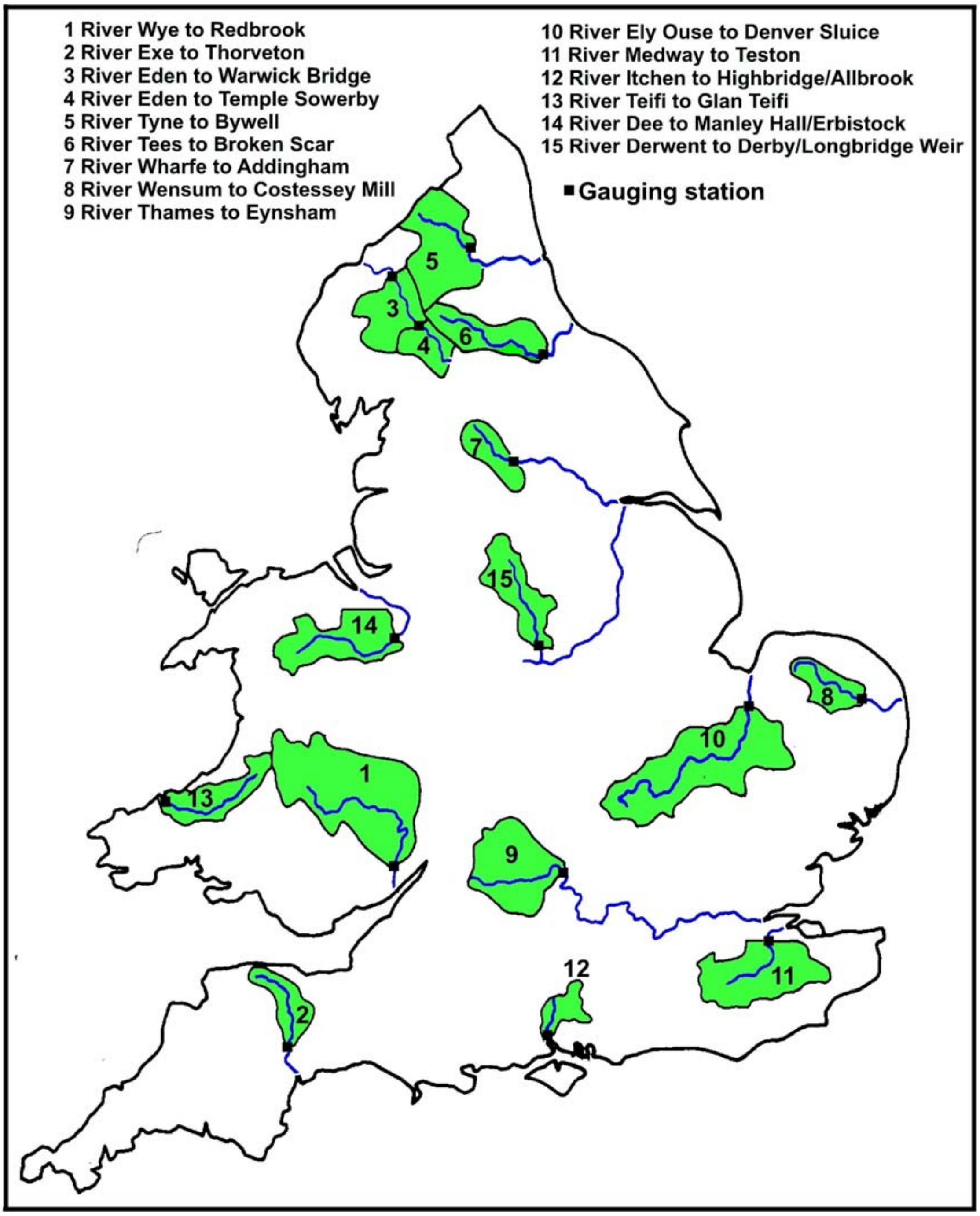

Figure 1.1 **Catchment outlines with flow gauging stations**

Table 1.2 Details relating to catchment observed-flow series (gauged and naturalised)

Catchment	Observed flows used in 1995 and 1997 reconstructions	Observed (gauged) flows obtained for the current work	Naturalised flows obtained for the current work	Calibration periods (original parameter estimation)
Tyne	1956-93 (NRA)	1956-2003 (CEH) 1957-2003 (EA)	1956-1993 (CEH) [7]	1962-1977 [9]
Tees [5]	1956-93 (NRA)	1956-2002 (CEH) 1982-2003 (EA)	1956-1993 (CEH) [7]	1957-1971 [9]
Wharfe [2]	1962-93 (NRA)	1973-2002 (CEH) 1974-2003 (EA)	1995-2000 (EA)	1964-1977 [9]
Derwent	1977-93 (NRA) [6]	1935-2003 (CEH) 1935-2003 (EA)	1977-1997 (EA)	1977-1993 [10]
Ely Ouse [4]	1926-93 (NRA)	1959-1976 (CEH) 1950-2003 (EA)	1958-1975 (CEH) 1980-2002 (EA)	1962-1977 [9]
Wensum [5]	1960-93 (NRA) [6a]	1960-2002 (CEH) 1961-2003 (EA)		1964-1974 [9]
Thames [1]	1954-93 (NRA)	1951-2002 (CEH) 1955-2003 (EA)	1951-2002 (CEH) 1955-2003 (EA)	1964-1976 [9]
Medway [3]	1957-94 (NRA) [6]	1956-2003 (CEH)	1956-1977 (CEH) 1920-1996 (EA) [8]	1970-1993 [10]
Itchen [3]	1959-88 (NRA) [6]	1958-2003 (CEH) 1959-2003 (EA)	1970-2000 (EA) [8]	1969-1988 [10]
Exe	1956-93 (NRA)	1956-2003 (CEH) 1957-2003 (EA)		1958-1977 [9]
Wye [2]	1937-93 (NRA)	1936-2003 (CEH) 1970-2003 (EA)		1956-1975 [9]
Teifi	1959-95 (NRA)	1959-2003 (CEH) 1960-2003 (EA)		1971-1994 [10]
Dee [1]	1970-89 (NRA) [6]	1937-2003 (CEH) 1970-2003 (EA)	1969-2001 (CEH) 1986-2002 (EA)	1970-1989 [10]
Eden1 (to TS) [1,2]	1965-93 (NRA)	1964-2002 (CEH) 1976-2003 (EA)		1965-1977 [9]
Eden2 (to WB) [2]	1967-93 (NRA)	1959-1998 (CEH) 1960-1996 (EA)		1967-1977 [9]

Notes: For more details relating to the above series, see Annex 1.

[1] Potential for inaccuracies in flow gauging at very high flows
[2] Changes made/expected in flow series due to rating changes
[3] Naturalisation methods have changed with potential problems for reconstruction-model calibration parameters
[4] Doubts regarding the homogeneity of flow series
[5] Gauged flow series are in need of naturalisation
[6] Naturalised series were used for reconstruction-model calibration
[6a] A partially naturalised series was used during the 1995 flow reconstructions
[7] There are significant missing periods within the naturalised series
[8] Different naturalised series have superseded those used in earlier work (see [3])
[9] For more details of calibrations, see Jones, 1984
[10] For more details of calibrations, see Jones and Lister, 1997

2. FLOW RECONSTRUCTION METHOD

Few catchment models have been specifically developed for riverflow reconstruction. Exceptions are the conceptual models of Porter and McMahon (1971) and Manley (1978), and the empirical model developed by Wright (1978), at the Central Water Planning Unit (CWPU), used in this study. Two versions of Wright's model are available, depending on the time base, monthly or daily. In the version used here, values of the logarithms of mean monthly riverflow are related to linear combinations of data on soil moisture and effective precipitation (precipitation minus actual evaporation) by regression techniques. The monthly model is described in detail in Jones (1983). Both the latter paper and Jones (1984) are included as Appendix C in the earlier Jones and Lister (1995) report.

The monthly incremental time-step of the model (used here) is one of the principal reasons for its simplicity of operation. The monthly time-step, however, can lead to (short-term) erroneous model output (reconstructed flow) in cold winter periods unless precipitation is stored as a snowpack until thaw conditions prevail. The model can be run in conjunction with a daily temperature database, which allows for the build-up and thawing of snowpacks, and thus allows a readjustment of the timing of the arrival of precipitation into the catchment flow networks. For consistency with Jones and Lister (1995, 1997) the use of this model component has not been incorporated in the present updating of the reconstructed flow series. However, significant snowpacks only occur in particularly cold winters; usually in the more upland parts of catchments in northern England. The relatively long run of mild winters in the UK means that the absence of the daily temperature model function has had minimal effect.

The model is straightforward to calibrate, the relationships between rainfall and riverflow being determined by regression techniques. The principal inputs required by the model are monthly time series of catchment areal precipitation estimates. The model additionally uses constant monthly values of actual evaporation (AE) based on long-term averages, rather than variable estimates of potential evapotranspiration (PET) calculated, for example, using Penman's (1948) method. Wright (1978) argues that the use of these seasonally constant values leads to more accurate modelling of riverflow than estimating actual evaporation by methods such as described by Thom and Ledger (1976). A study by Burt and Shahgedanova (1998) using long-term observations for Oxford suggests increases in PET since 1815. MORECS data for 1961-2002 would also suggest increases again for PET. Roderick and Farquhar (2002), in contrast, report global-scale decreases of pan evaporation over the last 50 years, so AE trends may not follow those of PET. The modelling accuracy achieved by Jones (1984), Jones and Lister (1995, 1997, 1998) and this study, particularly in independent verifications, is further justification of the use of seasonally-constant AE values. Additional support for the relative constancy of AE comes from Marsh (2001).

The current modelling exercise has used the same calibration parameters as those calculated/used in the earlier flow reconstruction exercises (Jones 1983, Jones 1984 and Jones and Lister 1997). This is important to the maintenance of homogeneity of reconstructed flow series. In all cases (during the earlier work), where the availability of observed flow data permitted, an independent verification period was used, in addition to the calibration period, for model validation purposes. The current work has enabled us to extend the previous model validation periods. The extension of validation periods has further tested the model under a wider range of climatic conditions. Drought and low flows were very much a feature of the earlier work. Recent high rainfall periods have ‘exposed’ the model to extreme flood conditions (see Section 5).

3. CATCHMENT RAINFALL SERIES

During all previous flow reconstruction work (e.g. Jones 1984), catchment (areal) rainfall was based on a stable network of rain gauges, for all catchments. Stability is essential for the maintenance of homogeneity in areal rainfall calculations. Flow reconstruction model calibrations rely upon the homogeneity of rainfall and flow series so that flow reconstructions outside the calibration period range are reliable.

Stable networks were difficult to maintain during the updating exercise that took place in 1994 (Jones and Lister, 1995, 1997, 1998), due to the closures of many raingauge stations. To maintain catchment networks when a gauge closes, it is necessary to find another current record that is within a reasonable distance of the former. The new record can then be appended provided parallel records for a sufficient length of time are available to allow the adjustment of one record to that of the other (*via* scaling with respect to long-term annual averages).

At the beginning of the current flow reconstruction work, requests were made to the EA for updates to all previously used rainfall records. Early replies indicated that it was going to be impossible to maintain anything like the original catchment raingauge networks. The pace of change, with regard to UK rain gauge network, appears to have accelerated in recent years. Alternative strategies were therefore invoked to enable updating of catchment rainfall series to 2001/2002, whilst maintaining homogeneity.

Two options became available. CEH maintain catchment/ sub-catchment rainfall series for most river basins in the UK. At the time of request, CEH areal rainfall series were updated to the end of 2001. CEH were able to supply series for all 15 study catchments offering series (produced by the Met. Office), based on key raingauges on or near the catchment. However, due to the large-scale loss of key gauges by 1986, the Voronoi (a variant of the more well-known Thiessen polygon method) approach (which uses all available raingauges) has been used after 1986 (Terry Marsh, CEH, *pers. comm.*). CEH also supplied areal series that were wholly based on the Voronoi approach and began in 1961. We found, during sample comparisons, that the two (key to 1986 then Voroni from 1987 and solely Voronoi) series were very similar. We opted to further test the series based wholly on the Voronoi approach, in the belief that these may be marginally better with regard to homogeneity, as they have been produced in a consistent manner throughout their length.

The other option for extending our catchment rainfall series came *via* 5km x 5km gridded rainfall files that have been produced by the Met Office (henceforth MetO). These daily files begin in 1958 and are currently available to the end of 2002. Details of the production of the gridded time-series are in the form of an, as yet, unpublished report by Matthew Perry and Daniel Hollis, Met Office, Exeter (John Caesar, *pers. comm.*). All rainfall data available to the Met Office were used, with interpolation to the high-resolution grid, additionally incorporating latitude/longitude/elevation and distance from the coast.

We were able to extract from the MetO dataset individual grid-box series by catchment. By choosing the grid boxes that contained our original (1995 and 1997) raingauge locations, we were able to follow more closely the original methodology, which used the following equation to produce catchment areal rainfall. The base periods 1941-70 and 1916-50 were used in the original work, so were maintained here. For the current work, grid-box series are treated as gauge series.

$$ACC = \frac{1}{N}\sum_{i=1}^{N}\frac{AAAR}{AAR_i}g_i$$

where, g_i is the monthly total at gauge i of N gauges,
AAR_i is the 1941-70 annual average rainfall at gauge i ,
$AAAR$ is the 1916-50 areal annual average rainfall for a catchment (derived by the Met Office in the 1960s) and
ACC will be the monthly average catchment rainfall

Catchment areal average rainfall series produced with this method and CEH's Voroni determinations were compared with the overlap rainfall series from the previous work (overlap 1961-1993 or 1995). Catchment averages from the earlier (NRA/EA) work (e.g. Jones and Lister, 1995, 1997 and 1998) showed the best agreement with the series produced from the MetO data. Not all of the rainfall series produced from the 5km x 5km (MetO) files were closer to the original NRA/EA series, but the majority were. We opted for consistency by choosing the MetO dataset and the above equation for the production of all areal rainfall series. In addition, the use of these series allows the flow reconstructions to run through to the end of 2002 – a year longer than would have been possible with the CEH series.

For a more detailed appraisal of the evidence that determined the outcome of our areal rainfall series comparisons, see Figure A2.1. Here time series of annual totals, on a catchment by catchment basis, show the NRA/EA, MetO and CEH series. Double-mass plots could have been used, but those in Figure A2.1 are more informative. The plots for, in particular, the Tyne to Bywell, the Tees to Broken Scar, the Thames to Eynsham and the Ely Ouse to Denver Complex, show that the MetO data are closer to the NRA/EA than the CEH series. There is no notable problem with regard to the MetO series on any of the study catchments.

In addition, a similar exercise has been undertaken for winter (DJF) and summer (JJA) rainfall (Figures A2.2&.3). The closer fit of the MetO series for, notably, the Tyne, Tees, Thames and Ely Ouse is again evident. Table 3.1 compares the NRA/EA, CEH, and MetO areal rainfall series in terms of the annual average, maximum, minimum and standard deviation (calculated over the period 1961-1993). The choice of the MetO rainfall series, over those from CEH, is a direct result of our ability to follow the original methodology in constructing the areal rainfall series. We are not in a position to say which of the series more accurately reflects the true catchment rainfall, but the more important consideration is the maintenance of homogeneity. The catchment rainfall/runoff model has been tuned (by regression) to the series used in the earlier NRA/EA work (Jones and Lister, 1995, 1997 and 1998), so on this basis alone, the MetO data should produce more reliable and homogeneous runoff series.

After calculating the catchment areal rainfall series, there is one further step required in order to maintain the consistency (with regard to calibration periods) of the new rainfall series, and thus reconstructed flows. This is scaling (where necessary) of the MetO monthly areal rainfall series; so as to maintain the same period average as the NRA/EA areal rainfall series used earlier, during their overlap. Figure A2.4 shows these comparisons. Table 3.2 shows the catchments where scaling of the new monthly rainfall series was deemed necessary. All scaling factors (calculated based on annual average data) only adjust the MetO series by between ± 1 and 3%. In addition, the time-series comparisons in Figure A4.4 serve as a further homogeneity test for the new rainfall series. Any significant differences would be visible in these plots.

Table 3.1 Descriptive statistics for the three annual rainfall series (mm) 1961-1993

Catchment rainfall	Minimum	Maximum	Mean	St. Dev. Annual (1961-2002)
Wye_NRA/EA	752	1190	1006	111
Wye_CEH	762	1165	1014	108
Wye_MetO	746	1202	1015	112
Exe_NRA/EA	951	1478	1232	133
Exe _CEH	976	1477	1256	138
Exe _MetO	962	1483	1235	134
Eden1_NRA/EA	853	1474	1172	142
Eden1_CEH	852	1446	1141	137
Eden1_MetO	896	1525	1206	141
Eden2_NRA/EA	935	1637	1304	150
Eden2_CEH	903	1616	1273	148
Eden2_MetO	999	1707	1351	150
Tyne_NRA/EA	782	1277	1052	126
Tyne _CEH	766	1212	1019	115
Tyne _MetO	783	1296	1051	127
Tees_NRA/EA	891	1497	1209	144
Tees _CEH	863	1442	1148	136
Tees _MetO	858	1430	1171	134
Wharfe_NRA/EA	1108	1663	1422	164
Wharfe _CEH	1072	1659	1383	165
Wharfe _MetO	1081	1631	1389	160
Wensum_NRA/EA	520	884	698	90
Wensum _CEH	503	847	674	82
Wensum _MetO	514	879	702	89
Thames _NRA/EA	535	939	766	101
Thames _CEH	510	884	737	94
Thames _MetO	543	932	770	99
Ouse_NRA/EA	456	778	619	82
Ouse _CEH	460	724	592	74
Ouse _MetO	457	783	621	84
Medway_NRA/EA	570	974	751	88
Medway _CEH	560	970	747	84
Medway _MetO	563	966	751	87
Itchen_NRA/EA	566	1123	840	110
Itchen _CEH	584	1112	835	106
Itchen _MetO	574	1118	850	111
Teifi_NRA/EA	1074	1724	1376	153
Teifi _CEH	1064	1721	1375	167
Teifi _MetO	1080	1741	1407	161
Dee_NRA/EA	1100	1664	1420	154
Dee _CEH	1079	1585	1364	149
Dee _MetO	1089	1621	1397	145
Derwent_NRA/EA	719	1274	1000	131
Derwent _CEH	724	1251	1008	125
Derwent _MetO	736	1238	1002	127

Table 3.2 Average ratios (NRA and EA / MetO) for the 15 catchments

	Catchment	Average ratio (NRA and EA/ MetO)
1	Wye	0.99
2	Exe	1.00
3	EdenTemple	0.97
4	EdenWarwick	0.97
5	Tyne	1.00
6	Tees	1.03
7	Wharfe	1.02
8	Wensum	1.00
9	Thames	0.99
10	Ouse	1.00
11	Medway	1.00
12	Itchen	0.99
13	Teifi	0.98
14	Dee	1.02
15	Derwent	1.00

If the MetO data deviated from the NRA/EA (original) series by a factor of more than +/-0.01 then the MetO records were adjusted (by multiplying them by the corresponding factor). The series which needed to be adjusted are shaded. The adjusted ratios are plotted in Figures A2.5 (note that in the new series the mean is plotted in magenta).

4. RESULTS

Complete details of the catchment model calibration exercises are included in the previous studies (Jones and Lister, 1995 and 1997). The calibration periods used are given in Table 1.2. In this study the rainfall/runoff model has been further validated in a more comprehensive manner for the 15 catchments in England and Wales *via* the use of longer and more recent validation periods (and thus a greater range of climatic conditions). The reconstructed flow series have been extended to the end of 2002. The flow reconstructions rely upon the maintenance of homogeneous catchment monthly precipitation series (see Section 3). The graphical analyses used in the maintenance of the precipitation series are shown in Figures A2.1-A2.5.

The results of the model validation exercise are shown graphically by the use of annual, seasonal and monthly time-series plots (Figures A2.6-A2.8), which compare observed and reconstructed flows. Discrepancies, on a short- or long-term basis are immediately apparent from the use of the graphical output. Table 4.1 compares various statistics between the observed and reconstructed flows, for the period 1980-2002 (for three catchments the periods are slightly shorter due to lack of available naturalised flows, see also Table 1.2). Figure A2.12 compares the distributions of observed and reconstructed flows through the use of flow duration curves. The period used here is generally 1961-2002, but this is reduced on a few catchments. These are a useful means of comparison, which look at the wider distribution of flows. As long as comparisons are made within a common timeframe, a close match between the flow distributions of observed and reconstructed flows shows that the model is capturing the catchment characteristics and how these translate into flow behaviour. The long (updated) flow series are shown in annual and seasonal time-series plots (Figures A2.9-A2.11). A visual examination of these series allows a rapid appraisal of the temporal occurrence of wet and dry periods. The medium- to long-term fluctuations in flow behaviour (with a focus on annual and seasonal values) in response to climatic fluctuations, are easily recognized in these plots.

Specific analysis on a catchment-by-catchment basis is given in Annex 1, with some general discussion, when relevant to all catchments in section 5. In Table 4.1, model biases over the 1980-2002 period are both positive and negative, but all are within a few percent of observed averages. Reconstructed flows are higher than observed on 11 catchments on an annual basis and on 12 catchments for winter (December to February average). Lower flows than observed are reconstructed on the Wye, Exe and Tyne for annual and winter averages. In summer (June to August average), 7 reconstructions give higher flows and 7 lower, with the Medway average exactly as observed. The standard deviation of annual average flows is higher than observed over the 1980-2002 period on 10 catchments, but only on the Thames and Ely Ouse are the differences large. Q95 is a well-used measure of low flows (being the flow exceeded 95% of the time). Eight of the catchments have higher reconstructed Q95 than observed, but all values are within 15% of the observed values, except for the Wensum where the value is overestimated by over 50%. Finally, the Durbin-Watson D statistic is a measure of the autocorrelation of the residual (observed minus reconstructed) flows. For the sample size of 276 (23 years by 12 months) values below ~1.3 would indicate that the residuals are seriously autocorrelated (i.e. consistent differences of one sign or the other for long periods). It is not surprising that these occur on the Wensum and Ely Ouse, catchments with high groundwater contributions and thus long-term memories of past winter rainfall totals. The Wensum results are also influenced by the change in the abstraction point for public water supply for Norwich and this not being accounted for with a naturalised flow series.

