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The impact of climate change on severe droughts

River-flow reconstructions and implied groundwater levels

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Executive Summary

Rainfall records for Eden and Ely Ouse catchments have been extended back on a monthly basis to 1800. Many of the records are not listed in the Met Office archives, but are available in the 10-year books held at the Met Office. An essential part of this work is to assess these long records for homogeneity. Monthly average river flows on the catchments were then extended back to this date, using a statistically based rainfall-runoff model, which has been used in a number of earlier studies. This model uses pre-determined equations that relate monthly rainfall totals to runoff, incorporating lags of up to 3 months for the Eden and 18 months for the Ely Ouse. Earlier work has shown that the model reproduces over 90 per cent of the variance of the monthly flows.

The extended sets of flow records were assessed for the lowest flow sequences of 6 months duration on the Eden catchments and 18 months for the Ely Ouse. On the Eden, three of the four most severe drought periods (according to this definition) occurred within the instrumental gauging period (since the early 1960s). The three droughts were in 1989, 1995 and 1996. The second most severe drought since 1800 was estimated to have occurred in 1826. A number of other, but less severe, drought episodes also occurred prior to the instrumental period. On the Ely Ouse catchment, the most severe drought was in 1803, with a number of other droughts prior to instrumental gauging on the catchment (which began in the late 1920s). Five of the worst 12 droughts occurred in the instrumental period. The long series have been used, in an analogue approach, to develop daily series for 204 years for all intake points on the respective water resource systems in the two regions. These longer sequences will be used with reservoir and other water resource systems to reassess reliable yields in a later part of the study. In addition, these sequences will be perturbed by the additional factor of future climate change, to further investigate yields.

The monthly Central England Temperature (CET) was adjusted for location and elevation to provide an historical temperature record for the two catchments. The purpose of this simple exercise was to develop monthly estimates of Potential Evapotranspiration (PET) which, with the temperature series, will be used in later aspects of the study.

Groundwater level records, like runoff records, are also relatively short in most regions of England and Wales. Using annual minimum groundwater-level data for the past 30-50 years, regression models have been developed based on monthly rainfall and temperature records for two sites, Washpit Farm and Skirwith. The models are slightly less good than the runoff models, but still explain about 60 per cent of the variance of groundwater levels. The models were then used to reconstruct groundwater levels back to 1800.

The different integrating nature of the system means that the lowest levels are only loosely related to the lowest reconstructed flows. For Washpit Farm, 11 of the lowest values occur before measurements began in 1950. For Skirwith, only three of the lowest levels occurred before measurements began in 1978.

Contents

1. Introduction

The purpose of this project is to assess the implications of severe droughts for the water resources of England and Wales. This work will be undertaken using a 'bottom-up' approach; that is, the reconstruction of specific climate events followed by an assessment of their potential impact and identification of the possible management and/or adaptation measures that could be taken to mitigate those impacts. This is complementary to the 'top-down; approach that has been taken more often, in which scenarios of future climate are developed that include a range of different climate events and the overall impact of such sequences of possible future 'weather' are assessed. The range of events contained in such 'top-down' approaches can be dependent upon the particular methods, and the particular sequences of the observed and/or simulated weather, used to construct the scenarios. The 'bottom-up' approach, however, can be used to consider the impacts of a specific weather or climate event and its possible intensification (or other modification) through climate change. The two approaches are implicitly linked via the need to quantify how the frequency, intensity or duration of such events might change in the future.

The range of natural variability experienced over multi-decadal time scales is unlikely to be characterised fully by records that cover recent decades or even the past 100 years. There is an advantage, therefore, in looking further back in those locations where observed data permit. Extending records back to the early 1800s would help to place recent extreme events within a larger context. It could possibly sample naturally occurring extremes that are of greater magnitude than more recent events – for example, there is evidence for very dry periods in the 1850s and 1890s, respectively (Barker *et al.*, 2004; Jones *et al.,* 1997).

There is a need, therefore, to reconstruct river flow and groundwater records back into the early 1800s, and to achieve this long precipitation and temperature records must be developed. Analysis of these extended records can be used to identify severe drought events, supported strongly by an assessment of documented evidence for drought events and their impact. Such severe drought events can then form the basis of an assessment of future climate change impact, on the premise that they are natural events that could recur, maybe more frequently or more severely through future climate change. The resilience of water supply and distribution systems to the recurrence of such events (or of more severe events) can be modelled, to identify the need for adaptation responses to the changing risk of severe droughts. Such adaptations could take place at a range of levels, including planning and policy, as well as practical measures and the communication of risk.