Table 4.1 Descriptive statistics for the observed and reconstructed river flow series over the period 1980-2002 (all flows in m^3s^{-1})

Catchments (Observed based on 1980-2002 unless stated)	Annual Mean		Winter (DJF) Mean		Summer (JJA) Mean		Standard Deviation (of annual average flows)		Q95		Durbin-Watson D Statistic
	Obs	Rec	Obs	Rec	Obs	Rec	Obs	Rec	Obs	Rec	
Wye to Redbrook	83.11	79.10	150.11	142.97	27.91	26.73	14.70	14.81	13.00	11.55	1.34
Exe to Thorverton	17.08	16.26	29.90	28.87	5.49	5.11	3.21	2.85	2.40	2.00	1.77
Eden to Temple Sowerby	14.86	15.30	26.88	28.32	5.42	5.46	2.56	2.91	2.10	2.17	2.37
Eden to Warwick Bridge	36.70	36.90	61.55	63.44	16.46	15.24	6.05	5.91	8.40	7.30	1.32
Tyne to Bywell	47.76	46.39	79.40	74.11	22.34	21.45	7.94	8.32	9.20	7.16	2.12
Tees to Broken Scar	17.22	20.63	28.84	35.76	7.73	7.81	3.47	3.94	4.10	2.35	1.37
Wharfe to Addingham	14.21	14.93	23.07	23.42	6.41	6.79	2.74	2.61	2.20	2.96	1.66
Wensum to Costessey Mill	4.05	4.90	5.83	7.12	2.31	2.78	1.13	1.35	1.20	1.88	0.81
Thames to Eynsham	15.70	17.47	28.50	32.40	5.84	6.10	4.00	8.01	2.40	1.73	1.60
Ely Ouse to Denver Complex	17.14	21.20	26.84	31.91	9.25	9.55	5.40	8.42	4.59	3.73	0.76
Medway to Teston (1980-96)	10.94	11.64	21.25	21.80	2.86	2.72	2.98	4.24	1.23	1.34	1.59
Itchen to Highbridge/Allbrook (1980-2000)	6.08	6.59	6.87	7.83	5.37	5.37	0.93	1.04	3.99	4.28	1.35
Teifi to Glan Teifi	29.53	28.97	48.76	48.92	9.98	9.49	4.88	4.64	3.70	3.95	1.60
Dee to Manley Hall/Erbistock	32.95	34.89	55.09	60.35	12.28	11.32	5.23	7.59	4.94	5.77	1.69
Derwent to Derby/Longbridge (1980-1997)	19.94	21.41	32.61	33.56	9.76	10.38	3.84	4.78	5.30	5.57	1.96

5. ANALYSIS AND DISCUSSION

The results of the current flow reconstruction exercise (Section 4) indicate that the model has worked well over the extended validation period. Most of the major differences between the reconstructed and observed flow series can be related to problems with the observed flow series. On the Derwent, the Tees and Wensum, the naturalised flow series do not extend to 2002. The use of different naturalisation techniques (as with the Itchen and Medway) has affected model performance. Here, it would be best to recalibrate the model using the improved naturalised flows.

The relative simplicity, and thus ease of operation of the flow reconstruction technique used here, requires some clarification of the potential weaknesses that result from the simple approach (also see Section 2). The principal areas of possible error are:

- The use of constant monthly values for evapotranspiration losses
- The potential for snowpacks to build up in winter periods, particularly in colder winters, on the catchments having significant areas at high elevation
- Possible modification of the regression relationships through time due to factors such as changes in land use
- Changes in the locations and numbers of raingauges on the catchments

Evaporation issues have been discussed in Section 2. The use of constant monthly evapotranspiration values is vindicated by the accuracy of the reconstructions developed here and in the earlier work (Jones, 1983; Jones, 1984; Jones and Lister, 1995 and Jones and Lister, 1997). In summer, when evaporation is highest, average reconstructed flows (for 1980-2002, see Table 4.1) were higher on 7 catchments than observed and lower on 7 with the Medway being exactly the same. Apart from the Wensum (where there is clear issue due to a change in abstractions, see Annex 1), all reconstructions are within 10% of observed summer averages. Errors due to snowfall in winter have not been serious due to the majority of winters in the past 10 years being mild and also it is only a problem for monthly runoff averages if the snowpack lasts from one month to the next. The influence of changing model performance, due to factors such as land-use changes, is difficult to discern for some catchments, as first, differences between naturalised flows used in the earlier NRA/EA work (Jones and Lister 1995 and 1997) and those recently available from the EA must be assessed. Changes to the raingauge network can influence areal catchment estimates, but these have been mitigated in this work by using the MetO data and only selecting grid boxes where gauges were located in the earlier NRA/EA work.

In addition, it should be noted that the model calibration periods should be long enough to ensure that sufficient extreme drought/low flow and high rainfall/flood flow periods are "experienced" by the calibration process. During all earlier flow reconstruction work (Jones, 1983, Jones, 1984, Jones and Lister, 1995 and Jones and Lister, 1997), there was due regard for the need for "full weather spectrum" calibration periods. However, this does not preclude the occurrence of even more extreme events (drought or flood) which may come along at some later time. The current work has extended the validation period for all catchments by a further seven or nine years (see Sections 2 and 4).

From the perspective of model validation, it has been disappointing that maintenance of the homogeneity of observed flow series (through naturalisation processes) has lapsed or not even begun for several catchments. The main reasons for the inhomogeneity in the observed flow series is the general increase in flow modifying activities due to increased use of water resources. On two catchments, reassessment of rating curves has caused changes in historic observed flows. Differences between observed and reconstructed flows, therefore, serve to emphasize the need for modelling exercises of this nature to maintain long-term homogeneous observed flow series.

The high rainfall and extreme flood situations that affected many parts of the UK in the autumn of 2000, (Marsh and Dale, 2002) were certainly beyond the experience of earlier calibrations (see also Tables 1.2 and 5.1). It is possible that any discrepancies, between observed and reconstructed flows during this period, were due to conditions beyond the range experienced by the statistical model. However, a more likely explanation of discrepancies during the year 2000, for many of our study catchments, would be the inadequacy of flow gauging installations during such conditions (see Annex 1).

Despite the potential weaknesses of this model (see above), there is no evidence that it has performed less well than during the earlier calibration and validation work. An individual catchment appraisal of model performance is given in Annex 1. The current work has increased confidence in the homogeneity of model output (reconstructed flows) and allows a more rigorous statistical examination of the long reconstructed flow series.

Table 5.1 (below) lists the five most extreme (reconstructed) high-flows for annual (Jan.-Dec.), autumn (SON) and autumn/winter (Oct.-April), on all 15 catchments, during the 138-year period 1865-2002. Table 5.1 helps to illustrate the extreme nature of the autumn 2000 rainfall and resultant high flows into early 2001. For nine of the 15 catchments in the study, the annual mean flows, during 2000, equalled or exceeded the fourth most extreme event since 1865. Looking at autumn flows (September to November), nine catchments equalled or exceeded the fourth most extreme high flows since 1865. Indeed, for five of the catchments, the annual and autumn flows were either the most or second most extreme events in the 138-year period. For the other catchments, the events were still extreme for both annual and autumn flows, with rankings of tenth or below in all but two cases (Itchen for annual and Thames for autumn). Comparable periods to 2000/2001, on the long reconstructed series, occurred in 1903/1904 and in 1872/1873 and to a slightly lesser extent in 1954/1955 and 1960/1961. All periods, as expected, were exceptionally wet, with 1872 the wettest year in the England and Wales rainfall series, which extends back to 1766.

Shifting the focus to low flows, Table 5.2 lists the lowest five calendar-year and summer (June to August) average flows for the period 1865 to 2002. Extreme low flows were recorded on many catchments during a number of years (*e.g.* 1870,1887,1921,1933/4,1976 and 1984). In the last 15 years, the years 1989 and 1995 are evident on more than one catchment, particularly 1995.

The general increase in winter runoff during the last 15 years compared to the 1960s is likely due to the shift in the North Atlantic Oscillation (NAO). More positive values of the NAO indicate stronger westerly airflow has prevailed over Britain since the late-1980s. This can be associated with higher winter rainfall totals (Wilby et al, 1997). Various NAO indices are formerly defined by Jones et al (1997) and an NAO influence on British weather is clear during the months of November to April, most particularly for temperature. Climatological winter (DJF) NAO series explain about 40% of the variance of winter temperature variability for Scotland and Northern Ireland (Jones and Lister, 2004).

Table 5.1 The occurrence of extreme high flows within the reconstructed flow record (1865-2002), for each catchment. The five most extreme annual (Jan-Dec.), autumn (SON) and autumn/winter (Oct.-April) high mean-flows are ranked and expressed in percentage terms with respect to their mean values during the period 1961-90

	Tyne	Tees	Wharfe	Derwent	Ely Ouse	Wensum	Thames	Medway	Itchen	Exe	Wye	Teifi	Dee	Eden1	Eden2
Extreme high annual-mean flows															
1	**2000**	**1872**	**2000**	**2000**	**2001**	**2001**	**1951**	**2000**	**2001**	**1872**	**1872**	**1872**	**1872**	**1903**	**1903**
	154%	172%	157%	167%	264%	190%	293%	239%	155%	158%	205%	175%	180%	181%	167%
2	**1903**	**1903**	**1872**	**1872**	**1877**	**1872**	**1960**	**2001**	**1866**	**1960**	**1960**	**1903**	**2000**	**1872**	**1872**
	153%	167%	142%	157%	213%	166%	292%	209%	141%	152%	175%	165%	177%	168%	161%
3	**1872**	**1877**	**1954**	**1877**	**1937**	**1994**	**1916**	**1960**	**1951**	**1924**	**1903**	**1882**	**1903**	**1928**	**1954**
	148%	161%	140%	153%	207%	163%	291%	191%	140%	150%	167%	152%	157%	163%	152%
4	**1916**	**2000**	**1877**	**1966**	**1883**	**1912**	**1930**	**1951**	**1936**	**1882**	**2000**	**2000**	**1999**	**1954**	**2000**
	145%	159%	137%	146%	187%	160%	271%	190%	135%	149%	166%	145%	156%	162%	150%
5	**2002**	**1876**	**2002**	**1960**	**2000**	**1883**	**1915**	**1937**	**1961**	**2000**	**1877**	**1877**	**1960**	**1990**	**1877**
	143%	146%	135%	142%	174%	158%	264%	181%	134%	145%	161%	143%	144%	156%	149%
Extreme high autumn-mean flows															
1	**1903**	**1903**	**2000**	**2000**	**1875**	**1872**	**1960**	**2000**	**1960**	**1960**	**1872**	**1903**	**2000**	**1954**	**1954**
	267%	249%	242%	296%	347%	251%	832%	539%	175%	265%	308%	265%	307%	299%	258%
2	**2000**	**1954**	**1954**	**1960**	**1903**	**1993**	**1875**	**1960**	**1903**	**1924**	**1960**	**1872**	**1872**	**1967**	**1872**
	240%	242%	208%	231%	338%	241%	725%	427%	158%	244%	300%	228%	263%	214%	193%
3	**1944**	**2000**	**1967**	**1872**	**1882**	**2001**	**1903**	**1974**	**1879**	**1882**	**1875**	**2000**	**1954**	**1938**	**1967**
	230%	238%	178%	225%	316%	236%	670%	313%	150%	243%	272%	210%	258%	208%	188%
4	**1954**	**1872**	**1872**	**1903**	**1880**	**1912**	**1935**	**1935**	**1924**	**2000**	**1903**	**1954**	**1903**	**1903**	**2000**
	226%	218%	176%	222%	312%	221%	631%	295%	142%	237%	271%	193%	240%	203%	184%
5	**1967**	**1935**	**1944**	**1954**	**2000**	**1987**	**1882**	**1939**	**1951**	**1954**	**1954**	**1930**	**1960**	**2000**	**1891**
	219%	209%	168%	212%	304%	217%	605%	282%	141%	232%	259%	185%	215%	200%	181%
Extreme high autumn/winter-mean flows (year labels apply to the period Jan.-April so 2001 is October 2000 to April 2001)															
1	**1877**	**1877**	**2001**	**2001**	**2001**	**1994**	**1930**	**2001**	**2001**	**2001**	**1877**	**2001**	**2001**	**1995**	**1913**
	177%	185%	146%	184%	303%	215%	431%	349%	181%	164%	194%	159%	186%	166%	152%
2	**1979**	**1995**	**1981**	**1966**	**1883**	**1873**	**1961**	**1961**	**1961**	**1961**	**2001**	**1904**	**1930**	**1903**	**1939**
	149%	166%	144%	170%	245%	199%	365%	208%	176%	160%	191%	143%	164%	165%	151%
3	**1904**	**2001**	**1995**	**1877**	**1877**	**2001**	**2001**	**1937**	**1936**	**1994**	**1930**	**1877**	**1994**	**1990**	**1925**
	141%	158%	142%	156%	233%	191%	359%	202%	158%	150%	189%	142%	154%	164%	147%
4	**2001**	**1939**	**1869**	**1883**	**1961**	**1988**	**1883**	**1995**	**1866**	**1995**	**1873**	**1873**	**1995**	**1939**	**1995**
	140%	158%	138%	149%	228%	179%	312%	187%	151%	149%	176%	141%	148%	163%	146%
5	**1939**	**1873**	**1867**	**1995**	**1994**	**1883**	**1936**	**1912**	**1904**	**1930**	**1883**	**1995**	**1999**	**1925**	**1903**
	140%	145%	134%	146%	225%	163%	300%	187%	148%	148%	161%	140%	142%	161%	145%

Table 5.2 The occurrence of extreme low flows within the reconstructed flow record (1865-2002), for each catchment. The five most extreme annual and summer (JJA) lowest mean-flows are ranked and expressed in percentage terms with respect to their mean values during the period 1961-90

	Tyne	Tees	Wharfe	Derwent	Ely Ouse	Wensum	Thames	Medway	Itchen	Exe	Wye	Teifi	Dee	Eden1	Eden2
Extreme low annual-mean flows (Jan.-Dec.)															
1	**1870**	**1989**	**1887**	**1887**	**1921**	**1949**	**1871**	**1898**	**1921**	**1921**	**1964**	**1887**	**1933**	**1955**	**1973**
	66%	63%	62%	52%	33%	54%	35%	45%	75%	52%	55%	65%	59%	60%	59%
2	**1955**	**1905**	**1902**	**1921**	**1934**	**1948**	**1874**	**1921**	**1934**	**1870**	**1921**	**1921**	**1887**	**1973**	**1955**
	66%	65%	66%	59%	35%	56%	37%	45%	75%	55%	57%	69%	60%	60%	65%
3	**1989**	**1887**	**1933**	**1934**	**1976**	**1921**	**1893**	**1973**	**1976**	**1887**	**1973**	**1964**	**1893**	**1887**	**1964**
	66%	66%	66%	63%	44%	57%	38%	49%	76%	61%	62%	69%	62%	67%	67%
4	**1904**	**1964**	**1955**	**1976**	**1902**	**1973**	**1921**	**1901**	**1944**	**1896**	**1887**	**1892**	**1896**	**1941**	**1971**
	67%	66%	67%	65%	48%	58%	38%	53%	77%	66%	63%	70%	65%	67%	70%
5	**1973**	**1902**	**1964**	**1893**	**1944**	**1874**	**1934**	**1884**	**1989**	**1905**	**1890**	**1933**	**1902**	**1971**	**1996**
	68%	68%	69%	66%	49%	62%	38%	56%	77%	66%	67%	70%	68%	67%	71%
Extreme low summer-mean (JJA) flows															
1	**1868**	**1995**	**1995**	**1868**	**1976**	**1921**	**1976**	**1976**	**1976**	**1870**	**1976**	**1976**	**1976**	**1984**	**1984**
	21%	16%	22%	48%	8%	58%	20%	45%	65%	26%	34%	31%	28%	28%	28%
2	**1995**	**1976**	**1887**	**1976**	**1921**	**1944**	**1870**	**1921**	**1921**	**1887**	**1870**	**1995**	**1870**	**1995**	**1995**
	26%	22%	23%	50%	20%	59%	22%	52%	74%	27%	40%	36%	33%	28%	36%
3	**1984**	**1989**	**1976**	**1887**	**1934**	**1874**	**1874**	**1949**	**1944**	**1976**	**1995**	**1984**	**1995**	**1887**	**1887**
	28%	22%	29%	51%	23%	61%	24%	52%	74%	29%	42%	38%	35%	30%	39%
4	**1887**	**1984**	**1869**	**1921**	**1868**	**1949**	**1896**	**1995**	**1938**	**1921**	**1896**	**1975**	**1868**	**2001**	**1976**
	29%	23%	37%	52%	33%	61%	28%	52%	76%	31%	43%	40%	39%	32%	43%
5	**1949**	**1869**	**1870**	**1959**	**1870**	**1976**	**1893**	**1893**	**1929**	**1876**	**1984**	**1869**	**1869**	**1868**	**1869**
	29%	25%	37%	54%	35%	61%	31%	53%	78%	32%	43%	42%	43%	33%	45%

6. CONCLUSIONS

There is no doubt that flows, in many of the UK's catchments, are becoming less natural as resource use practices change. Although most the 15 catchments are still suitable for flow reconstruction, changes on the Wensum and Ely Ouse since the mid-1980s make them less useful for this sort of work. The need for long homogeneous flow series is thus more important to assess, and, at the same time, predict some of the effects of the changes taking place. Added to this are the potential effects of climate change and how such changes may affect catchment rainfall-runoff behaviour.

Naturalised flow series can only extend to the length of observed flow series and require considerable information regarding historic water use/management practices. The naturalisation of flow series is a very complex exercise, particularly where resource use is extensive and complex (see e.g. EA Naturalisation Guidance V2.0, 2001). The exploitation of groundwater, and thus the effect on flows *via* groundwater dynamics, adds further tiers of complexity and thus uncertainty to naturalisation processes. This makes naturalisation a very involved and costly process.

The flow reconstruction model has performed as well as during previous reconstruction work. The model validation period now includes both extreme dry and wet periods. This increases the confidence in reconstructed flows, which, for many purposes, are a more viable alternative to the production of naturalised flows.

The long-run reconstructed flow series are now available to assist with the planning of long-term water resource and water quality management strategies. The series can also be used for neighbouring catchments with similar hydrologic and geologic conditions. The principal cost to develop long series for new catchments is in the development of long monthly rainfall series for a number of sites within or near to a new catchment.

7. LOGISTICAL PROBLEMS AND RECOMMENDATIONS

The main recommendations from the current flow reconstruction exercise are in response to the logistical problems that emerged whilst undertaking the work. The logistical problems (listed below) have been emphasized due to their general worsening since previous flow reconstruction work was completed in the early to mid-1990s. The problems are centred upon the need to acquire appropriate data for the input to and assessment of the flow reconstruction model. The main problems encountered were:

1. It is clear that the operation of many raingauge stations has ceased on almost all the 15 catchments studied. This has serious implications for the maintenance of homogeneous precipitation series.
2. Flow data series were not as readily available from the EA as was originally hoped. Considerable effort was required (following a centralized request to regional personnel) to extract the required data for some catchments. Data formats (received) varied considerably.
3. The existence and length of naturalised flow series was disappointing. These are vital to the calibration and validation of a variety of catchment models. Whilst acknowledging the difficulties with the naturalisation process for the more complex catchments, it is surprising that more effort has not gone into this process. The discontinuation of previous naturalised flow series caused problems with validation exercises, given the use of earlier calibrated model parameters for flow reconstructions (using the now discontinued series). We recognise, however, that naturalisation techniques should always take advantage of new methods and additional information. Reassessment of stage/discharge relationships has also occurred on a couple of the catchments.
4. The apparent lack of easily available metadata relating to the recording of flows, at specific locations, caused as many problems as the difficulties encountered with the acquisition of the flow data series. Homogeneous observed flow series, particularly during model calibrations and validations, are essential to the optimization of model performance. Any information, which allows an assessment of observed flow series with regard to homogeneity, is vital. Local knowledge of gauge performance is also important, particularly at different levels of flow.

7.1 Recommendations

We suggest that the following measures would benefit those, both inside or outside of the EA, who have the need for reliable riverflow and related precipitation data. These are very much appropriate to any future updating (or extension) of the reconstructed flow series.

1. Pressure should be exerted by Met Office and the EA, aimed at the maintenance/restoration of vital raingauge stations/networks. The availability of long-term homogeneous rainfall records is essential for many reasons – including catchment-modelling purposes. The updating/future updating of the reconstructed flow series would not have been possible without the use of the gridded 5km x 5km gridded resource from MetO. However, the usefulness (homogeneity) of this resource is threatened, if long-run rainfall records are allowed to be discontinued at the rate seen in recent years.

2. In consultation with the Met Office, the real-time updating of the riverflow reconstructions could be easily made, if the MetO gridded data are routinely updated.

3. The collation and quality control processes which precede the distribution of precipitation data should not be unduly delayed. Met Office quality assessments of daily precipitation data can take several months.

4. More effort (including the better co-ordination of the different parties involved) should go into the provision of a regularly maintained national database for riverflows. Of particular importance here is the need for a comprehensive metadata listing.

5. The EA should address the needs for greater effort towards flow naturalisation exercises.

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ANNEX 1 A DETAILED DISCUSSION OF RECONSTRUCTION-MODEL PERFORMANCE WITH THE FOCUS ON VALIDATION

A1.1 Introduction

This section looks at model performance, both recent and that from earlier work, on a catchment-by-catchment basis. This is done by reference to different ways (both statistical and graphical) of comparing observed and reconstructed flows. The current flow reconstruction exercise has updated the reconstructed flow series and, effectively, extended the model validation period on all catchments. Since the quality of observed flow series is of paramount importance to the validation exercise, matters relating to their quality figure largely in the following sub-sections.

Observed flow data are required to both calibrate the statistically-based catchment model (undertaken in earlier papers and reports, see Jones and Lister, 1995, 1997 and 1998) and to assess the accuracy of the reconstructed flows. Divergence between reconstructed and observed flows does not necessarily mean that there is something wrong with the statistical model or the catchment rainfall input series. It could just as easily be that a catchment begins to exhibit changed flow behaviour that could be due to a change in the contribution of artificial influences on the flow regime, or some inhomogeneity occurs within the observed flow record.

For any statistical based (multiple regression) runoff model to function properly – in the same way as previously, calibration should use naturalised flow series or be based on an observed flow series relating to a period when (unnatural) external influences on the flow regime were minimal and at a relatively constant level. If these assumptions are satisfied, together with the maintenance of homogeneous areal rainfall series, divergence between observed and reconstructed flows is an indicator of either changes in the characteristics of the catchment (perhaps due to changing land use) or in the observed flows themselves.

At the beginning of the current work to update the flow reconstructions for 15 catchments in England and Wales, it was hoped that the Environment Agency could provide observed flow series for all catchments. It was also hoped that the EA could provide naturalised series for those catchments that have significant flow modification due to abstractions and discharges or other aspects of flow management. A request was made through the Technical Advisor, Hydrometry Monitoring and Assessment Process, for observed and observed/naturalised flow series (wherever available). In addition, any information was requested which is relevant to the quality of observed flow series.

It soon became apparent that the necessary flow data and associated information were not readily available. For this reason, a parallel request was made to the National Riverflow Archive (run by CEH, Wallingford). We therefore received observed flow series form two different sources. In addition, we have the observed flow series (NRA/EA) that were used for the earlier flow reconstruction studies. The CEH web-based resources were used heavily within following sub-sections for general catchment descriptions and metadata relating to flow gauging activities (see http://www.nwl.ac.uk/ih/www/products/iproducts.html).

It was necessary to collate and compare all of the flow data and associated information. In addition to deciding which of the flow series was best (in terms of appropriate period, accuracy, missing values *etc.*) for comparison with the reconstructed flows, it was necessary to make comparisons with the original flow series used in the earlier work. The latter exercise was undertaken by reference to overlap periods. This was vital to the maintenance of continuity (homogeneity) of the observed flow series.

A1.2 Dee to Manley Hall/Erbistock

A1.2.1 Catchment basics and flows

The upper reaches of this catchment drain land which has elevations approaching 900 m. A combination of high elevations and a westerly location means high rainfall, with annual totals exceeding 2000 mm, for parts of the upper catchment (see Table 1.1 and Jones and Lister, 1997).

The flow regime for the Dee, to the gauging point, has been subject to a high degree of management since the latter half of the 19th Century. For this reason, the flow reconstruction-model calibration exercise used naturalised flows (Jones and Lister, 1997). The available flow series ended in 1989. For the current updating operation, the EA have supplied a naturalised series from 1986 to 2002. This series agrees perfectly with that used in the original calibration work – for the overlap period 1986-89. CEH have also supplied the same naturalised flow series. We have been able to update observed (naturalised) flows to the end of 2002.

A1.2.2 Model performance

The flow reconstruction model calibration and validation work (Jones and Lister, 1997) was hampered by the rather short (1970-89) naturalised flow series that was available at the time. The whole of the observed flow series was used for calibration. Validation had to rely on somewhat indirect methods with use of a less reliable flow series (1938-55) for Erbistock and a series from Lake Vyrnwy. Model performance was assessed as being good. There was a tendency to both over- and under-estimate winter high flows, which was thought to be due to the build up and loss of snowpacks (see general discussion in Sections 2 and 5).

The comparison of reconstructed and observed flows, during the current work, shows that mean annual flows (Table 3.1.) are well reconstructed during the period 1986-2002. The Durbin-Watson D statistic, at 1.95, shows that there is little autocorrelation in the residual (reconstructed – observed) flows for this catchment. The flow duration curves (Figure A2.12) shows very close agreement between observed and reconstructed flows.

There is, however, a significant discrepancy during the years 1999 and 2000 (see Figure A2.6), when the reconstructed flow value is *c.a.* 20% higher than the observed. These two years were exceedingly wet in this region (also see discussion in Section 5. concerning model calibrations and extremes). Indeed, the total annual precipitation, for both years, was higher than any year since at least 1958 (Figure A2.1). The flow gauge at Manley Hall “drowns” at flows in excess of 200 m^3s^{-1}. In addition to the extreme flooding in the autumn of 2000 (see Section 5), there was some severe flooding on this catchment during December 1999. It is possible that the peak flows during the periods of maximum flows were underestimated.

A1.3 Derwent to Derby St. Marys/Longbridge Weir

A1.3.1 Catchment basics and flows

This largely upland catchment receives high rainfall amounts in its upper reaches. The sub-catchment above Yorkshire Bridge gauging station has an annual average rainfall in excess of 1300 mm. As with the Dee (above), the Derwent catchment has a long history of flow management, for the purposes of public supply (see also Table 1.1 and Jones and Lister, 1997).

The naturalised flow series used in the original model calibration covered the period 1977-93 (Jones and Lister, 1997). The EA has supplied a naturalised series that extend to 1997; but this series appears to have been discontinued. There is perfect agreement between the old and new naturalised series, for their period of overlap 1977-93. However, due to the lack of naturalised data since 1997, we can only update the observed (naturalised) series by four years for the purposes of comparing reconstructed and "observed" flows.

A1.3.2 Model performance

The flow reconstruction model calibration and validation work (Jones and Lister, 1997) was slightly hampered by the rather short (1977-93) naturalised flow series that was available at the time. The whole of the observed flow series was used for calibration. Validation relied upon comparisons of reconstructed flows with a partially naturalised flow series for Longbridge Weir, which covered the period 1936-74. Model performance was good throughout the calibration and validation periods.

The comparison of reconstructed and observed flows, during the current work, shows that mean annual flows (Figure A2.6 and Table 3.1.) are still being accurately reconstructed, at both annual and seasonal scales. The Durbin-Watson D statistic (1.96) shows no autocorrelation in flow residuals. It is unfortunate that there are no naturalised flows available beyond 1997 (see above). However, there are no problems apparent with the reconstruction model for this catchment.

A1.4 Eden to Temple Sowerby

A1.4.1 Catchment basics and flows

This upland catchment on the western slopes of the Northern Pennines receives high rainfall, with a 1961-90 catchment average of 1146mm (see Table 1.1). It is not highly developed with regard to water resources. The flow record has not been regarded as needing naturalisation; but the following observations should be noted when using the observed flow record at this site.

Flow gauging at Temple Sowerby utilizes an open channel site which has had numerous rating changes due to relatively slight changes in the downstream bed and channel. Extreme floods used to bypass and flood the building (holding the stage recorder) before the extension of floodbanks and the raising of the building in 1995. It seems that re-calculations will require new flood ratings and these will extend prior to the 1995 changes. In addition, a low bed control weir was built in 2002 and a new rating is required from then (Susan Taylor, *pers. comm.*). High flows at this location are, therefore, suspect. Any inaccuracy with high flows would affect the accuracy of annual mean flows. Recent improvements should improve the future quality of gauged flows.

A1.4.2 Model performance

During the earlier flow reconstruction work on this catchment (Jones and Lister, 1995), model performance was seen as good. In the current flow reconstruction work, there are no systematic problems apparent when observed and reconstructed flows are compared, on annual and seasonal scales (Figures A2.6. and A2.7.). Mean annual and seasonal statistics (Table 3.1.) reveal no significant problem. The Durbin-Watson D statistic shows no autocorrelation in the flow residuals for Temple Sowerby. It is difficult to focus on any isolated discrepancies in the light of the problems with flow gauging on this catchment. It is likely that the reconstructed flows, for this catchment, are a useful guide to the errors within the observed flow records.

A1.5 Eden to Warwick Bridge/Great Corby

A1.5.1 Catchment basics and flows

Warwick Bridge/Great Corby is downstream of Temple Sowerby. However, the flow regime is still that of an upland catchment that receives high rainfall. There is some artificial influence on the flows in this catchment, through abstraction for public supply. However, there have been no receipts of naturalised flows from either CEH or EA and it seems safe to assume that flows are essentially natural. The 1961-90 catchment average is 1272 mm (see Table 1.1).

From the perspective of flow measurement, Warwick Bridge is another open channel site that has always been affected by weed growth. Regular rating changes over the period of record to 1988 have probably kept pace with the changed flow characteristics. Thus the quality of low to medium flows (to 1988) is assessed as reasonable. The use of a single rating equation after 1988 means that low to medium flow measurement could be poor after that date. In addition, the assessment of the quality of high flows, throughout the period of record, is said to be poor and high flow values should be treated with extreme caution. (Susan Taylor, Hydrometry Officer, EA, North West Region *pers. comm.*).

Warwick Bridge gauging station was closed in 1998. A new gauging station (believed to be a purpose built structure) at Great Corby, was opened in 1998. This site is about 3km upstream of Warwick Bridge. The quality of flows at this site is said to be good. Unfortunately, we have not received any parallel flow series (overlapping data from Warwick Bridge and Great Corby), which would have allowed a comparison of the two series and thus information that would have guided any attempt at merging the Great Corby flow series with that from Warwick Bridge. However, given the uncertainty over the accuracy of gauged flows at Warwick Bridge since 1988, the close proximity of the two gauging locations and the lack of any significant abstractions/discharges or tributary confluence points between them, the combination of the two flow series seems reasonable.

A1.5.2 Model performance

During the earlier flow reconstruction work on this catchment (Jones and Lister, 1995), model performance was seen as good. In the current flow reconstruction work, there are no systematic problems apparent when observed and reconstructed flows are compared, on annual and seasonal scales (Figures A2.6. and A2.7.). Mean annual and seasonal statistics (Table 3.1.) reveal no significant problem. The Durbin-Watson D statistic shows some autocorrelation in the flow residuals with the reconstructions for the Eden to Warwick Bridge/Great Corby. It is difficult to focus on any isolated discrepancies (see Figures A2.6 and A2.7) in the light of the problems with flow gauging on this catchment. It is likely that the reconstructed flows, for these catchments, are a useful guide to the errors within the observed flow records.

A1.6 Exe to Thorverton

A1.6.1 Catchment basics and flows

The upper reaches of the Exe drain Exmoor, in the south west of England. Annual rainfall is high at 1248 mm (Table 1.1). Flows from this catchment appear to be subject to a significant amount of interference - in the form of abstractions and discharges. In addition, flow regulation is listed as an artificial influence on flows. Low flows are affected significantly by flow management practices. However, neither CEH nor EA were able to supply a naturalised series. We have assumed that the degree of flow modification has not been considered sufficiently large to warrant flow naturalisation exercises. Comparison of observed flow series showed no material differences between the CEH and EA series. In addition, the observed series used previously agreed with the EA and CEH series.

A1.6.2 Model performance

Despite the potentially flow modifying activities (above), during the previous flow reconstruction work (Jones and Lister, 1995), the reconstruction model performance was classed as good, for both high and low flows. The generally close agreement, in the current work, between reconstructed and observed flows (Figure A2.6.), suggests that the flow modifying activities may have been relatively constant since the model was originally calibrated (Jones, 1984). The annual and seasonal statistics (Table 3.1.) add to the general impression of good model performance. The Durbin-Watson D statistic (1.77) shows low levels of autocorrelation in the flow residuals. There is a period between 1979 and 1988 (Figure A2.6.), when observed flows are predominantly higher than reconstructed. There is no obvious reason why this phenomenon should be apparent.

A1.7 Itchen to High Bridge/Allbrook

A1.7.1 Catchment basics and flows

The Itchen catchment is situated in the south of England and receives an annual rainfall (1961-90) of 833 mm (Table 1.1). It is very permeable and the flow regime is heavily dominated by the groundwater component (see Jones and Lister, 1997). The degree of flow management, through abstractions and discharges, is relatively constant through the year due to the dominance of groundwater exploitation, for public supply purposes. When the original reconstructed flow model was calibrated (Jones and Lister, 1997), a naturalised flow series was provided which covered the period 1959-88. This series was provided by the Hampshire Area Office, National Rivers Authority. The naturalisation process used was not sophisticated in that groundwater components were not processed through a groundwater model (Joe Pearce, *pers. comm.*). The loss to flows, from comparing the observed and naturalised series during their period of overlap (1959-88), was 1.03 m^3s^{-1}. However, this naturalised series has not been updated.

Observed (non-naturalised) flows have been provided by EA and CEH. EA have also produced a naturalised series (covering the period 1970-2000), which uses a modelling approach (the Itchen Groundwater Model has a 250 m grid and twice monthly time-steps). The model was developed for EA by Entec (Alison Rennie, *pers. comm.*). This is different to the naturalisation methods used for the 1959-88 series (above). Some simple comparison (Table A1.1) has been undertaken between the NRA and newly acquired naturalised series during their overlap period, 1970-88:

Table A1.1 Comparing the NRA and EA naturalised flow series for the Itchen

1970-88	NRA	EA
Mean	6.317	6.171
Min	3.295	3.294
Max	10.996	11.654
Q1	4.926	5.036
Q3	7.655	7.205
Stdev	1.682	1.565

The EA-modelled and NRA naturalised series are in close agreement during the 1970-88 period (correlation = 0.94). It therefore seems reasonable to use the EA naturalised series for the purposes of updating when comparing reconstructed and "observed" flows.

A1.7.2 Model performance

During the current flow reconstruction exercise, the comparison of observed and reconstructed flows is not as good as it was in the earlier work. (see Figures A2.6, A2.7 and Table 3.1). The naturalised flow series in current use has a different and more sophisticated means of derivation (see above). This is not the same series used for model calibration and validation and this could be the reason for the apparently lower model performance in the current work. The Durbin–Watson statistic has a value (1.35, see Table 3.1.) which indicates less autocorrelation than in the earlier reconstruction work. This may be due to the use of a more sophisticated naturalisation model. Some further consideration should be given to the question of a model re-calibration exercise for this catchment.

A1.8 Medway to Teston

A1.8.1 Catchment basics and flows

This catchment is situated in the drier south east of England. Annual rainfall (1961-90) is 744 mm (Table 1.1). Water resource use in this catchment, whilst not heavy, is complex and sufficiently large to merit flow naturalisation. Flow modification can arise from abstractions, discharges and flow augmentation measures. When the flow reconstruction model was calibrated for this catchment (Jones and Lister, 1997), a naturalised flow series was used.

This series was provided by personnel from the Worthing Office *via* the East Malling Office (Kent Area) of the NRA. The series covered the period 1957-94.

Recent enquiries with the EA suggest that there has been no continuation of this naturalised series. Instead, a new series has been produced which is based on the "Catchmod" (EA in-house catchment rainfall-runoff model). This model is relatively sophisticated (with simulation of ground store dynamics) and should not necessarily be expected to follow the naturalised flow series that was used for the earlier model calibration work. The current observed (naturalised) series is rather different to that used in model calibration. The comparison of annual mean flows (reconstructed and naturalised, see Figure A2.6), shows that the reconstruction model is producing flows that are lower than those "observed".

A detailed comparison of the NRA and EA naturalised series (Figure A1.1, below), and the CEH observed series, over their common period (1957-94), shows that the EA modelling operation is producing higher flows in winter months. This suggests that there is either a problem with the modelling process or the earlier naturalised series was in error, for winter high-flow months. If the latter explanation is the correct one, the original calibration exercise was biased.

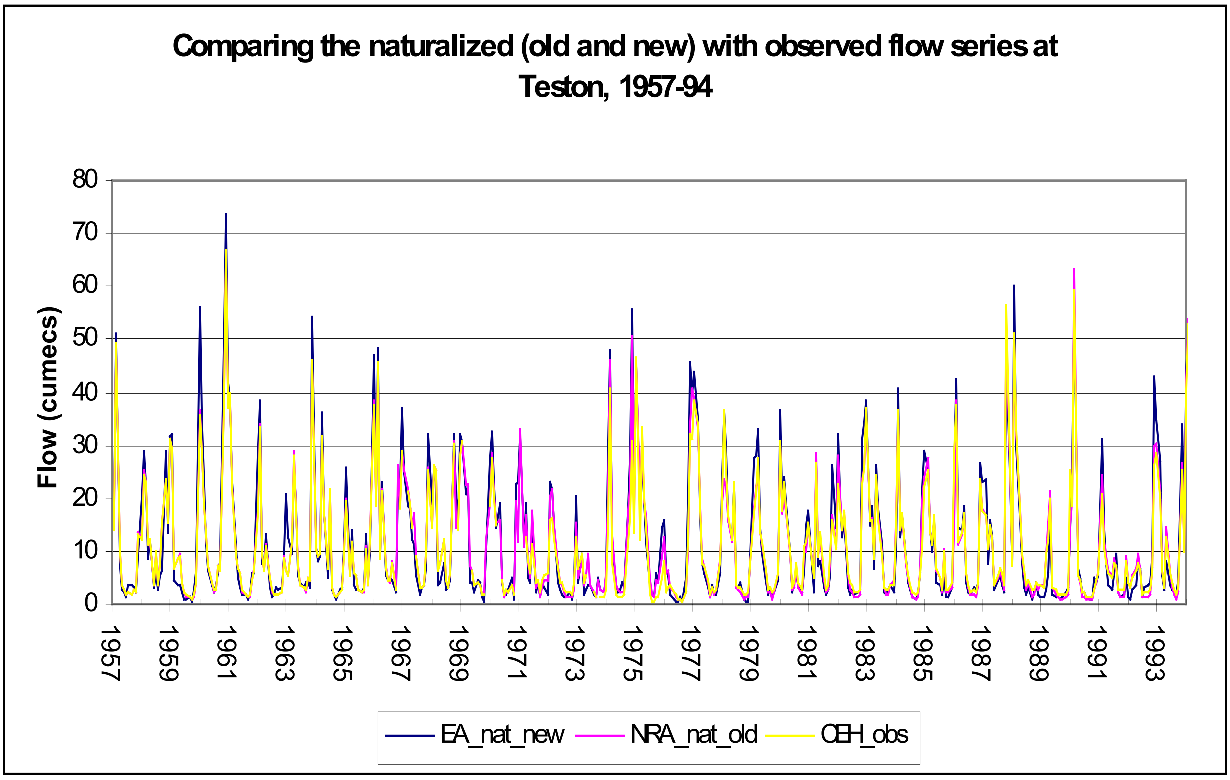


Figure A1.1 Comparing observed with the NRA and EA naturalised flows, Medway to Teston, 1957-94

A1.8.2 Model performance

In the earlier flow reconstruction model calibration and validation work (Jones and Lister, 1997), a naturalised series was obtained for the Medway, which covered the period 1957-94 (see above). This divided into calibration and validation periods (1970-93 and 1957-69, respectively); during which the performance of the flow reconstruction model was better for the calibration period (Jones and Lister, 1997). Mean flows were 10.42 m^3s^1 (obs.) and 10.08 m^3s^{-1} (rec.) during calibration. For the validation period, mean flows were 12.25 m^3s^{-1} (obs.) and 10.88 m^3s^{-1} (rec.). With the Durbin-Watson statistics > 1.5, there was little autocorrelation in flow residuals.

As with the Itchen, the naturalisation methodology has changed. This means that the current flow reconstructions are based (*via* model calibration) on a different flow series to that currently available for comparison. Examination of the time series of annual-mean reconstructed and observed flows (Figure A2.6), shows that, during the period 1963-88, observed flows are consistently higher than the reconstructed ones. This is not inconsistent with the earlier work where the original calibration/validation modelled output had a problem with under prediction of flows, particularly during the validation period. Added to this is the effect that the new naturalised (observed) series, during the period 1970-93 has a mean flow, which is 0.5 m^3s^{-1} higher than that of the original naturalised (observed) series. This "additional flow" is primarily appearing in the wet winter months (see Figures A2.6. and A2.7.).

It seems likely that the earlier naturalised series, used for calibration and (earlier) validation, had problems and these problems have adversely affected the calibration parameters; such that a new calibration exercise (using the current naturalised series) is required. However, observed and reconstructed flows are close towards the end of the comparison shown in Figure A2.6. In addition, the current naturalised series is based on a modelling exercise that was calibrated by reference to a (non-modelled) naturalised series that covered the period 1990-96 (Tim Norton, *pers. comm.*). It is difficult to ascertain whether or not the use of the original calibration parameters is still justified. A more in-depth comparison of the two naturalised flow series is necessary before the existing calibration parameters are rejected.

A1.9 Ely Ouse to Denver Complex

A1.9.1 Catchment basics and flows

This large lowland catchment is utilized extensively for water resources and effluent discharge purposes. The mean annual rainfall (1961-90) is low at 587 mm (Table 1.1). However, the flood threat, due to its large area (3430 km^2) and the associated potential to deliver large flows to its low-lying, lower reaches during prolonged wet periods, has implications for flow measurement activities in the downstream channel. The low elevation of the valuable agricultural land, in much of the lower reaches poses problems of prolonged water logging of soils. With a long history of complex engineering works to improve drainage and prevent flood damage in the lower flood plain, the flow measurement considerations are equally complex – with a great deal of artificial influence and potential for error.

Flows from the Ely Ouse can be diverted through a flood relief channel at times of high flow. In addition, there are other possible (managed) routes of flow, for resource use purposes. The measurement of flows, coming from the Ely Ouse, is thus a complex process at this point. Hence, the availability of flow series is rather restricted. However, a naturalised flow series has been received from EA for Denver Complex which covers the period 1980-2002.

A previous flow reconstruction exercise (Jones and Lister, 1995) obtained an observed flow record for the Ely Ouse at Denver Complex which was not naturalised. A comparison of this series with that from the EA (above), shows a net loss of *c.a.* ten percent. That is, resource use within the catchment to Denver reduces flows by about ten percent. This is a significant reduction.

A1.9.2 Model performance

During earlier flow reconstruction work for this catchment (Jones and Lister, 1995), the model performance was satisfactory, with most deficiencies probably due to the complexity of both the catchment and its water-use strategies. This includes the potential for measured flows to be greatly affected by, for example, land drainage/flood control measures. In addition, a long lag (up to 18 months) between rainfall events and their manifestation as riverflow, (*via* groundwater movements) is built into the reconstruction model for this catchment. The Durbin-Watson D statistic, at *c.a.* 1, indicated a fair degree of autocorrelation in flow residuals. Reconstructed flows tended to be higher than observed though this was probably, in part, due to the non-availability of a naturalised flow series at the time. Indeed, it was difficult to get an observed flow series that reflected the net "arrivals" at Denver Complex, due to the complexity of flow management at this point.

The current flow reconstruction work for this catchment is suffering from the lack of a lengthy homogeneous naturalised flow series – from the perspective of comparing reconstructed and observed flows. The series recently obtained from the EA covers the period 1980-2002. The comparison between reconstructed and observed annual-mean flows (Figure A2.6.), shows reasonably good agreement between 1980 and 1991. However, there is a notable discrepancy during the period 1992-1995 and even larger discrepancies around 2000/2001, when the reconstructed flows are significantly higher than the naturalised values. Autocorrelation is less than it was during the previous flow reconstruction exercise with a Durbin-Watson D statistic of 1.2.

The large discrepancies between reconstructed and observed flows for this catchment, in recent years, cast serious doubt on the current validity of the original (parameter) calibrations. However, it is also possible that the observed flow series, for the Ely Ouse to Denver, contain large-scale inhomogeneities. Given the quantity and extent of channel and other modifications (for drainage and flood control) in this catchment, the likelihood that observed flows do not always accurately reflect the flows that are generated within the catchment, appears to be high – especially under flood-flow conditions. Despite extensive enquiries to EA regional offices, it has not been possible to determine the exact nature of the problems with the Ely Ouse flows (reconstructed or observed). Unless more information can be obtained, which will allow judgement on the use of the original calibration parameters for this catchment, flow reconstructions by the current technique should be discontinued.

A1.10 Teifi to Glan Teifi

A1.10.1 Catchment basics and flows

This catchment has many high flow events due to high elevation in the upper reaches and its location in the west of the UK. Mean flow is 29 m^3s^{-1} and average rainfall (1961-90) is 1382 mm (see Table 1.1 and Jones and Lister, 1997). It has a relatively low level of development with regard to water resources. For this reason, flows are regarded as being almost natural. Thus, only standard observed flow series are available.

Updated flow series have been received and there are few discrepancies when compared with those used in the original reconstruction modelling exercise for the overlap period, 1959-95 (Jones and Lister, 1997). However, a notable exception was apparent when the EA observed flow series was used to compare observed and reconstructed flows, on a seasonal basis. Summer (JJA) average flows showed large disagreement during the years 1966, 1970 and 1972. Part of this problem was explained when it was realized that there was an error in the EA flow data for 1972. This does not explain the remaining summer discrepancies during the late 1960s-early 70s. We conclude that there may have been a problem with the flow gauging at Glan Teifi during this period.