1.1 Project objectives

Overall, the aim of the project is:

- To provide an improved understanding of the impact of past and possible future severe droughts on water resources, taking case studies from the east of England and from north-west England.

This overall aim will be achieved by the following principal objectives:

1. extend meteorological records of precipitation and temperature back to the early 1800s;
2. use empirical models to reconstruct the river flow and ground water levels that are likely to have accompanied the meteorological conditions, again back to the early 1800s;
3. identify and assess the evidence for severe drought events during the 1800s according to the meteorological and hydrological data, and documented evidence of impacts, and thus extend (and provide a longer context for) catalogues of recent events;
4. use the information provided by high-resolution climate models to predict climate change scenarios to identify possible changes to the frequency, intensity and/or duration of severe drought events;
5. use empirical models to simulate river flow and groundwater levels likely to accompany a more intense and/or longer duration drought event (consistent with the changes implied by the climate change scenarios);
6. examine the effect of historical droughts and possible future droughts on water resources and the resilience of the present supply and distribution systems;
7. consider the adequacy of current policy and guidance for managing water resources, in the context of severe droughts that may recur naturally, or as a result of climate change;
8. recommend improvements and/or adaptation strategies, applicable to both the case study regions and other regions or sectors, that cover aspects of planning, policy, management, risk communication, monitoring and practical infrastructure.

1.2 Report summary

This report details the results from objectives 1, 2 and 4, with some discussion also of area 3. A more detailed report on area 3 has been produced by Cole and Marsh (2005). This extends the results provided here by assessing drought frequency over wider geographical areas and further back in time. Sections 2–4 detail the work undertaken on the first two principal objectives, with some brief discussion of objective 3 for the specific catchments in section 4. Section 5 discusses the principal objective 5. A later report will address objectives 4 and 6–8. Section 6 provides some interim conclusions.

2. Extending meteorological records

2.1 Identification and digitisation of Met Office records

An assessment of existing work (such as Jones, 1984; Wigley *et al.*, 1984; Jones and Lister, 1998) and the availability of additional early rain gauge observations was undertaken. The result of this assessment showed that the longest extension to the historical record length could be achieved for the Ely Ouse in the eastern England region, and the Eden in the north-west England region. Many of the early records for these catchments were already digitised (Jones, 1984; Wigley *et al.*, 1984) and the newly compiled central Lake District record (Barker *et al.*, 2004) could also be utilised. *Figures 1* and *2* show the spatial extent of the two selected catchments.

The key records from the Met Office '10-year books' were identified and digitised for the decades from the late-18th century up to 1860. Areal catchment averages for the catchments were already available for the period from the early 1850s (see details in Jones *et al*., 2004 and Jones *et al*., 2005). The periods of record for these additional early rain gauges for the two catchments are shown in *Figure 3*. The Barker *et al.* (2004) record is shown in *Figure 3* as the 'Lake District Series'. With these records, estimates of catchment-average rainfall for the Ely Ouse and the Eden have been produced back to approximately 1800.

Less emphasis was placed on the extension of the temperature records further back in time, because of the greater spatial coherence of temperature anomalies when compared to precipitation anomalies. This allowed the use of the Central England Temperature (CET) record (Parker, *et al.*, 1992), which already extends back to 1772 with daily records and 1659 for monthly values. It is also more complex to create a new long homogeneous time series of temperature records compared with precipitation time series, because of greater biases introduced by changes in instrument exposure and recording practices. The CET record was adjusted for the differences in temperature between the CET 'area' and the two catchments by comparing the individual monthly averages (like for like) of the CET and the catchment averages of the Met Office 5 km × 5 km grid baseline temperature data sets for 1961-2000 (Perry and Hollis, 2005a, 2005b). The adjustment factors are given in *Table 2.1*.

These reconstructed temperature series have been used to create monthly potential evapotranspiration estimates based on the Thornthwaite approximation. The results of these calculations are shown in *Figure 5*.