A1.10.2 Model performance

In the original calibration/validation exercise, there was good agreement between observed and reconstructed flows. The Durbin–Watson D statistics > 1.5 for the calibration and validation periods suggests low autocorrelation in the flow residuals. During the current work, there is very good agreement between observed and reconstructed flows (see Table 3.1). There are a few occasions in the mid-1960s/late 1970s-early 80s, when some divergence is evident, from the time-series of observed and reconstructed annual mean flows (see Figures A2.6, A2.7 and above).

A1.11 Thames to Eynsham

A1.11.1 Catchment basics and flows

The catchment to Eynsham is primarily rural with development being mainly confined to the valley bottom. Annual rainfall (1961-90) is 730 mm and the mean flow is *c.a.*14 m^3s^{-1} - see Table 1.1. There are occasions when the complex system of flow gauging can be bypassed by extreme high flows. There is some development of water resource use, which affects flows. The effect on flows has increased considerably from a low level in the 1950s. The EA have maintained their naturalised flow series, which was used in the updating of flow reconstructions (Jones and Lister, 1995). Comparison of the flow series used then and that received recently (for their overlap period, 1970-93), shows excellent agreement.

A1.11.2 Model performance

In the earlier work (Jones and Lister, 1995), there was a tendency for the reconstructions to overestimate peak flows in winter. However, it was noted that some peak flows may be under-measured by the flow gauging facility (see above). In the current work, the flow reconstruction model has generally worked well in the estimation of flows. The Durbin-Watson statistic D (1.6) shows a degree of autocorrelation in flow residuals. There is still a tendency to overestimate, as the comparisons of observed and reconstructed flows show (see Figure A2.6 and Table 3.1). Given the occasions of very high flows during the late 1990s and, particularly, the autumn of 2000 (see Section 5), it is quite likely that measured flow series are in error for some months.

A1.12 Tees to Broken Scar

A1.12.1 Catchment basics and flows

This mainly upland catchment is located on the eastern slopes on the northern Pennines. Rainfall (1961-90) and average flows are quite high at 1141 mm and *c.a* 17 m^3s^{-1} (see Table 1.1). Due to its proximity to the conurbation of Teesside - with its industrial development - the Tees has a long history of exploitation for resource use. There is significant export of water to direct supply reservoirs and some upstream abstraction. In addition, flows can be augmented in drought years.

Despite the potential for significant flow modification, the EA have not been able to supply a naturalised flow record. Comparison between the flow series received from the EA and that used for the flow reconstruction updating exercise (Jones and Lister, 1995), shows considerable differences during the overlap period, 1982-93 (the new EA observed series begins in 1982).

CEH have provided a naturalised series for Broken Scar. This series spans the period 1956-93. However there are two significant missing periods: mid 1971-mid-1974, and mid-1978-end of 1985. Comparing all three flow series for their common period 1986-94, there are some significant differences:

Table A1.2 Comparing EA, CEH (naturalised) and NRA observed flows

1986-94	EA observed	CEH naturalised	NRA
Mean	17.11	22.64	19.13
Min	3.20	1.69	3.41
Max	57.00	70.25	64.77
Q1	6.77	8.85	7.79
Q3	24.85	33.74	28.14
Stdev	12.58	15.77	13.72

When the original model calibration for this catchment took place (see Jones and Lister, 1995, – Section 4.2), the flow series used was naturalised. The lack of a complete and lengthy naturalised series shows in the flow comparison plots (reconstructed versus observed) – see Figure A2.6. Reconstructed flows are consistently higher than observed. This is apparent from the mid-1960s to the present day. (Since the original reconstructions ran to the late 1970s, there is a suggestion that the observed flow series was reduced due to abstractions by the mid-1960s). A complete reassessment of all of the flow records for this location would seem to be warranted.

A1.12.2 Model performance

During the original flow reconstruction work for this catchment (see Jones and Lister, 1995), a naturalised flow series was used for calibration purposes. The effects of resource use have a significant impact on flows (see above). In the absence of a recent naturalised flow series for this catchment, we must conclude that the discrepancies between observed and reconstructed flows (see Figure A2.6) are due to the flow lost to abstractions. Annual differences in mean flows (observed *versus* reconstructed) are greater than 3 m^3s^{-1}, during the period 1980-2002. Looking at winter flows, the differences are greater at *c.a.* 7 m^3s^{-1}. It is likely that surface reservoirs are being replenished during the winter high flow periods. The differences between the observed and reconstructed series are in reasonable agreement with the differences between the NRA/EA observed and naturalised flows (from CEH) as discussed above.

It appears that the reconstructed flow series for this catchment is a good proxy for a naturalised series.

A1.13 Tyne to Bywell

A1.13.1 Catchment basics and flows

This mainly upland catchment lies between the northern Pennines and the Cheviot Hills. Rainfall (1961-90) and flows are quite high at 1016 mm and *c.a.* 34 m^3s^{-1} (see Table 1.1). The needs of the industrial conurbations of Tyneside and Wearside have a bearing on resource use in this catchment. This produces some flow modification. The presence of the large reservoir Kielder Water (designed as a river-regulating resource which was completed in 1982), in the north Tyne valley, gives the potential for significant flow modification. This reservoir supports flows in the Derwent, Wear and Tees as well as the Tyne itself. However, the Kielder scheme has not been used to the extent that was envisaged prior to construction and export/loss of flow has not occurred to the degree that had been proposed.

The EA was not able to supply any naturalised flow series for this catchment. CEH have supplied a naturalised series that covers the period 1956-93. However, there is a lengthy period with no data, which runs from late-1971 to the end of 1984. The NRA-observed series, which covers the period 1970-93 (see Jones and Lister, 1996), agrees very well with the recently supplied observed series from the EA.

The overlap periods between the CEH naturalised series and EA observed series occur before and after the presence/operation of Kielder Water. This allows an assessment of the effect on flows (at Bywell), that the operation of Kielder has had. Looking at the period 1957-69 (pre-Kielder), the naturalised and observed series are very close. Naturalised monthly flows, with one exception, are greater than those observed by an average value of two percent. During the period 1985-93 (post-Kielder), naturalised monthly flows are both greater and less than the observed values and the degree of flow modification is much larger than it was pre-Kielder. The maximum loss of flow was 19% and the maximum addition to flow was 133%. The mean effect on flows is, however, less than one percent (augmentation). These values are in-line with the concept of abstraction to maintain levels in Kielder with flow compensation for down-stream abstractions and flow augmentation in drought periods.

Looking at the comparison of observed and reconstructed annual-mean flows for this catchment (see Figure A2.6), the agreement is good. This corroborates the evidence that suggests a minimal net effect of Kielder Water on catchment flows.

A1.13.2 Model performance

There is considerable scope in this catchment for resource use (including flow augmentation practices) to significantly affected flows. However, whilst flows are considerably affected on a seasonal basis, the net annual effect is small (see above).

During the earlier flow reconstruction work (see Jones and Lister, 1995), the flow reconstruction model performance was good. Reconstructed flows, at 42.7 m^3s^{-1}, were just three percent below the observed (for the period 1970-93) value. The Durbin-Watson D statistic was > 1.7 and thus showed little autocorrelation in flow residuals.

In the current flow reconstruction work (for the period 1980-2002), the model is still under-predicting flows by about three percent. The Durbin-Watson D statistic, at 2.1 (see Table 3.1) shows virtually no autocorrelation in flow residuals. The reconstruction model appears to be working very well on an annual basis. Any divergence on a seasonal basis, which can be significant (see Figure A2.7.) is probably due to flow management activities.

A1.14 Wensum to Costessey Mill

A1.14.1 Catchment basics and flows

The Wensum is a small, lowland and mainly rural catchment. Situated in the drier east of England, rainfall (1961-90) and flows are low at 672 mm and *c.a.* 4 m^3s^{-1} (Table 1.1). Baseflow is an important component of runoff. Throughout the period of flow measurement (since 1960), flows to Costessey Mill have been affected by a moderate level of surface and groundwater abstractions.

A significant surface abstraction facility has operated at Costessey Pits since 1988. Water is taken at this point to contribute towards the public water supply for the City of Norwich. At the time of updating the reconstructed flow series for Costessey Mill in 1994 (Jones and Lister, 1995), a naturalised flow series was obtained which compensated for the flow loss at Costessey Pits. During the period 1988-93, the average loss of flow was around 0.5 m^3s^{-1}. Whilst this loss is not large when compared to larger catchments, it is significant for the Wensum at this point where the mean flow is about 4 m^3s^{-1}.

Neither the EA nor CEH have been able to supply an updated naturalised flow series. However the EA predict that one will be available in late spring, 2004. Examination of the mean-annual time-series of reconstructed and observed flows clearly shows the effect of the post-1987 abstractions (see Section A2.6) upstream of the flow gauge.

A1.14.2 Model performance

In the earlier flow reconstruction work (see Jones and Lister, 1995), model performance was good. A slight tendency for modelled flows to be greater than observed (4.3 *versus* 4.1 m^3s^{-1}) was seen as signs of greater losses due to increased groundwater abstractions. A Durbin-Watson D statistic of 1.3 indicates some autocorrelation in flow residuals. Comparisons in this work, used a flow series that was not fully naturalised but adjusted for a new abstraction intake (PWS), which has operated just upstream of the flow gauge since 1988.

In the current flow reconstruction work, we were unable to obtain any naturalised series. The comparison plot of observed and reconstructed flows (Figure A2.6.), shows a distinct and consistent difference between the two series from *c.a.* 1989 onwards. This is in accord with the known increase in surface abstractions close to the gauging station. The flow reconstruction model is effectively producing a naturalised series for this catchment. However, the recent catchment (gridded MetO) rainfall series shows a slight increase in recent times (when compared to the original – see Figure A2.5). The flow “discrepancy” due to the *post*-1988 abstractions may be underestimated.

A1.15 Wharfe to Addingham

A1.15.1 Catchment basics and flows

Flows in this predominantly upland and rural catchment originate over the eastern slopes of the Pennines. With high elevations and high rainfall (1961-90 average is 1383 mm), this relatively small catchment is high yielding. Mean flow is *c.a.* 14 m^3s^{-1} (Table 1.1). Gauged flows are affected by the operation of reservoirs. Both abstractions and regulation discharges are made upstream of the gauging point.

Both the EA and CEH have supplied observed series for this gauge. The two series are in very good agreement. When the latter observed series are compared with the earlier series used during the last flow reconstruction updates (Jones and Lister, 1995), there are some differences which tend to occur in the wetter months. The earlier series has higher values than the current observed versions (during the overlap period, 1970-93). The differences occur before 1982. It appears that a new rating has been applied to pre-1982 flows, which has reduced high flows. This is in accordance with information given by CEH, which implies the need for a new rating. However, the CEH text states that the “revised rating is still to be applied”; thus suggesting the latter comment is out-of-date.

The EA have been able to supply a short run of naturalised flows for the period, 1995-2000. The average loss to flow at Addingham is 0.6 m^3s^{-1}during this period. This amounts to about four percent of the average flow at this point.

A1.15.2 Model performance

The earlier model performance was very good, with observed and reconstructed mean flows of 14 and 14.1 m^3s^{-1}, respectively. The Durbin-Watson statistic D was 2.1 and thus indicated negligible autocorrelation in flow residuals. In the current work, observed and reconstructed flows (see Table 3.1) are still very close at 14.2 and 14.9 m^3s^{-1}, respectively. The Durbin-Watson D statistic, at 1.66 is showing a weak autocorrelation. The time-series plots (see Figure 2.6.), show good agreement between observed and reconstructed flows, at the level of annual mean-flow. The slight increase in the difference between observed and reconstructed flows (0.6 $m^3s\text{-}^1$), is in exact agreement with the current estimated loss to flows, due to resource use (see above).

A1.16 Wye to Redbrook

A1.16.1 Catchment basics and flows

This catchment is the largest of the 15 catchments involved in the current flow reconstruction exercise. Having a significant upland area and being situated in the west of the UK, the (1961-90) average rainfall is quite high at 1011mm (Table 1.1). Mean flows are large (*c.a.* 74 m^3s^{-1}), when compared with others in our sample. The flow regime is moderately affected by exports and regulations.

Observed flows have been supplied by EA and CEH. Agreement is very good between the two series. When compared with the NRA series, used in the earlier flow reconstruction exercise in 1994 (see Jones and Lister, 1995), differences are very small. Thus, with no significant disagreement between flow series, it can be assumed that observed flows are reasonably homogeneous and suitable for comparison with the reconstructed series. The EA do not expect to have a fully naturalised flow record for a few years. When it is available, it will only cover the period from 1989 (Kellie Hayes, *pers. comm.*).

A1.16.2 Model performance

In the previous flow reconstruction work for this catchment (Jones and Lister, 1995), the reconstruction model performed well. Observed and reconstructed flows were very close at 73.7 and 71.2 m^3s^{-1}, respectively. The Durbin-Watson D statistic was 2.2 and thus indicated little autocorrelation in flow residuals. In the current work, the comparison of observed and reconstructed (annual) time-series (Figure A2.6) shows good agreement, particularly, in the more recent period. There is a tendency for observed flows to be greater than reconstructed (83.1 *versus* 79.1 m^3s^1), for the period 1980-2002 (see Table 3.1). However, most of the "excess" observed flow occurred during the mid/late-1980s. This period of larger discrepancies was noted in the previous reconstruction work (Jones and Lister, 1995). There is no readily available explanation of this phenomenon. There is a potential for severe summer weed problems at the gauging station and a possibility that the most extreme flows can circumnavigate the gauging installation. Looking at the comparison of observed and reconstructed summer flows (Figure A2.7), does show where the weed problem may have induced some false high flow readings in the 1980s, but the discrepancies here are not as consistent as those in the annual mean-flow series. If any high flows had by-passed the gauging process, reconstructed flows would have been higher than those observed.

ANNEX 2 GRAPHICAL ANALYSES FOR THE AREAL RAINFALL DETERMINATION AND FLOW RECONSTRUCTION

This section holds all of the graphical analyses for the work relating to the production of catchment areal rainfall series and for the flow reconstruction exercise.

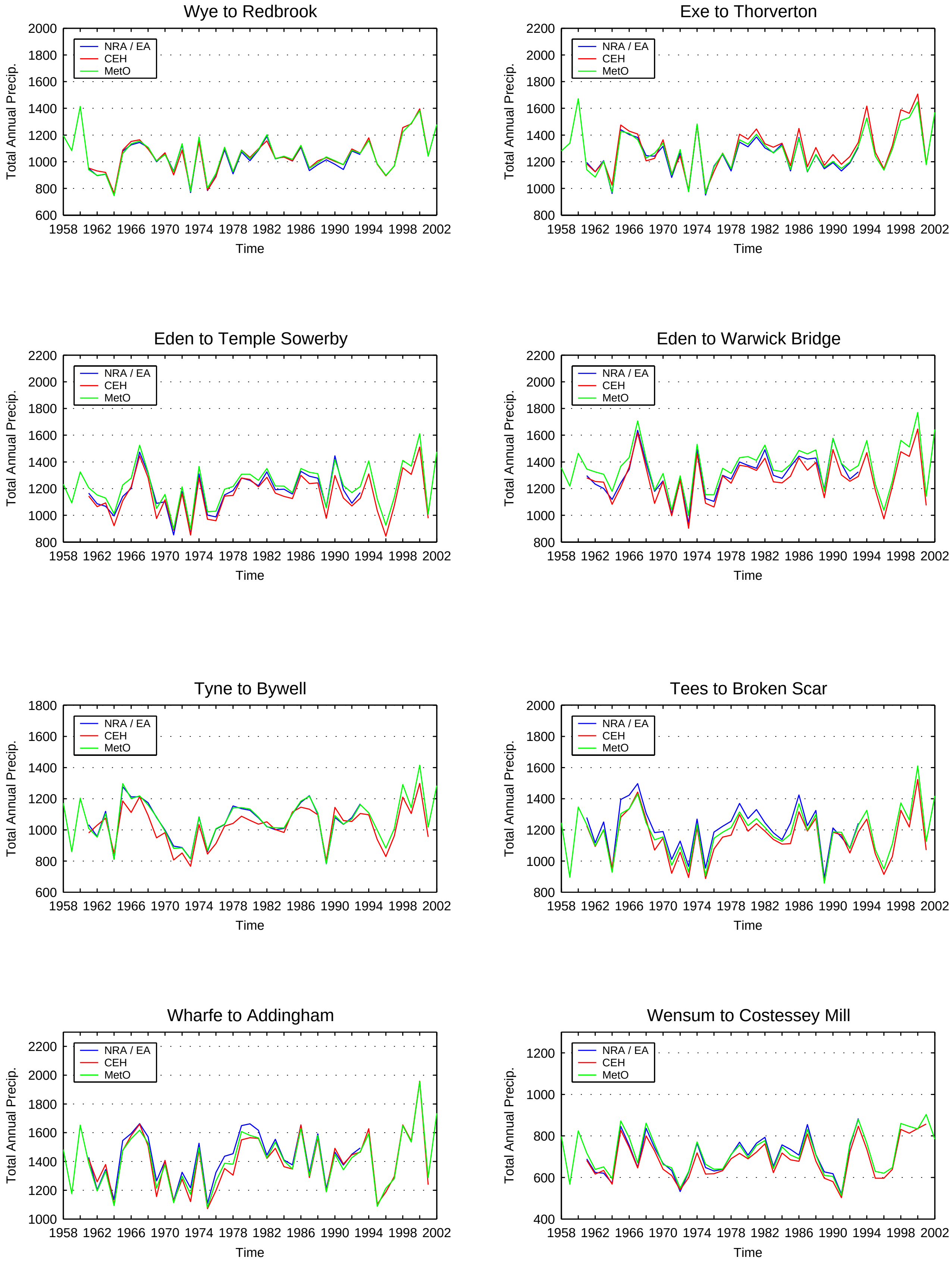
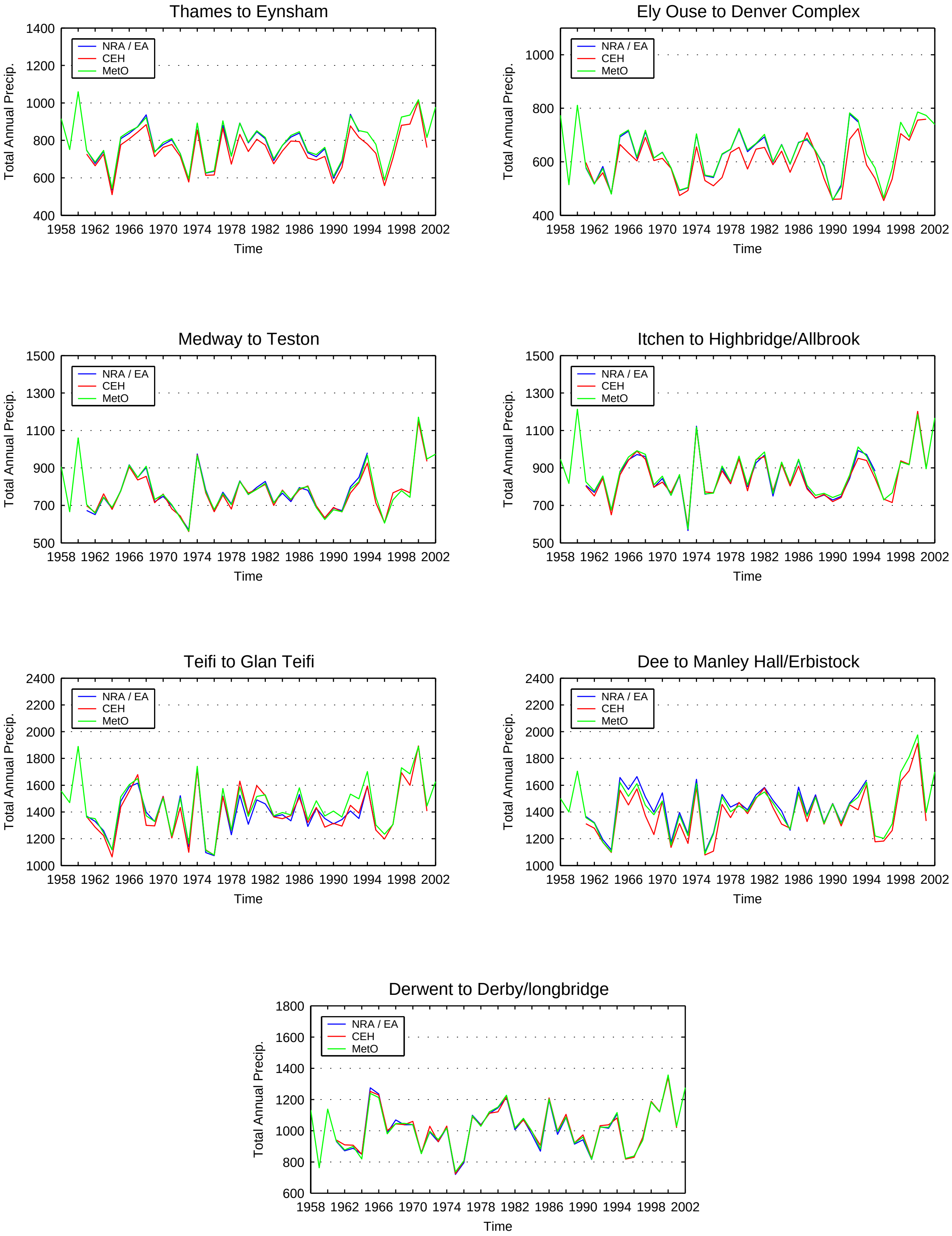


Figure A2.1 **Total annual rainfall (mm) for the original NRA/EA (blue line), CEH (red line) and MetO (green line) series**


Thames to Eynsham

Ely Ouse to Denver Complex

Medway to Teston

Itchen to Highbridge/Allbrook

Teifi to Glan Teifi

Dee to Manley Hall/Erbistock

Derwent to Derby/longbridge

Figure A2.1 (cont.) **Total annual rainfall (mm) for the original NRA/EA (blue line), CEH (red line) and MetO (green line) series**

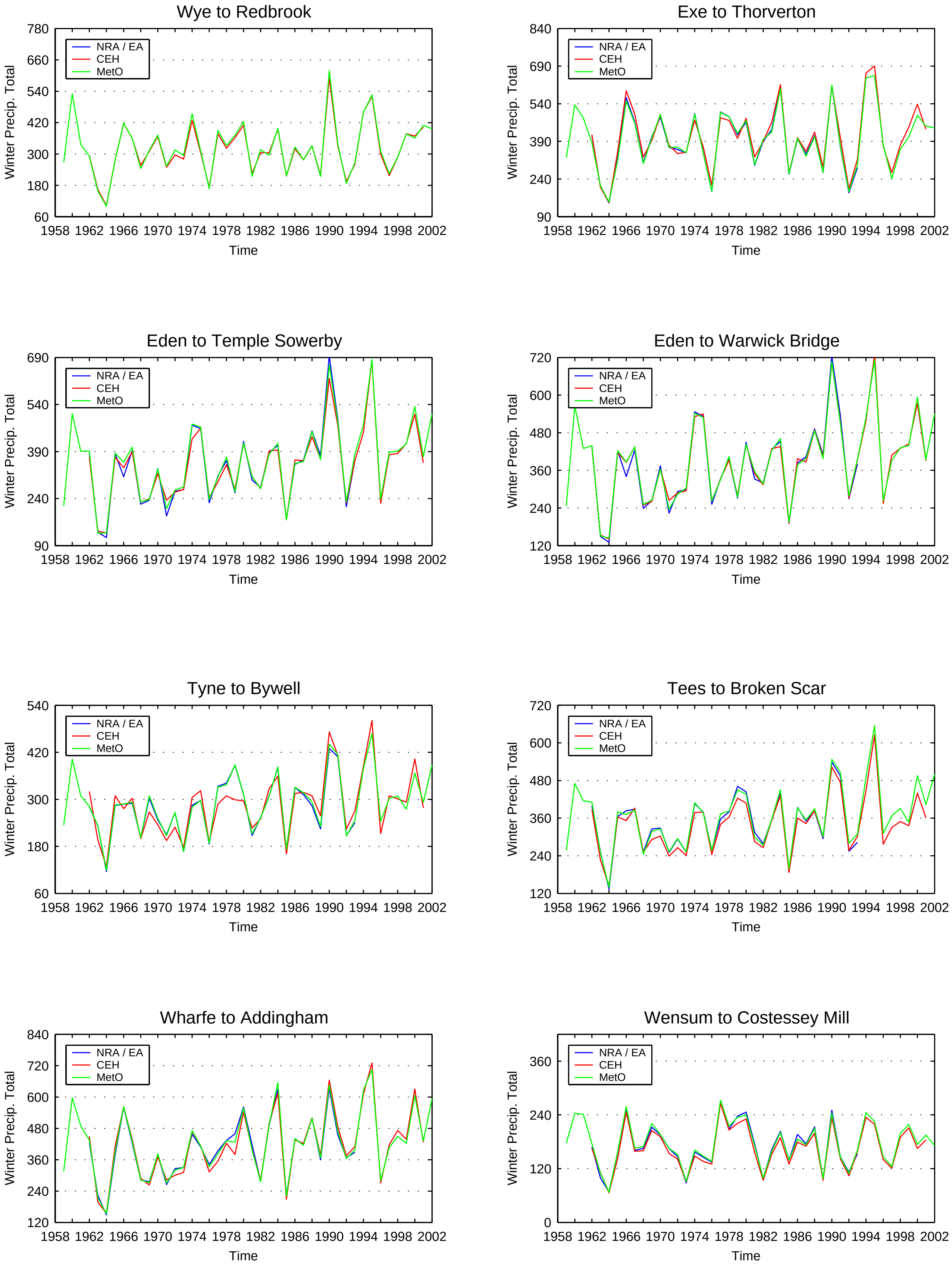


Figure A2.2 As in Figure A2.1 except for winter (Dec.-Feb.) total (mm)

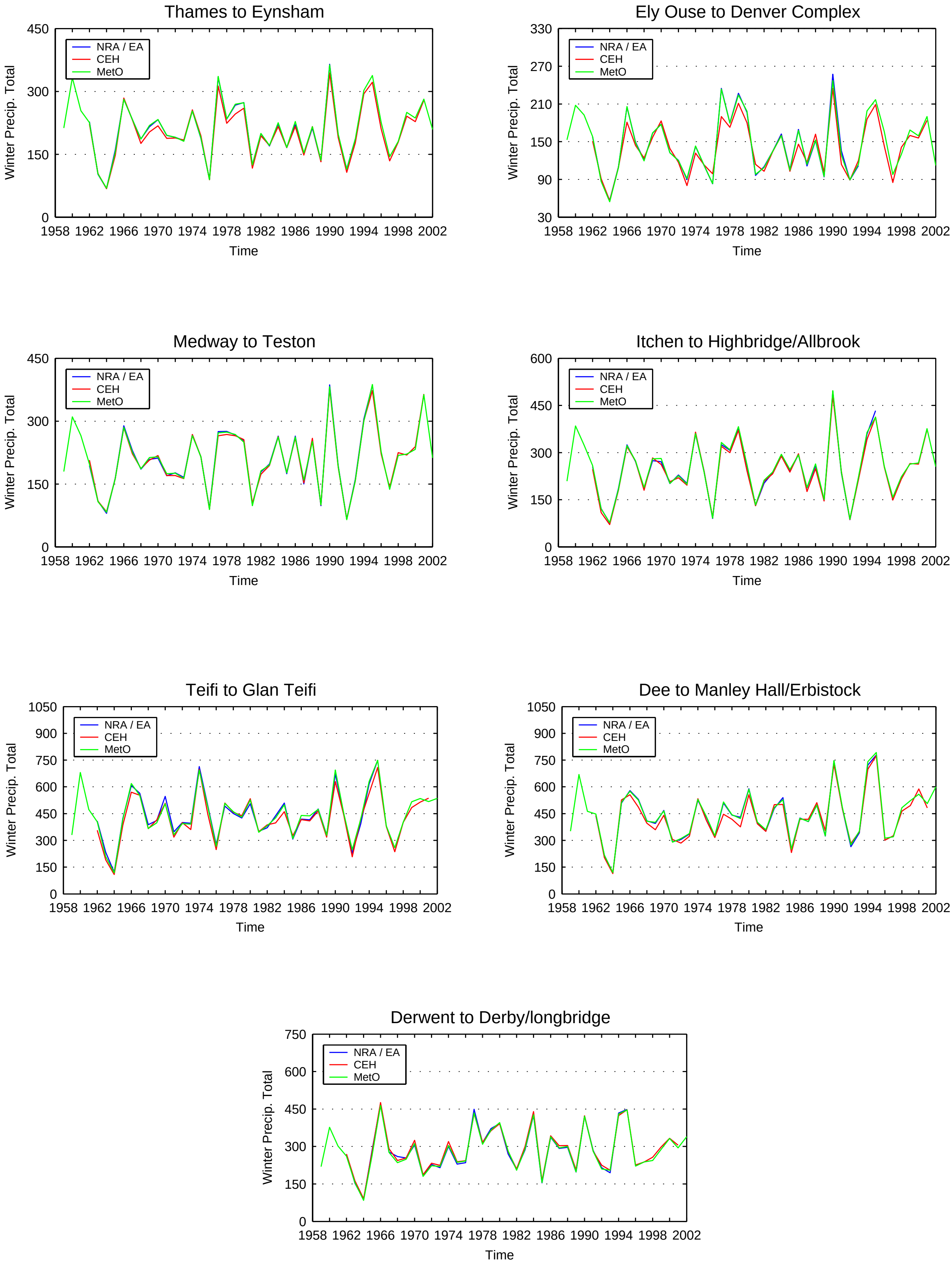


Figure A2.2 (cont.) **As in Figure A2.1 except for winter (Dec.-Feb.) total (mm)**

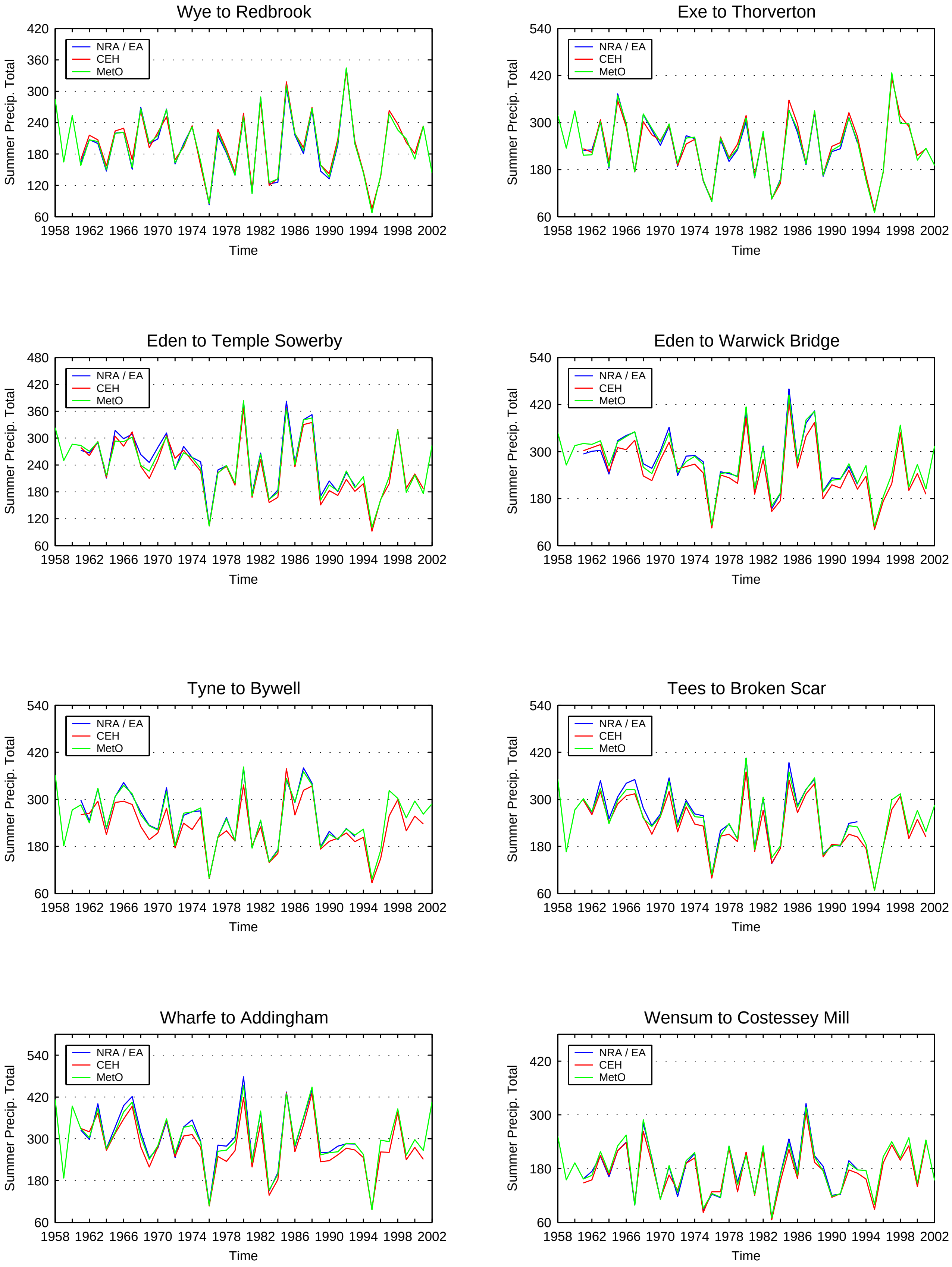


Figure A2.3 As in Figure A2.1 except for summer (Jun.-Aug.) total (mm)

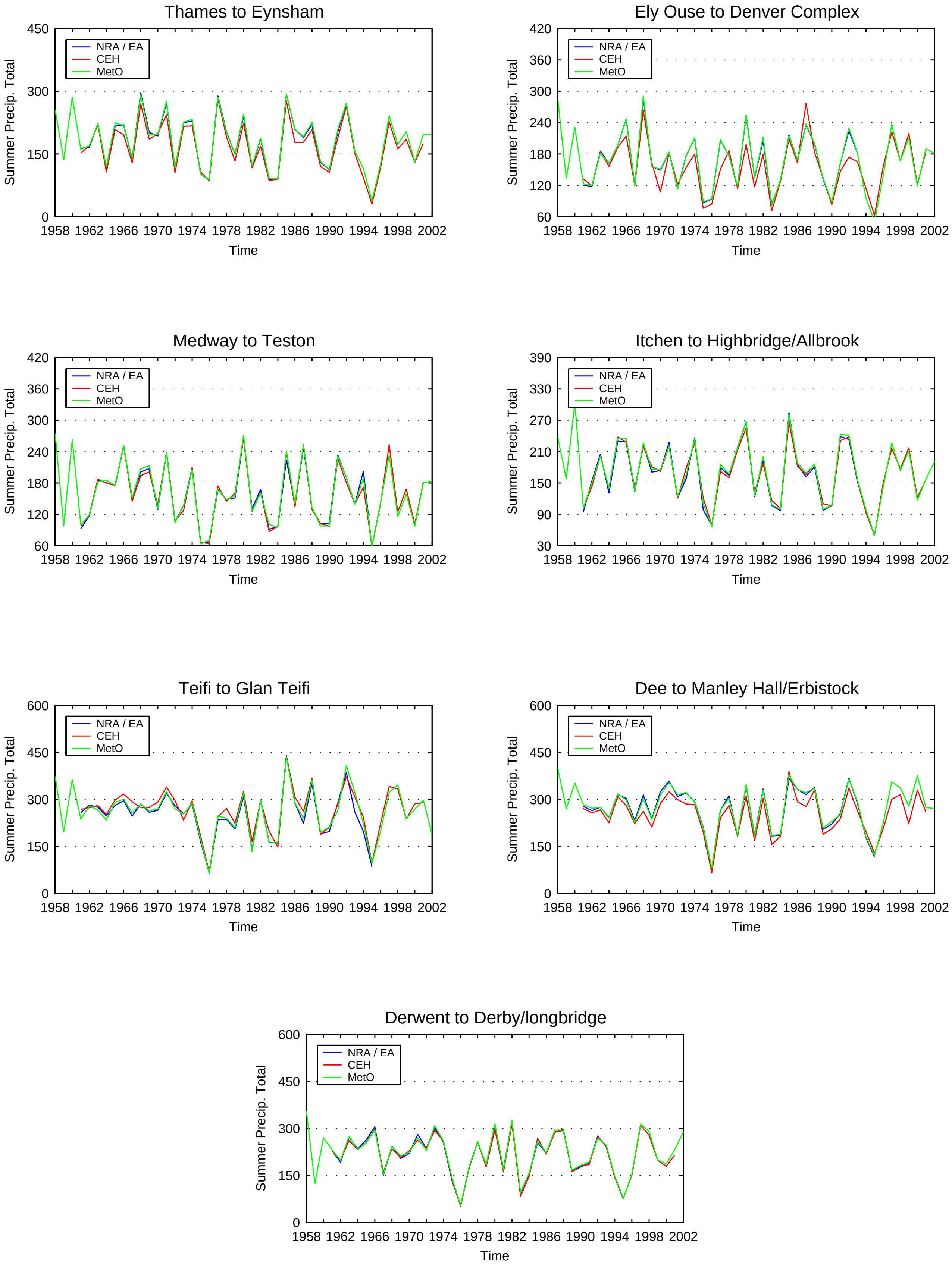


Figure A2.3 (cont.) As in Figure A2.1 except for summer (Jun.-Aug.) total (mm)

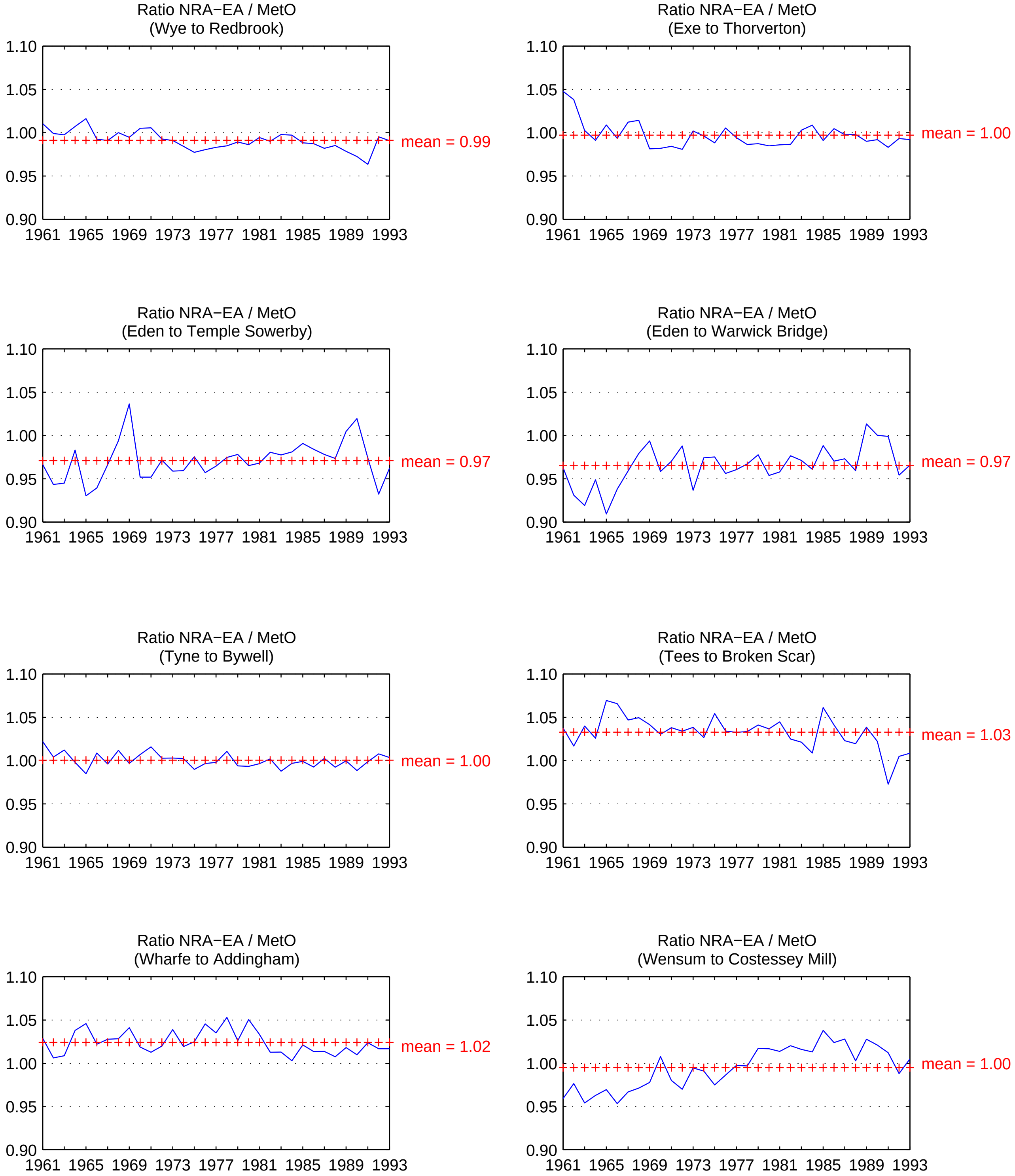


Figure A2.4 **Ratios of NRA-EA/MetO rainfall data**

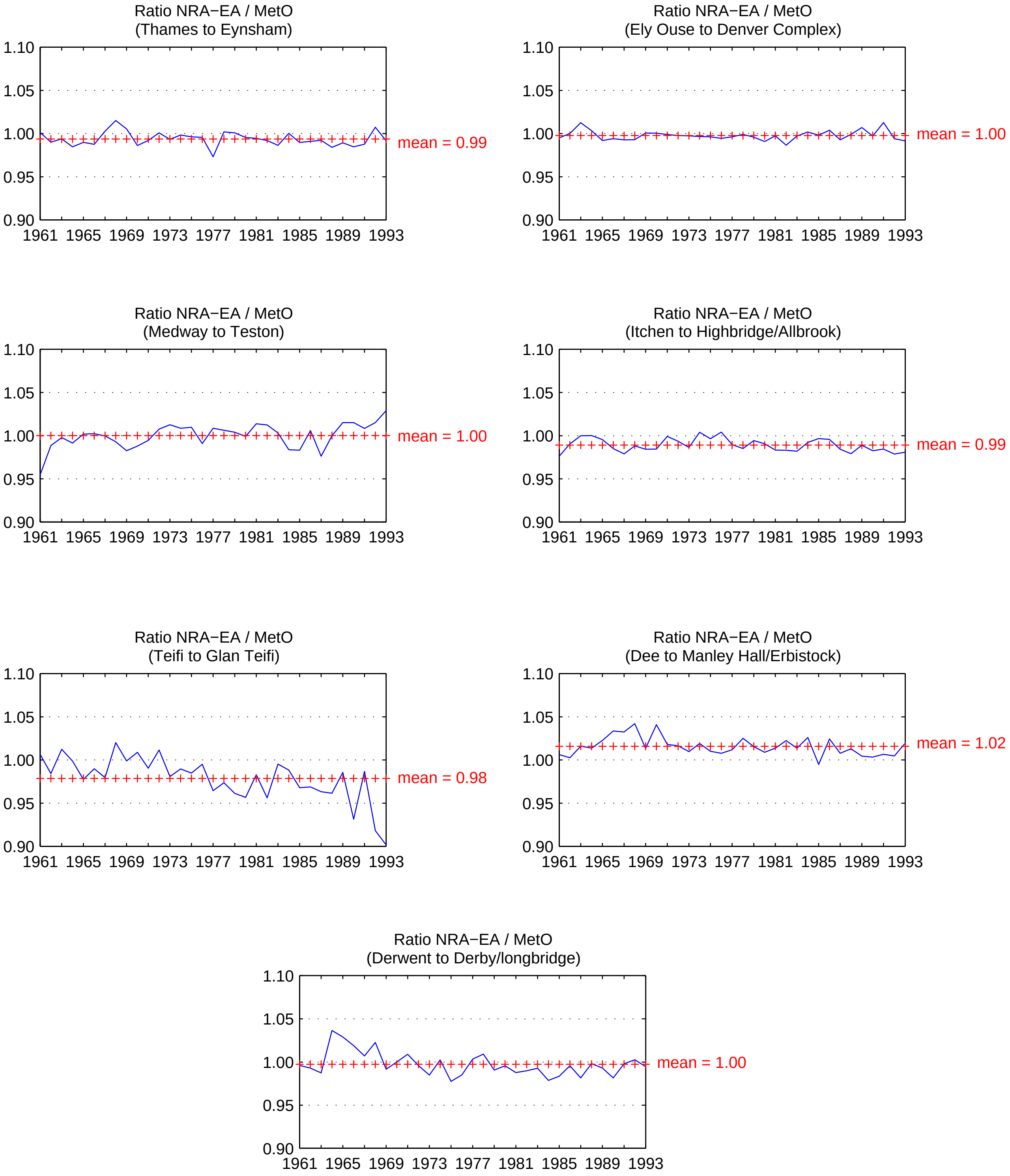


Figure A2.4 (cont.) **Ratios of NRA-EA/MetO rainfall data**

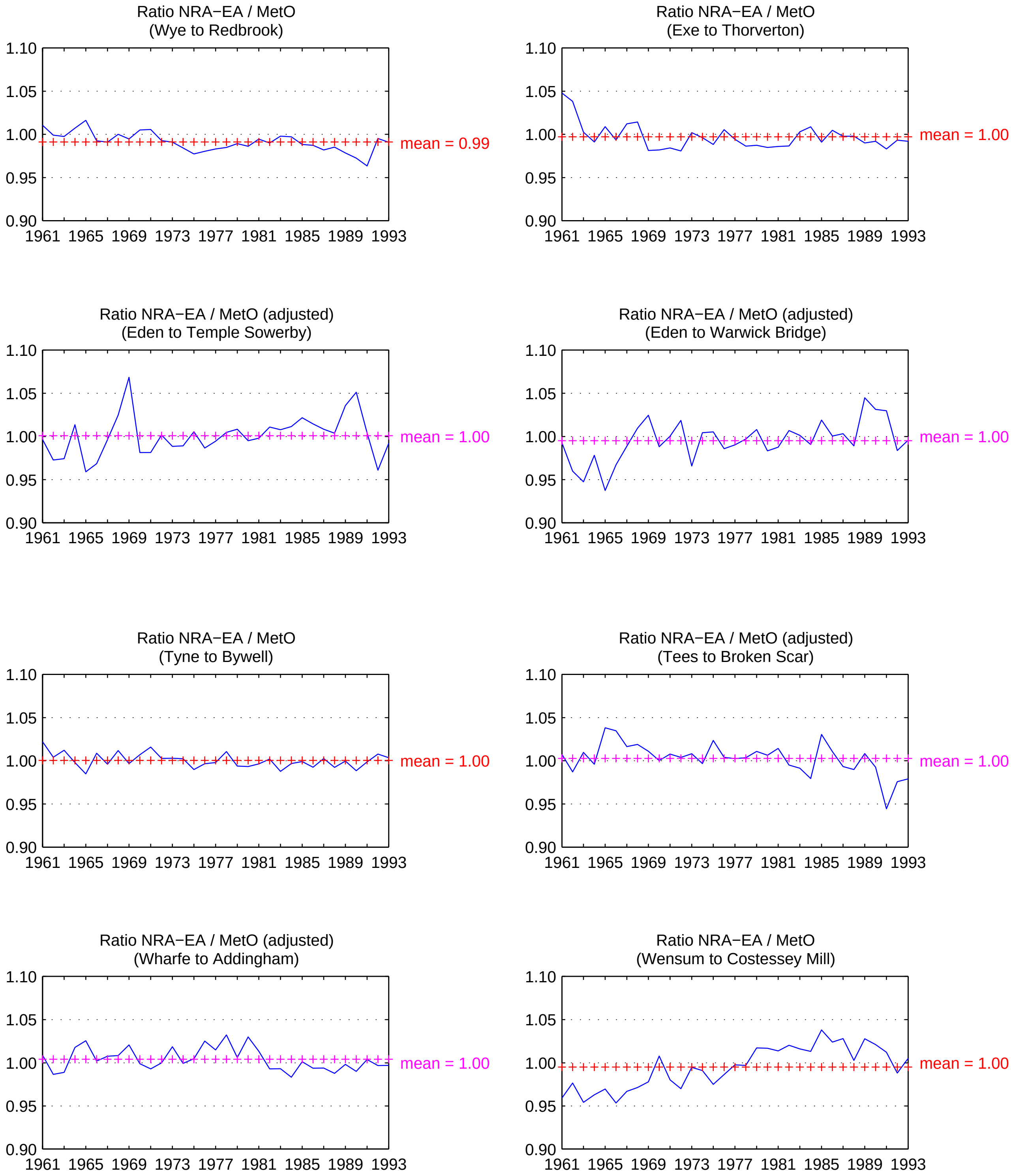


Figure A2.5 As in Figure A2.4 but with the adjusted ratios (plots with 'mean' in red colour are the same as in Figure A2.4. For the adjusted ratios, 'mean' is in magenta)