Table 2.1 CET adjustment factors for the two catchments

Month	*CET mean (°C) (1961-2000)*	*Ely Ouse adjustment*	*Eden adjustment*
January	3.9902	-0.4598	-1.9059
February	4.0561	-0.3059	-1.8720
March	6.0463	-0.1408	-2.2188
April	8.0805	-0.0885	-2.1805
May	11.3290	-0.0434	-2.2871
June	14.2460	0.0315	-2.4155
July	16.1900	0.1910	-2.6346
August	15.9560	0.3981	-2.5493
September	13.6830	0.3040	-2.4422
October	10.5370	0.0374	-2.1330
November	6.7268	-0.3299	-2.1327
December	4.6488	-0.4215	-1.9558

2.2 Assuring the homogeneity of the precipitation time series

When constructing a long-term areal catchment rainfall series, it is necessary to combine a number of shorter records and to ensure that (especially where those records are themselves composites) comparison with available long-term time series is good. It is known that the spatial variability of rainfall is greater on the Eden catchment than on that of the Ely Ouse (Wigley *et al.*, 1984), so greater emphasis was placed on ensuring the homogeneity for this catchment, to ensure the quality of the catchment average series as far back as possible. Homogeneity of the records for the post-1860 period had been assessed earlier (see Jones *et al.*, 2004, 2005, and references therein). *Figure 4* shows the comparison between the individual rain gauges, and excellent agreement can be seen between all gauges on both catchments. The catchment averages were produced using the technique discussed in Jones *et al.* (2004, 2005). *Figures 6*, *7* and *8* show the total annual, summer and winter catchment average rainfall for the two catchments.

3. Reconstructing historical flow records using empirical catchment models

Equations were already available for both catchments to transform the monthly areal catchment rainfall totals to monthly runoff at Denver Sluice for the Ely Ouse and both Temple Sowerby and Warwick Bridge/Great Corby for the Eden. These equations are based on those of the empirical catchment model of Wright (1978), later used by Jones and Lister (1998) and Jones *et al.* (2004, 2005). The model parameters were originally estimated by calibration against observed flow records by Jones (1984). Apart from the rainfall input, the model also requires seasonally constant estimates of actual evaporation (i.e., 12 monthly totals, each used for that month in all years). This model has been proven by comparison between observed and reconstructed flows over the past 40 years (Jones *et al.*, 2004, 2005), particularly for periods of low flow. The model parameters are calculated to give the best fit to the logarithm of the monthly flows, which implicitly places greater weight on achieving a good fit to the low flow values. These calibrated empirical models were fed the extended catchment average rainfall records, and the reconstructed monthly flows can be seen in *Figures 9*, *10* and *11*.

3.1 Providing input data for water resource modelling

The water resource models used by United Utilities (UU) and Anglian Water (AW) require daily flow record inputs at various stations throughout the catchments. As the reconstructed flow series from the empirical model (Section 3) are monthly averages, a scheme had to be devised that would allow the construction of daily reconstructed flow series from existing daily flow records (available for the shorter ‘observed period’) and the longer reconstructed monthly flow records. To represent natural variability in the reconstructed flows, the series were created by selecting the daily flow series from a corresponding month (i.e., January with January, February with February) whose mean closely matches the reconstructed mean flow and so develop an analogue series for each station. When selecting from the possible analogue months, preference was given to those months in which the first day's flow was close to the flow of the last day of the previous month. This prevents large jumps from occurring in the flow record at the end of one month to the start of the next. Once the analogue sequence had been created from the monthly flow data, a correction had to be applied to give the correct average values for the sites required by UU and AW (see *Figures 12* and *13*). The monthly R^2 of these adjustments has a range of 0.57-0.77 for the Ely Ouse and of 0.14-0.85 for the Eden. The weakest fits for the Eden are for sites where the daily flow series have been synthesised or in-filled (Dash Beck in *Figure 12* and Hause Gill, QHill and Worm Gill in *Figure 13*). Discounting these sites, the monthly R^2 range becomes 0.54-0.85.

The quality of the analogue series can be gauged by comparing the analogue flow record with the observed flow record for various conditions. The analogue and observed flows for the Ely Ouse are shown in *Figures 14*, *15* and *16* for the years 1975-1977, 1989-1991 and 1992-1995, respectively. From *Figures 14* and *15* it can be seen that the analogue approach works particularly well during low flow periods (such as the first half of 1976 and the summer of 1990). The analogue also represents well the overall shape of higher flow periods (*Figure 16*), but of course does not correspond exactly to individual daily flow events. Flow duration curves have been produced for two selected daily input sequences within each of the AW and UU study regions. These are shown in *Figures 17* and *18*.

4. Identification of severe drought events

Drought events were identified by comparing the flow records over a moving time window to the long-term average flow records. This window was set at 6 months for the Eden catchment and 18 months for the Ely Ouse, to reflect the longer groundwater residence time of the Anglian catchment. The severities of the drought events were ordered by the percentage of the long-term average flow represented by the average flow in the moving time window. The most severe droughts for the Ely Ouse, and southern and northern Eden catchments are shown in *Tables 4.1*, *4.2* and *4.3*.