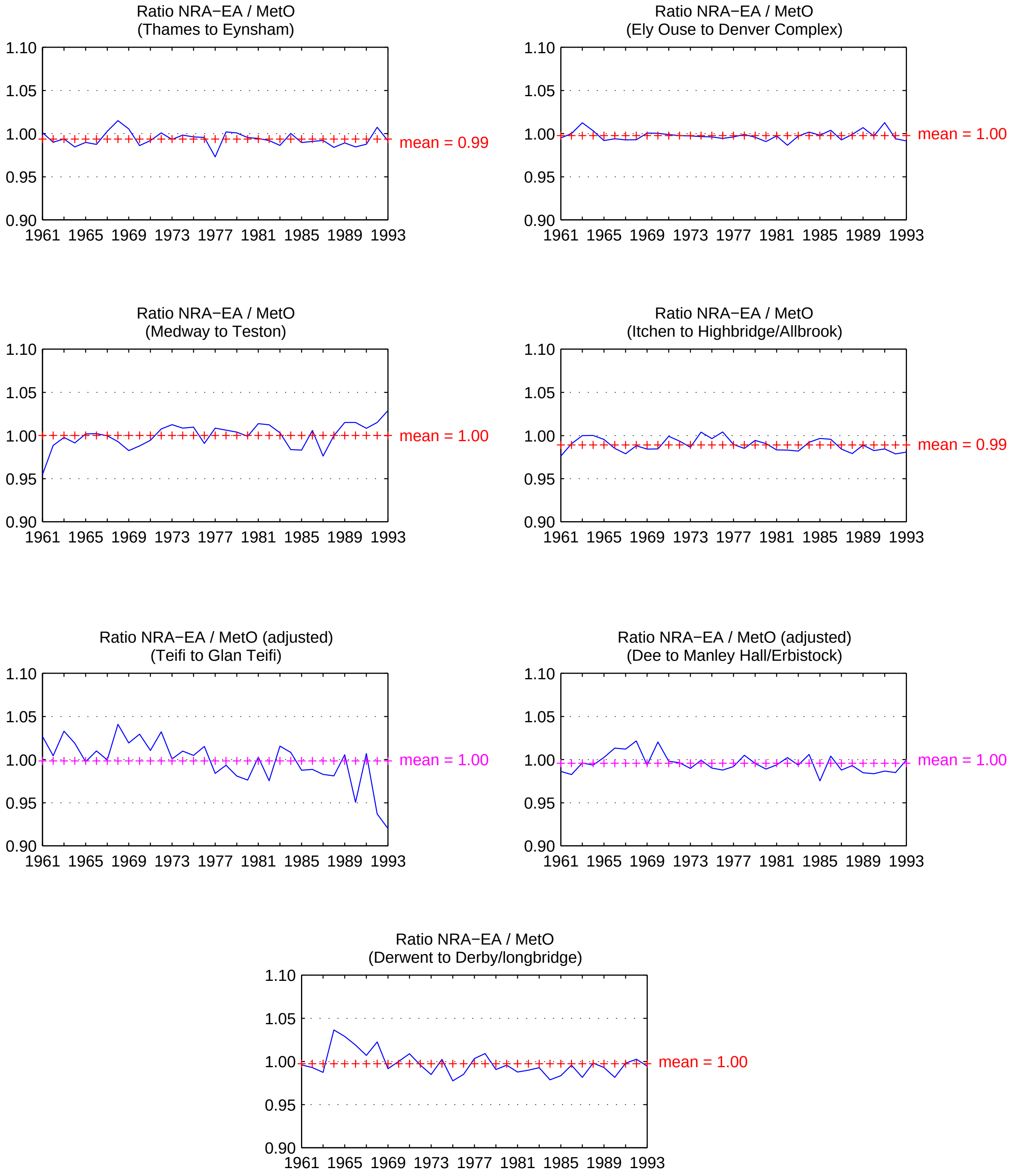


Figure A2.5 (cont.) As in Figure A2.4 but with the adjusted ratios (plots with 'mean' in red colour are the same as in Figure A2.4. For the adjusted ratios, 'mean' is in magenta)

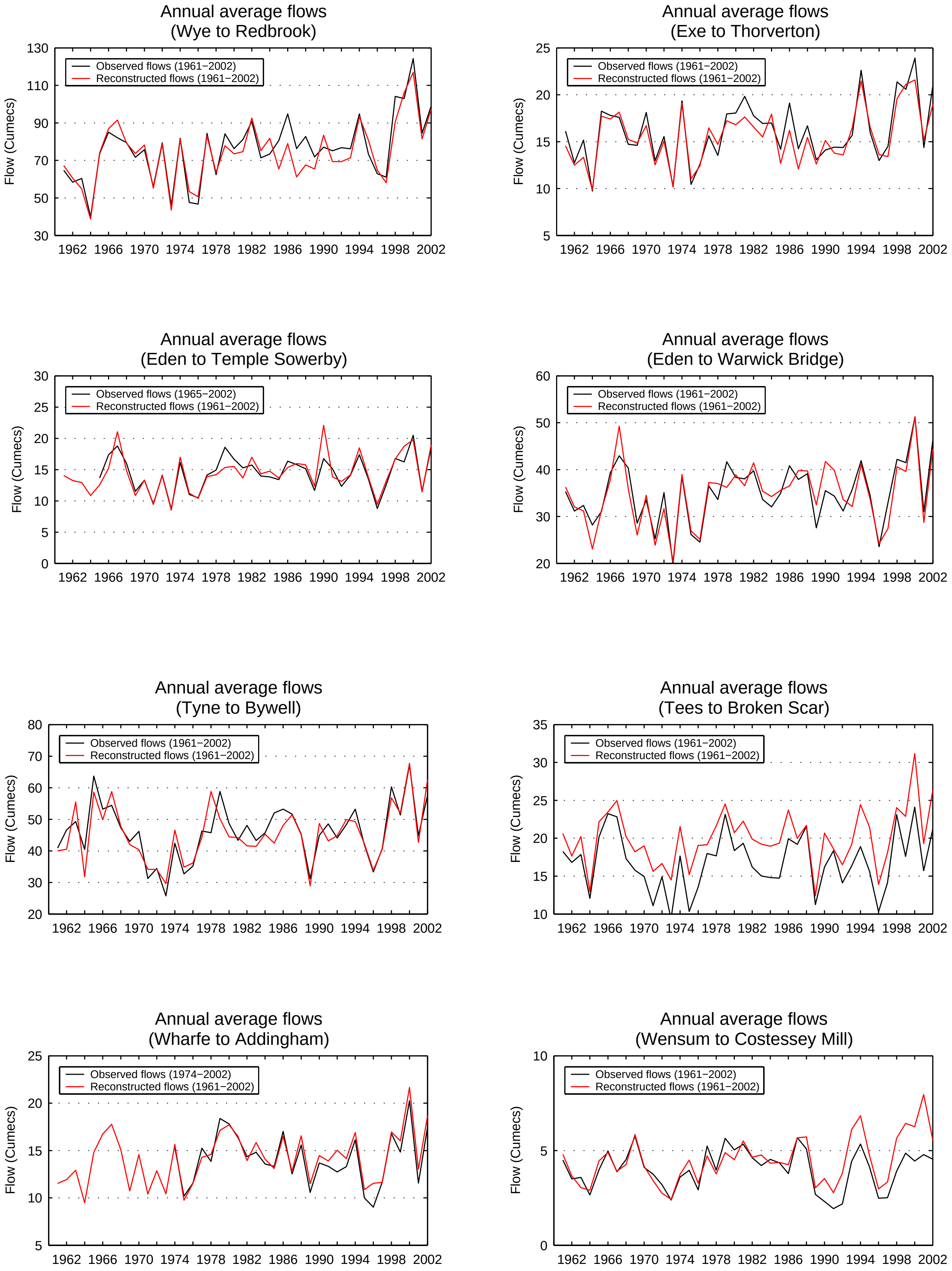
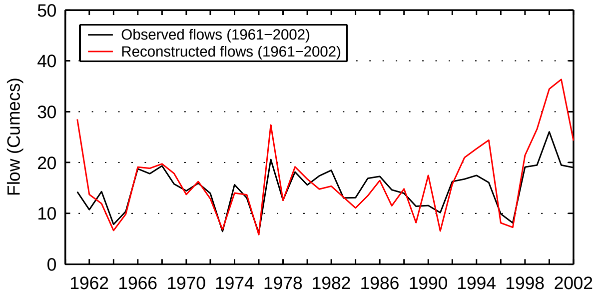
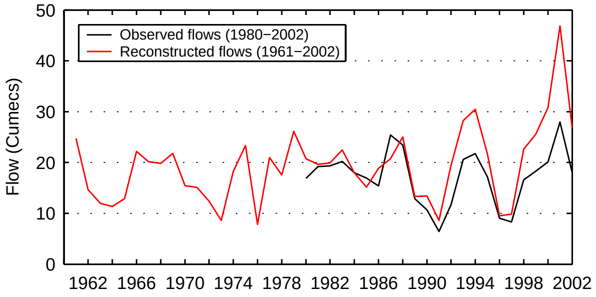
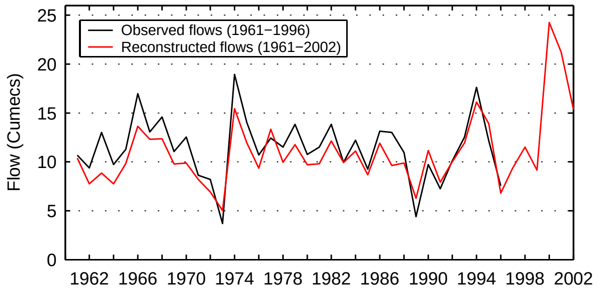
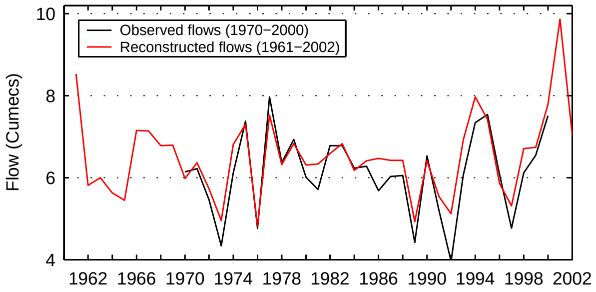


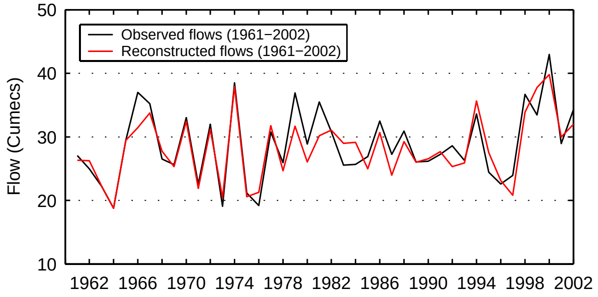
Figure A2.6 Annual average of observed (black line) and reconstructed (red line) flows

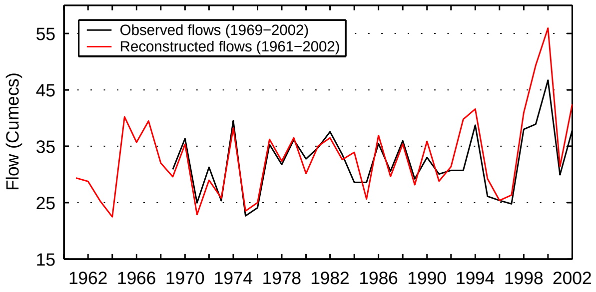

Annual average flows
(Thames to Eynsham)

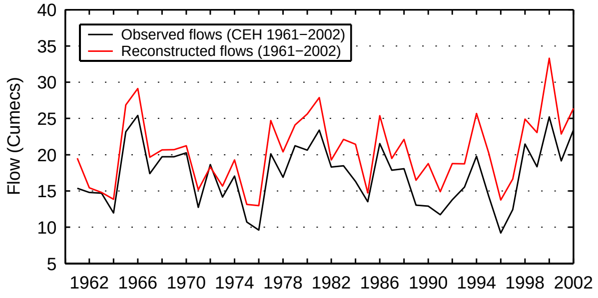

Annual average flows
(Ely Ouse to Denver Complex)


Annual average flows
(Medway to Teston)


Annual average flows
(Itchen to Highbridge/Allbrook)


Annual average flows
(Teifi to Glan Teifi)


Annual average flows
(Dee to Manley Hall/Erbistock)


Annual average flows
(Derwent to Derby/longbridge)

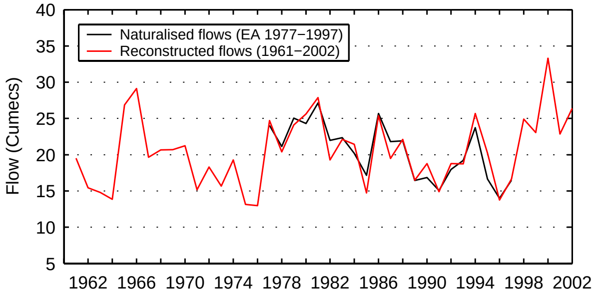

Annual average flows
(Derwent to Derby/longbridge)

Figure A2.6 (cont.) **Annual average of observed (black line) and reconstructed (red line) flows**

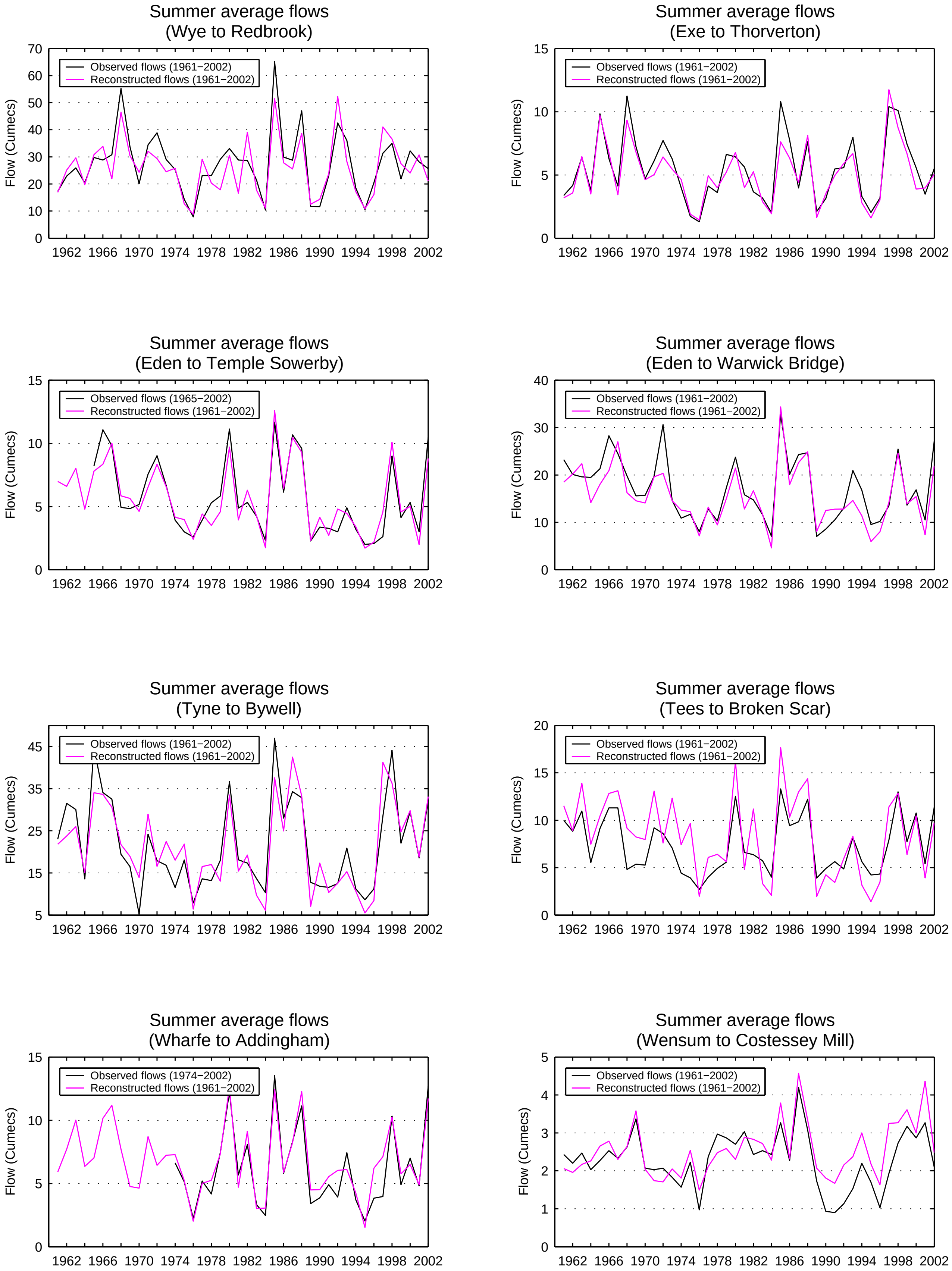


Figure A2.7 As in Figure A2.6 except for summer (June-Aug.) average flows

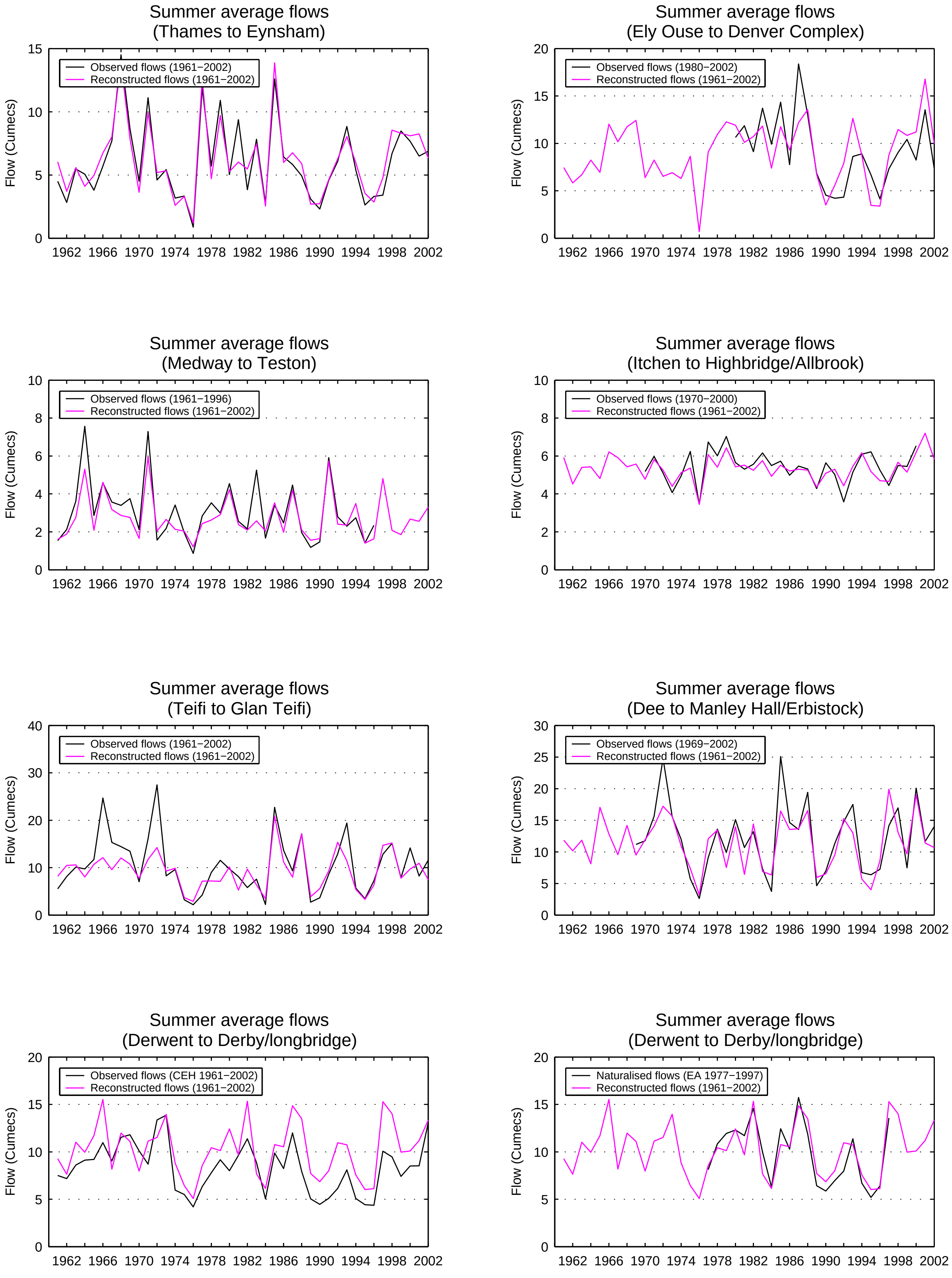


Figure A2.7 (cont.) **As in Figure A2.6 except for summer (June-Aug.) average flows**

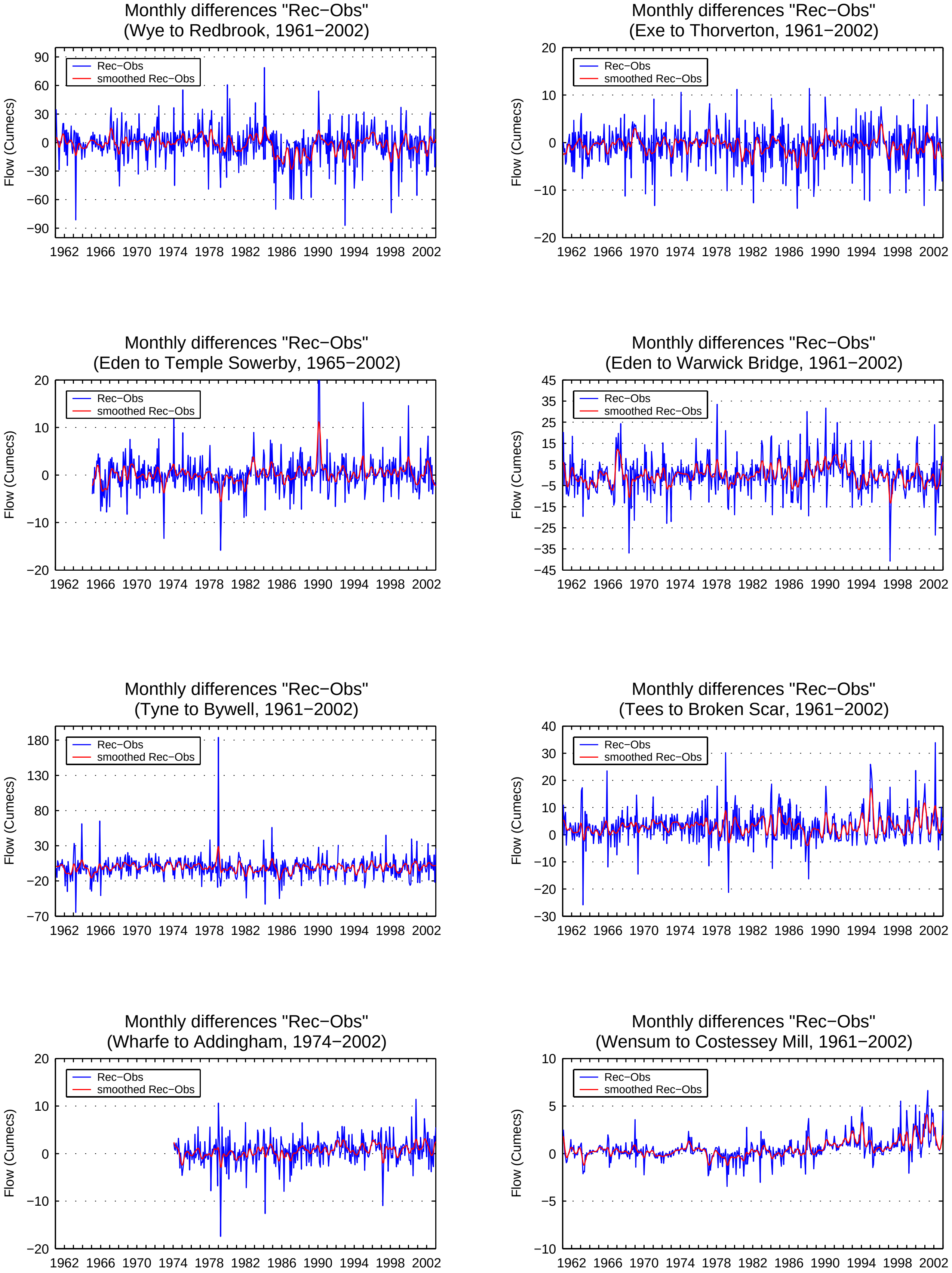


Figure A2.8 Monthly differences reconstructed – observed river flows (blue line). The red line shows the same values filtered with a 13 pt binomial filter.

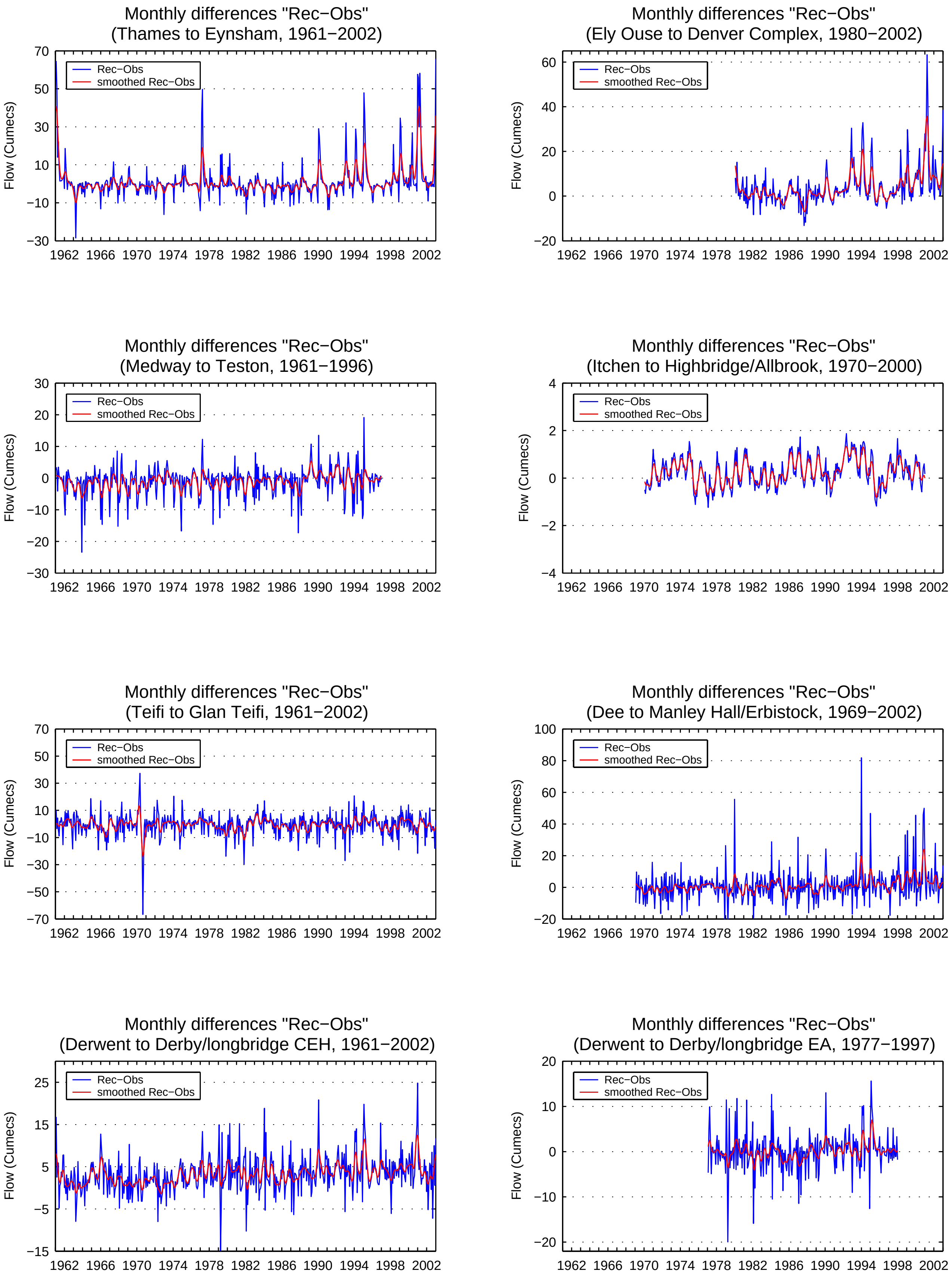


Figure A2.8 (cont.) **Monthly differences reconstructed – observed river flows (blue line). The red line shows the same values filtered with a 13 pt binomial filter.**