Table 4.1 Ely Ouse severe droughts

Rank	*Average flow (cumecs)*	*Long-term average flow (per cent)*	*End month/year*
1	5.03	29.70	11/1803
2	5.85	34.54	11/1934
3	6.30	37.15	10/1922
4	6.56	38.68	11/1815
5	6.56	38.70	11/1991
6	6.85	40.41	10/1944
7	7.06	41.64	10/1997
8	7.31	43.16	10/1894
9	7.40	43.64	11/1973
10	7.51	44.30	11/1902
11	7.73	45.59	10/1855
12	7.78	45.91	09/1808

Table 4.2 **Southern Eden (to Temple Sowerby) severe droughts**

Rank	*Average flow (cumecs)*	*long-term average flow (per cent)*	*End month/year*
1	2.61	17.96	09/1995
2	3.13	21.53	09/1826
3	3.45	23.76	09/1996
4	3.57	24.54	10/1989
5	3.64	25.01	10/1919
6	3.71	25.55	08/1869
7	3.92	26.97	09/1955
8	4.00	27.52	08/1984
9	4.00	27.55	10/1901
10	4.02	27.66	09/1941
11	4.03	27.73	09/1842
12	4.09	28.16	10/1913

Table 4.3 **Northern Eden (to Warwick Bridge) severe droughts**

Rank	*Average flow (cumecs)*	*Long-term average flow (per cent)*	*End month/year*
1	9.55	26.71	09/1995
2	9.81	27.44	09/1826
3	10.03	28.06	09/1984
4	11.00	30.76	10/1989
5	11.18	31.28	09/1996
6	11.57	32.35	10/1919
7	11.88	33.22	09/1806
8	12.08	33.78	11/1915
9	12.21	34.13	09/1870
10	12.28	34.33	10/1887
11	12.38	34.62	09/1955
12	12.46	34.85	08/1869

5. Reconstruction of historical groundwater levels using empirical models

5.1 Background to methodology development

A robust assessment of drought yield available from groundwater resources is an essential part of water resource and operational planning. In the report *Water Resources and Supply: Agenda for Action*, published by DoE in October 1996, water companies were given the task of preparing estimates of the yields of their systems. The approach to be adopted was set out in a set of guidelines produced by the Environment Agency. For groundwater, the guidelines were based on the UKWIR groundwater methodology to calculate deployable output (UKWIR, 2000).

It is important to distinguish between a number of factors related to borehole yield and deployable output of groundwater sources (UKWIR, 2002). The *hydrological yield* is the natural output of a source that can be supported by the aquifer feeding the sources for a given groundwater level. The hydrological yield can therefore be considered as the unconstrained yield. The *potential yield* is the yield for specified conditions and demands of a commissioned source or group of sources as constrained only by well construction and/or aquifer properties. The *deployable output* is the output for specified conditions and demands of a commissioned source or group of sources as constrained by licence, other constraints associated with the infrastructure at the source and local distribution network, or environmental and water quality considerations. Groundwater level is an important variable that affects the hydrological yield, although it is acknowledged that the potential yield and deployable output of a groundwater source may differ significantly from the hydrogeological yield through factors such as well construction, licence or other constraints associated with the infrastructure. An estimate of drought groundwater levels is required as part of the UKWIR groundwater methodology to calculate deployable output – a minimum groundwater level reached in an extreme or worst-case drought in the recent record, such as 1976, is usually used in the calculations for any particular groundwater source.

Given this context, this section describes a methodology that can be used to hindcast deployable output values for groundwater sources. It also provides estimates of historical groundwater level minima at two sites, based on the hindcast monthly rainfall and temperature time series available for the Ely Ouse and the Eden catchments.

However, the estimation of annual minimum groundwater levels using monthly rainfall and temperature data is problematic for a number of reasons:

- Unlike surface water flows, there are relatively few long groundwater level records (i.e., with records before 1960), and there are no reliable long groundwater level records in the Ely Ouse and the Eden catchments. So any calibration of empirical groundwater models has to be over a relatively short period, typically 40 years or less.

- The response of groundwater levels to rainfall events is usually highly damped and subject to relatively long lags. Rainfall signals are commonly highly attenuated.
- Annual groundwater level minima are primarily a function of antecedent groundwater level maxima and the length of the recession. The end of groundwater recession is associated with the removal of the soil moisture deficit and the onset of recharge. It is not satisfactory to develop predictive hindcast or forecast models that include antecedent high groundwater levels. This is because the models would need to include a calculation of the antecedent high groundwater levels at each iteration of the model and errors would rapidly accumulate in the predictions.