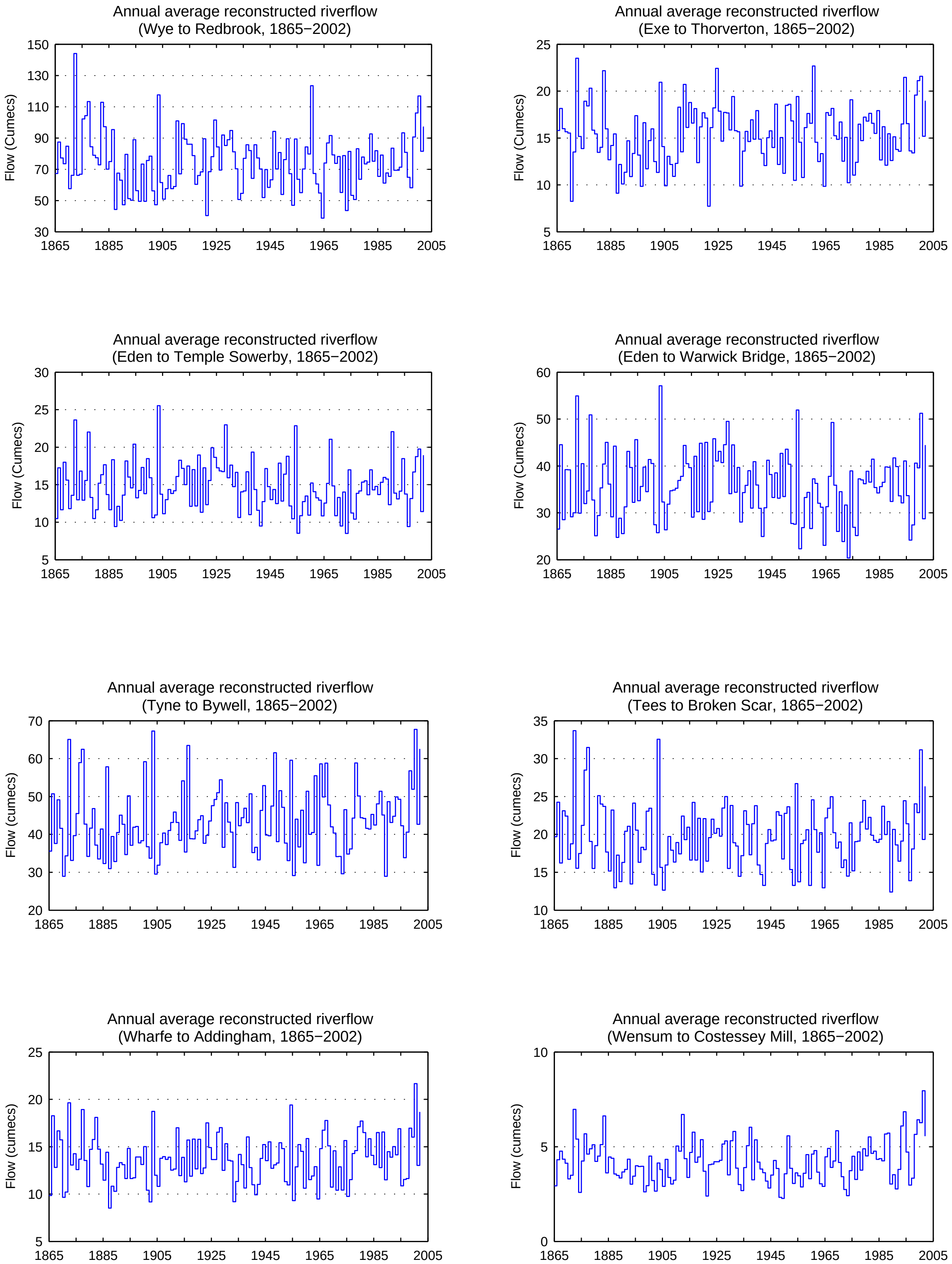


Figure A2.9 Annual average reconstructed river flows

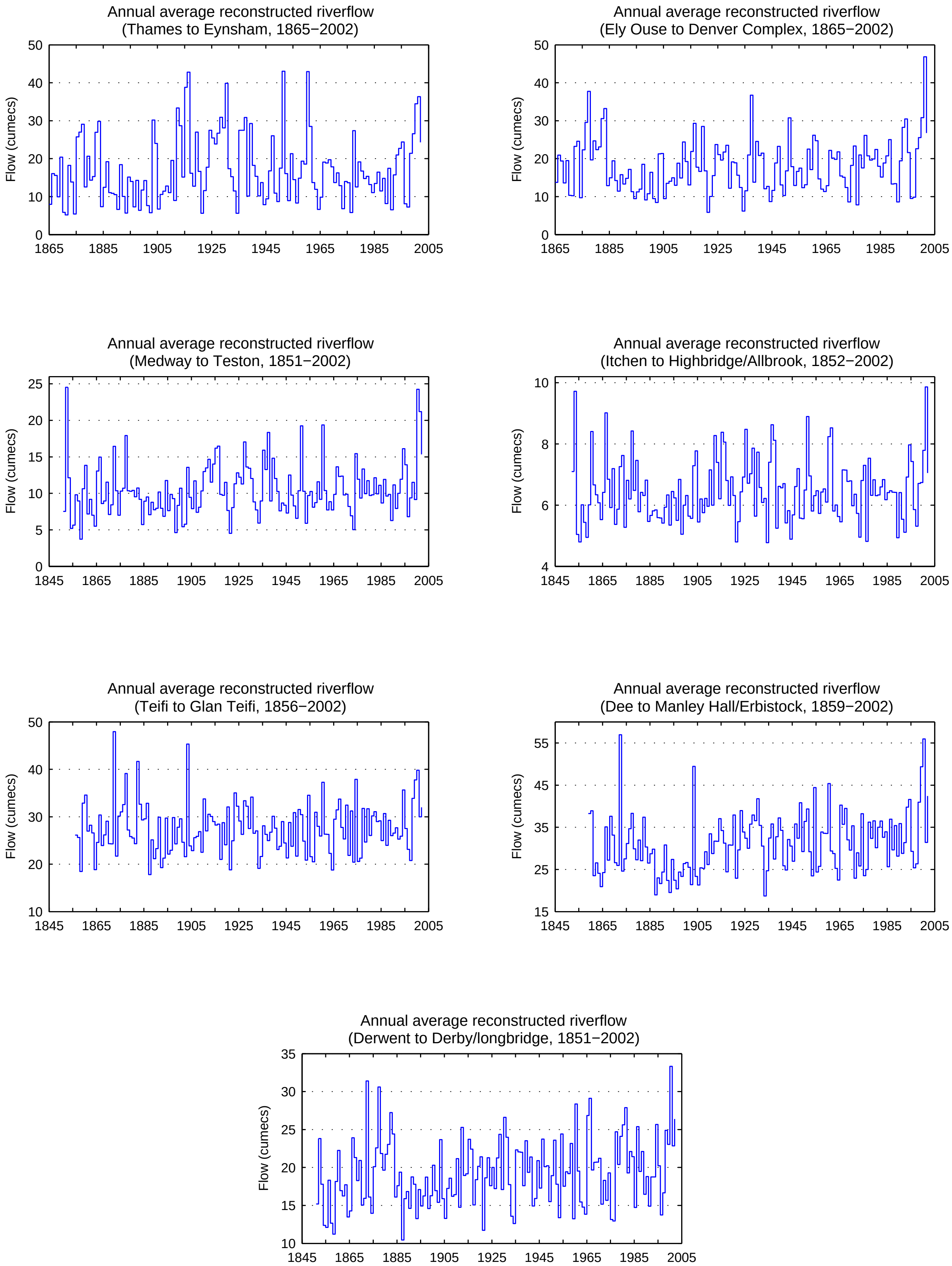


Figure A2.9 (cont.) **Annual average reconstructed river flows**

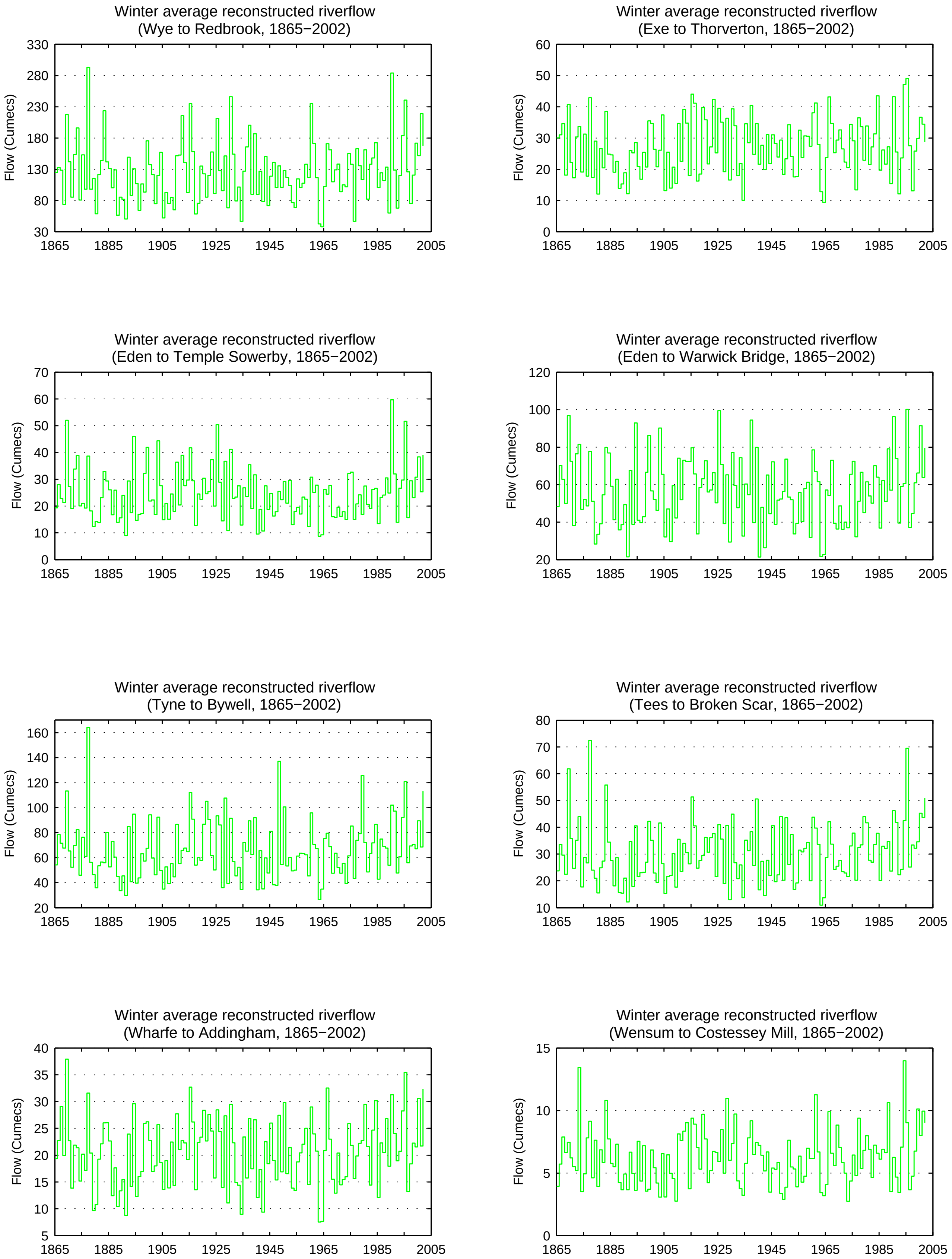


Figure A2.10 As in Figure A2.9 except for winter (Dec.-Feb.) average

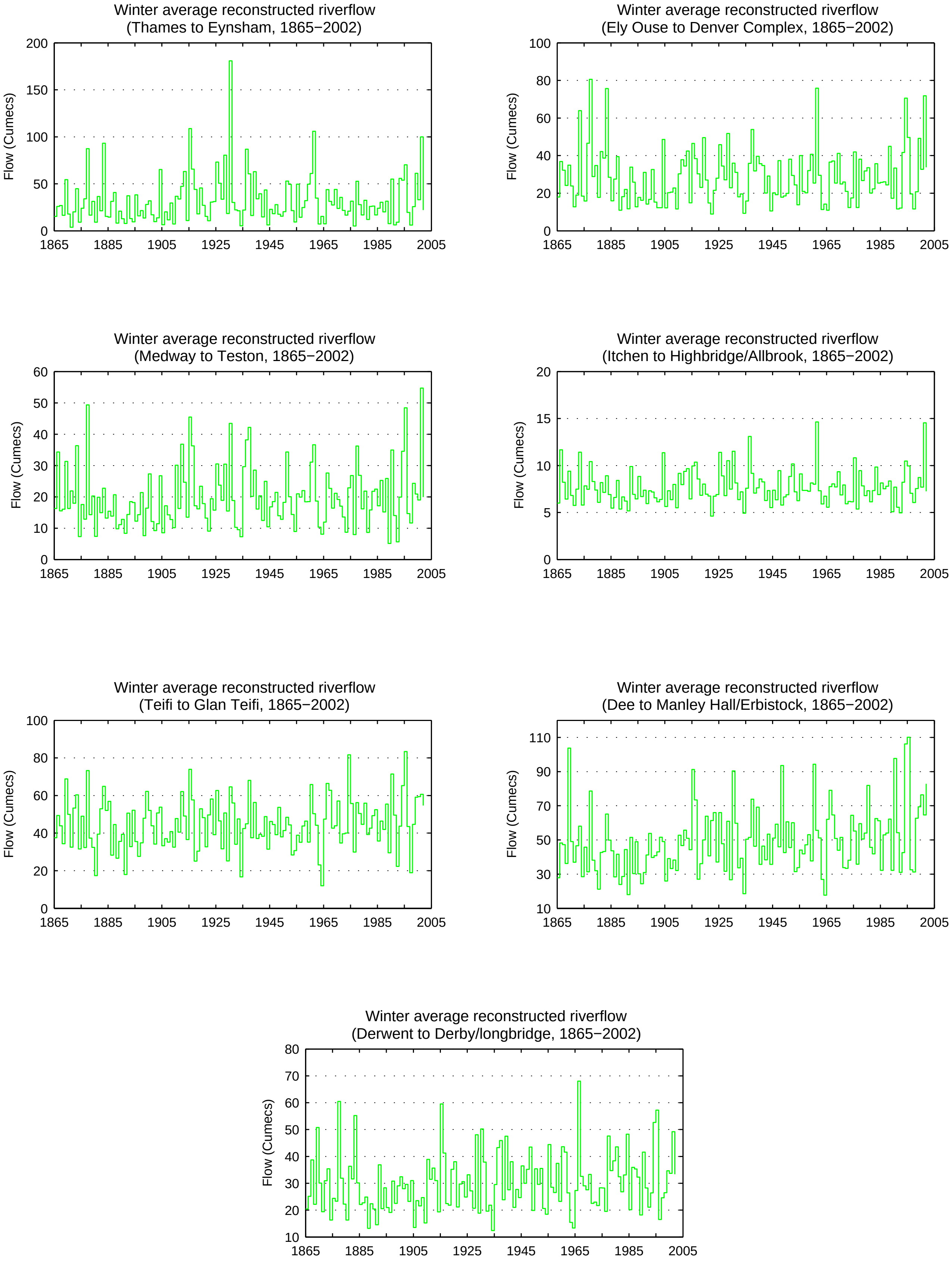
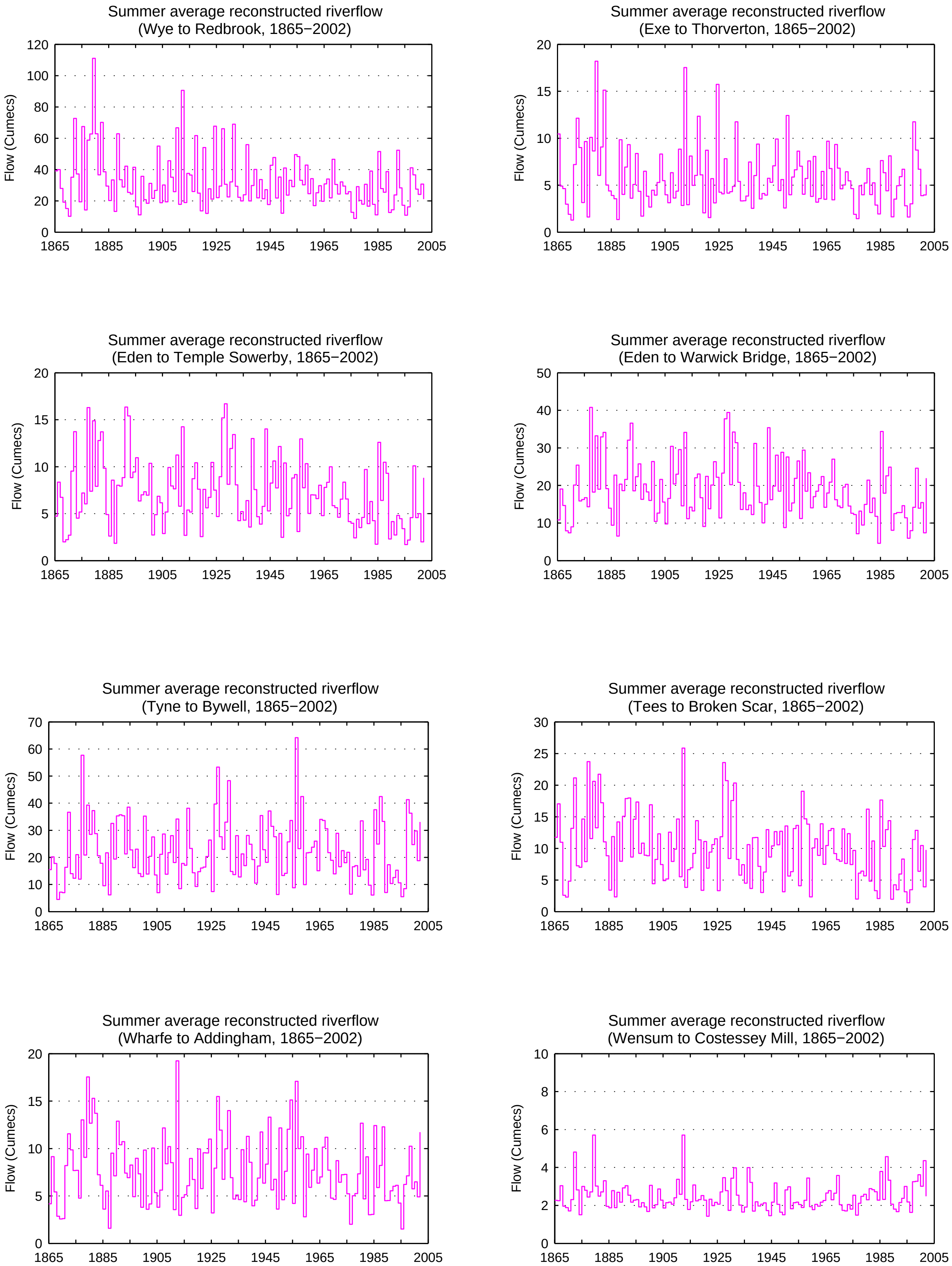


Figure A2.10 (cont.) As in Figure A2.9 except for winter (Dec.-Feb.) average


Summer average reconstructed riverflow (Wye to Redbrook, 1865−2002)

Summer average reconstructed riverflow (Exe to Thorverton, 1865−2002)

Summer average reconstructed riverflow (Eden to Temple Sowerby, 1865−2002)

Summer average reconstructed riverflow (Eden to Warwick Bridge, 1865−2002)

Summer average reconstructed riverflow (Tyne to Bywell, 1865−2002)

Summer average reconstructed riverflow (Tees to Broken Scar, 1865−2002)

Summer average reconstructed riverflow (Wharfe to Addingham, 1865−2002)

Summer average reconstructed riverflow (Wensum to Costessey Mill, 1865−2002)

Figure A2.11 As in Figure A2.9 except for summer (Jun.-Aug.) average

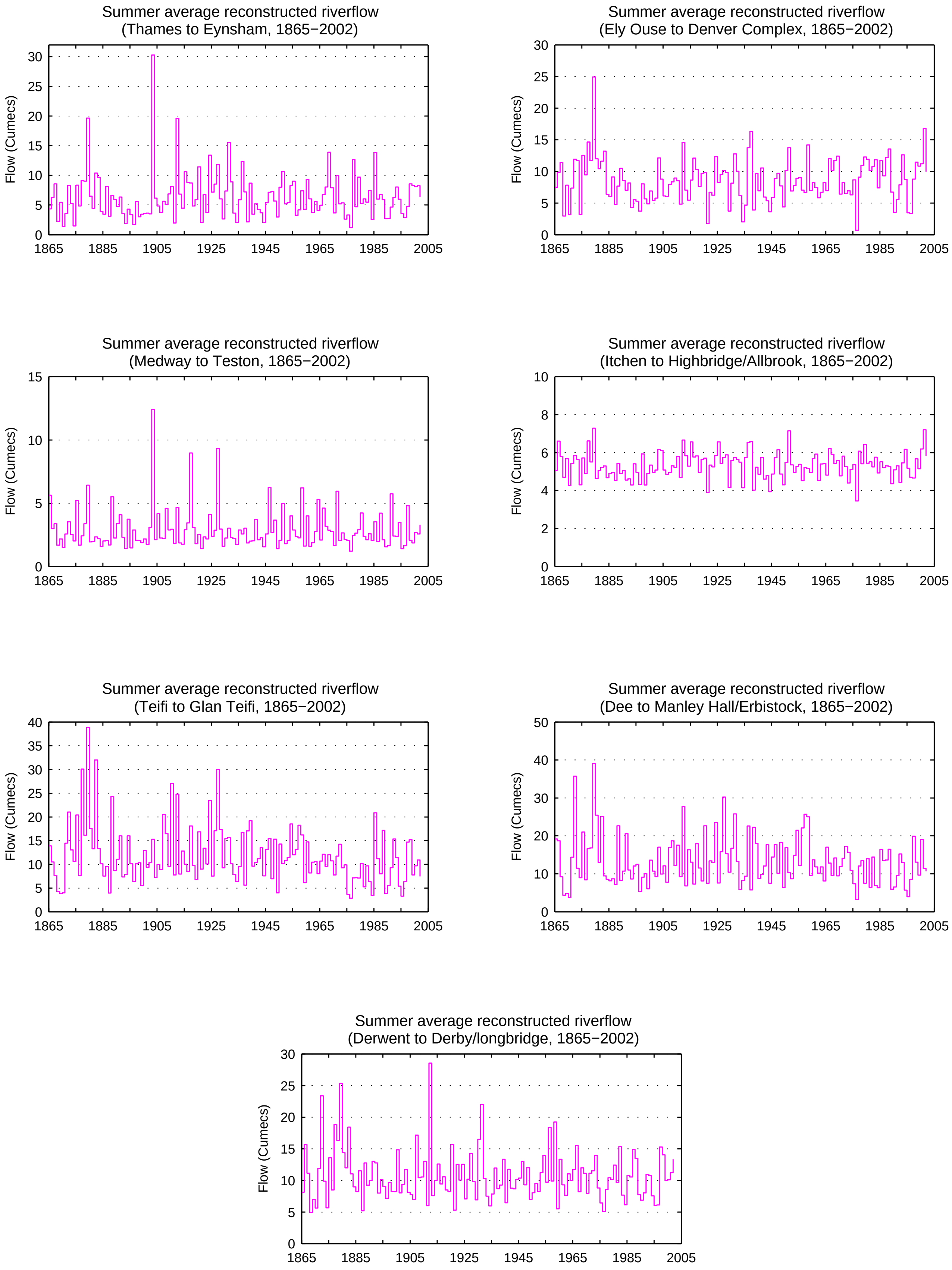


Figure A2.11 (cont.)   As in Figure A2.9 except for summer (Jun.-Aug.) average

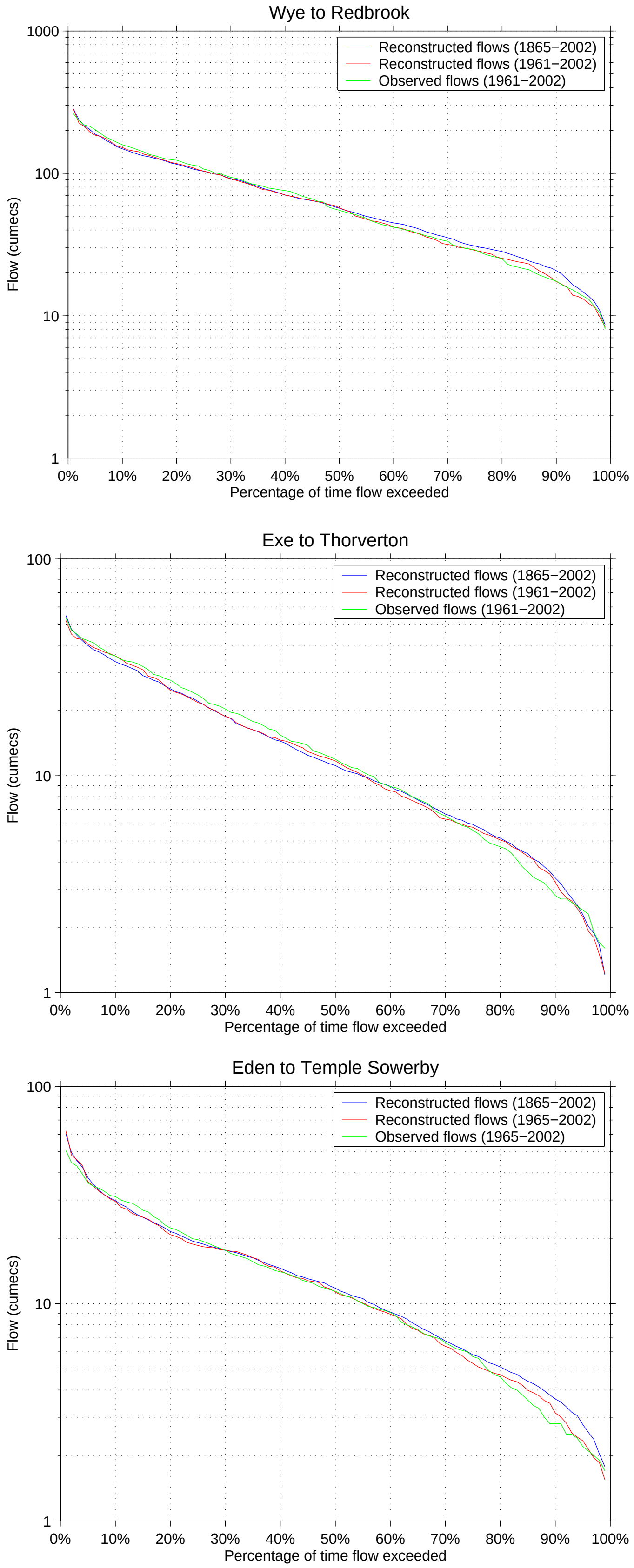


Figure A2.12 Flow duration curves of the reconstructed flows for the longer available period (blue line), the last 42 years (1961-2002, red line) and the observed flows (green line)

Figure A2.12 (cont.) **Flow duration curves of the reconstructed flows for the longer available period (blue line), the last 42 years (1961-2002, red line) and the observed flows (green line)**

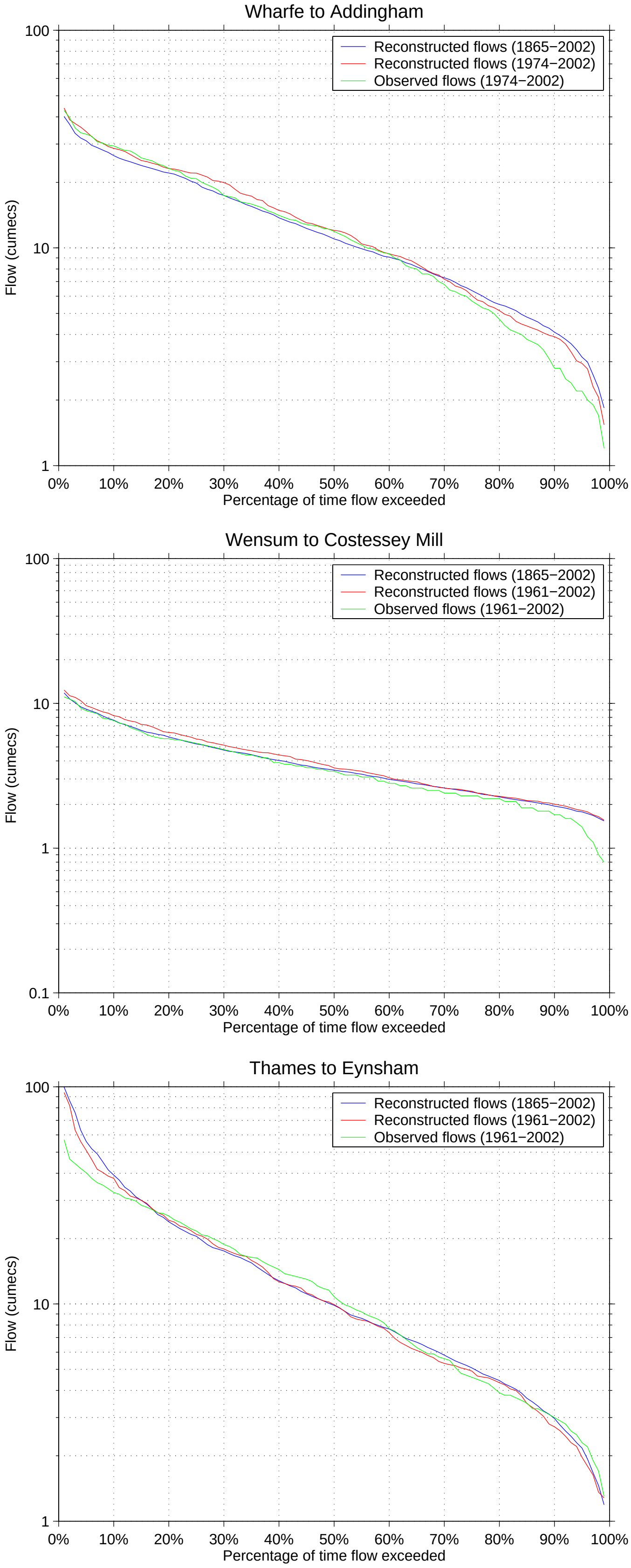


Figure A2.12 (cont.) **Flow duration curves of the reconstructed flows for the longer available period (blue line), the last 42 years (1961-2002, red line) and the observed flows (green line)**

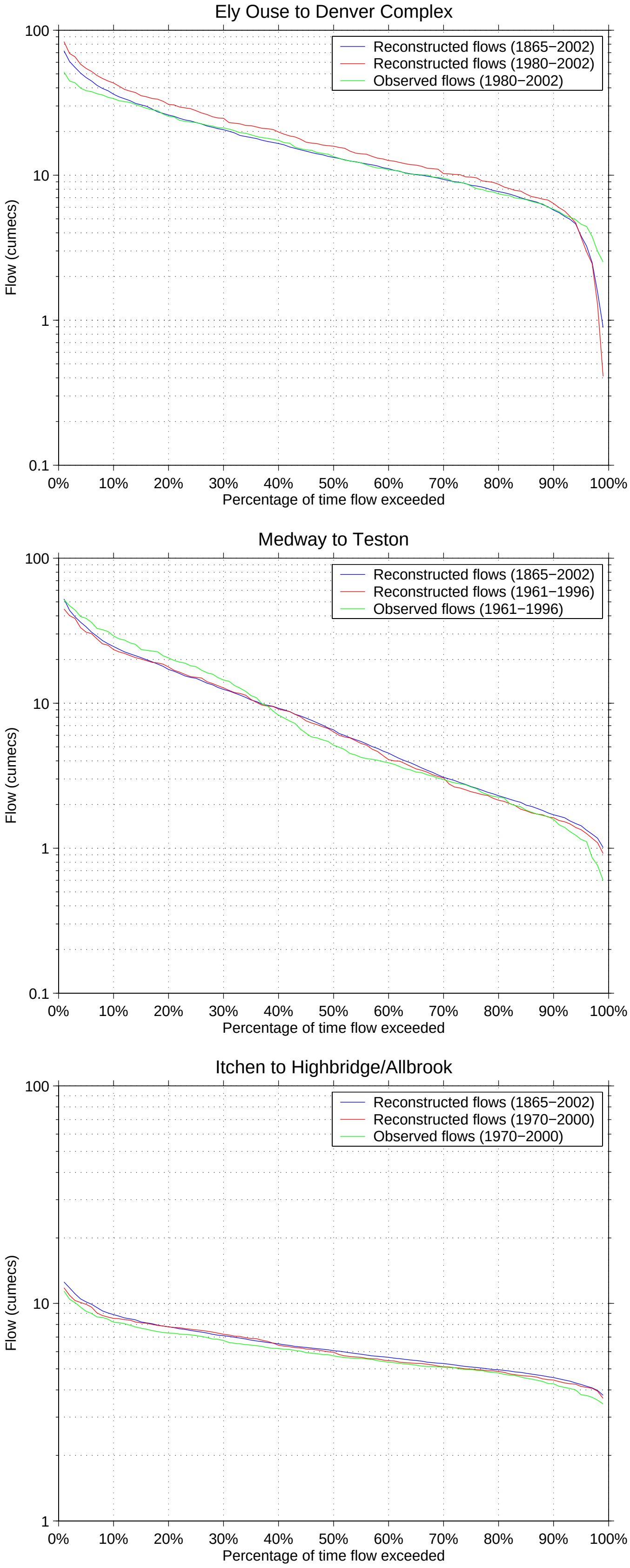


Figure A2.12 (cont.) **Flow duration curves of the reconstructed flows for the longer available period (blue line), the last 42 years (1961-2002, red line) and the observed flows (green line)**

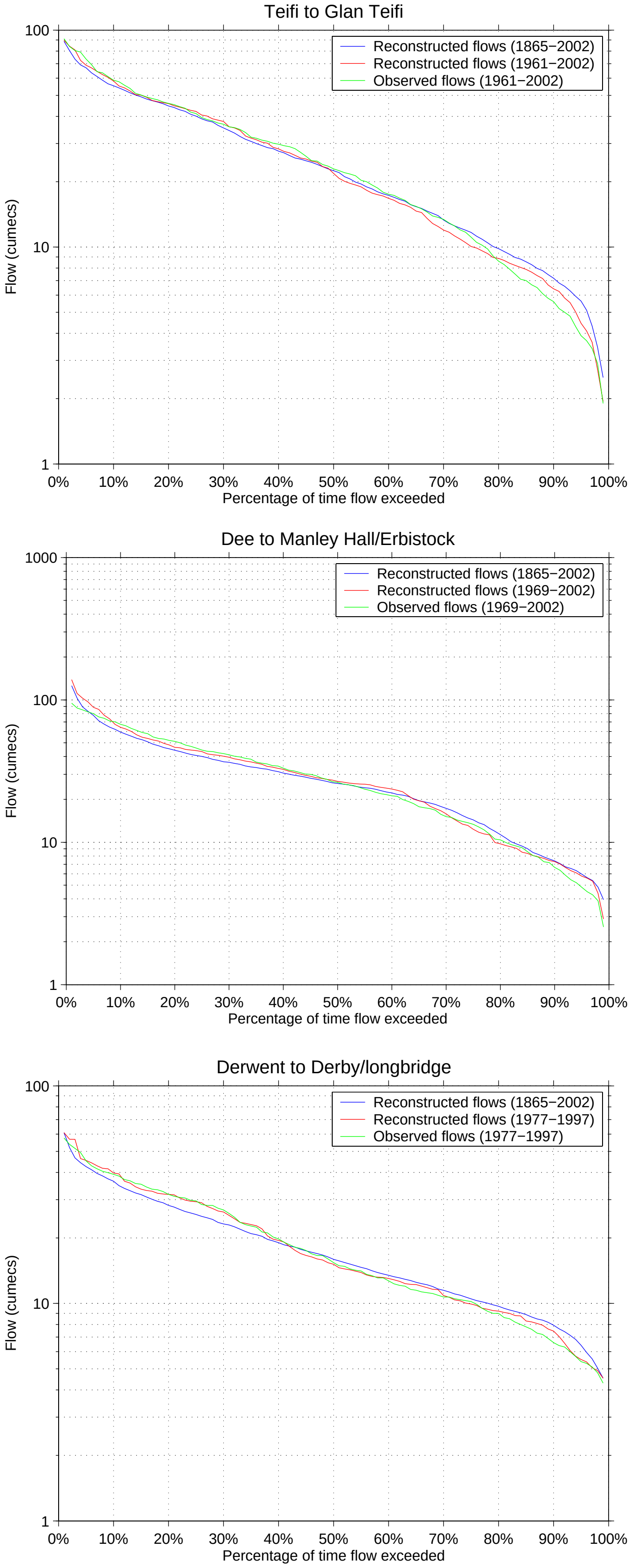


Figure A2.12 (cont.) **Flow duration curves of the reconstructed flows for the longer available period (blue line), the last 42 years (1961-2002, red line) and the observed flows (green line)**

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