5.2 Selection of sites and data used in the reconstruction

Groundwater level observation wells are used to monitor groundwater levels. Observation wells may be sited to monitor local effects associated with groundwater abstraction or other anthropogenic influences, or they may be used to monitor regional groundwater levels. In 1981 the British Geological Survey reviewed the national observation well network and selected 175 sites to be used to monitor regional groundwater levels. A number of these wells are known as Indicator Wells or Index Boreholes. These wells are thought to be the most representative of natural regional groundwater levels in the major aquifers of England and Wales. Groundwater levels are recorded typically at weekly or monthly intervals at the Index Boreholes. Sites were chosen from Index Boreholes held on the National Groundwater Level Archive.

Data from the monitoring network is held in the National Groundwater Level Archive, which can be found at:

http://www.nerc-wallingford.ac.uk/ih/nrfa/groundwater/index.htm

In addition to giving details of how the groundwater level data are collected, recorded and archived, the web site provides a map of the well locations and a list of all the monitored sites.

The two sites that were chosen for the present study are Washpit Farm for the borehole in the Chalk (Ely Ouse catchment) and Skirwith for the borehole in the Permo-Triassic sandstones (Eden catchment). These sites were chosen as they were the sites that had the most complete and longest groundwater level records of Index Boreholes near the two study catchments. Details of the two records are given in *Table 5.1*.

In both cases the groundwater level measurements consist of generally monthly with some weekly data. In addition, some monthly data are missing for the Skirwith record in the late 1980s. Consequently, the annual minimum groundwater levels taken from these records are likely to be a slight underestimate of the true minima. It is thought that both sites are relatively free of the influences of groundwater abstraction. *Figures 19* and *20* show the monthly groundwater levels for the Washpit Farm and Skirwith sites, respectively, with the annual minimum groundwater levels indicated by the pink symbols.

Table 5.1 Sites used in the groundwater models

Well number	*Grid reference*	*Site*	*Period of record*	*Comments*
TF81/2	TF 8138 1960	Washpit Farm	1950 to 2005	Irregular observations of groundwater level, at least monthly with some weekly data
NY63/2	NY 6130 3250	Skirwith	1978 to 2005	Irregular observations of groundwater level, generally monthly with some weekly data. Some monthly data missing in the late 1980s

The rainfall data used in the groundwater model calibration is Centre for Ecology and Hydrology (CEH) gridded rainfall data for 1 km squares that contain the two sites. The gridded rainfall is based on rainfall records from at least three nearest neighbour rain gauges and extrapolated to 1 km grid squares. The rainfall time series used in the groundwater models are shown in *Figures 21* and *22*.

5.3 Methodology

The method used to reconstruct historical groundwater levels consists of:

i. calibration using empirical groundwater level minima and rainfall data (see Section 3) in a regression model;
ii. hindcasting using hindcast rainfall and temperature data substituted into the calibrated model.

The methods used in each step are described briefly below.

5.3.1 Model calibration methodology

A multiple linear regression (MLR) similar to that used by Bennett (1996) and Bloomfield *et al*. (2003) has been used to produce a calibrated model of the observed annual minimum groundwater levels at each site. A number of assumptions should be satisfied if a linear regression model is used. These include:

- **Linearity** – linear regression analysis is a linear procedure.

- **No autocorrelation** in the dependent and independent variables and no cross-correlation between the independent variables.
- **No overfitting** (over-parameterisation) of the model. By adding additional independent variables, R^2 can be significantly increased. Cross-validation and related techniques can be used to check for overfitting.
- **Homoscedasticity** – the variance of the residual error should be constant for all values of the independent variables.
- **Normally distributed residual error** – a histogram of standardised residuals should show a roughly normal curve.

The approaches that were used for development of regression models for both the sites are described below and the regression models that were obtained are given in the results section.

Washpit Farm has a relatively long hydrograph, so it was unlikely that the model would be over-parameterised, but care was still taken not to use too many independent variables in the regression model. Inspection of the groundwater hydrograph for the site shows that the frequency distribution of annual minimum groundwater levels peaks in December (*Figure 23*), that minima are only weakly sensitive to monthly temperatures and that the lag between groundwater level response and rainfall events is in the range 2-12 months, with a maximum correlation at a lag of 6 months (*Figure 24*). Given the long record at this site, the relatively long lag between rainfall and groundwater level response, and the apparent weak sensitivity to temperature, it was decided to perform a regression using the monthly rainfall data from January to December and the monthly temperature data from March to September (taken as the effective growing season). A stepwise regression was performed to obtain a parsimonious regression model (i.e., one that used as few independent variables as necessary), and checked to see if it was hydrogeologically sensible. (A stepwise regression was chosen for the Washpit Farm and Skirwith models as this approach is often used if predictive models are required rather than models to develop and test theory. Where a stepwise approach is used it is particularly important to check the model results using some form of cross-validation.)

Skirwith has a relatively short record of groundwater level data, so care was taken not to over-parameterise the model. Other features of the hydrograph include the observation that the frequency distribution of annual groundwater level minima peak in November (see *Figure 23*), that groundwater level minima appear to be insensitive to monthly temperatures and that the lag between groundwater level response and rainfall events is in the range 1-6 months with a maximum correlation at a lag of 4 months (*Figure 25*). Based on the above, a regression model was built using monthly rainfall for June to December inclusive as the independent variables. A stepwise regression was performed to obtain a parsimonious regression model and checked to see if it was hydrogeologically sensible.

5.3.2 Hindcasting annual groundwater level minima

Historical groundwater levels have been reconstructed using the calibrated regression models combined with the hindcast rainfall and temperature data. Temperature and rainfall data for the appropriate independent variables have been abstracted from the hindcast time series (see Section 3) and substituted into the regression model for each hindcast year back to the 1800s to predict the hindcast groundwater levels for that year.

5.4 Results

5.4.1 Model calibration

Tables 5.2 and *5.3* give the results of the regression models for Washpit Farm and Skirwith, respectively.

Table 5.2 Regression model for Washpit Farm

Effect	*Coefficient*	*Standard error*	*Standard coefficient*	*Tolerance*	*T*	*p (2 tail)*
Constant	32.661	2.463	0	.	13.263	0
January rain	0.013	0.006	0.288	0.858	2.429	0.021
March rain	0.012	0.006	0.273	0.711	2.092	0.044
April rain	0.012	0.005	0.287	0.791	2.327	0.026
May rain	0.022	0.005	0.472	0.934	4.153	0
July rain	0.008	0.005	0.179	0.923	1.569	0.126
August rain	0.013	0.005	0.305	0.793	2.477	0.018
November rain	0.011	0.005	0.264	0.755	2.086	0.045
September temperature	0.342	0.154	0.255	0.915	2.224	0.033

Multiple *R*: 0.768

Table 5.3 Regression model for Skirwith

Effect	*Coefficient*	*Standard. error*	*Standard coefficient*	*Tolerance*	*T*	*p (2 tail)*
Constant	129.016	0.214	0	.	602.548	0
July rain	0.004	0.001	0.511	0.904	3.235	0.004
October rain	0.004	0.001	0.568	0.881	3.551	0.002
December rain	0.003	0.001	0.412	0.816	2.479	0.022

Multiple *R*: 0.742

Figure 26 shows the correlation between observed and modelled annual groundwater level minima and *Figure 27* shows the modelled annual minima plotted against the monthly groundwater level time series for Washpit Farm. The error bars on the modelled data in *Figure 27* are 90 per cent confidence intervals on the regression model. *Figures 28* and *29* are the equivalent plots for Skirwith.

Both models broadly satisfy the main assumptions related to linear regression models. There is a weak autocorrelation in the annual minimum groundwater levels at Washpit Farm and Skirwith (*Figures 30* and *31*), but no autocorrelation in any of the independent variables. The homoscedasticity assumption is met for both models as the residuals are dispersed randomly throughout the range of estimated dependent (*Figures 32* and *33*), and the residual errors are broadly normal in distribution (*Figures 34* and *35*) for each model.

Given that the regression assumptions are broadly satisfied, how valid are the regression models themselves? *Tables 5.2* and *5.3* show that both of the coefficients are significantly different from 0 at the 95 per cent confidence level. *Tables 5.4* and *5.5* show the analysis of variance for the Washpit Farm and Skirwith regression models. The analysis of variance table tests the goodness of fit of the entire model and shows that the regressions are significant at >95 per cent confidence.

Table 5.4 Analysis of variance table for the Washpit Farm regression.

Source	*Sum –of squares*	*df*	*Mean square*	*F-ratio*	*p*
Regression	37.501	8	4.688	6.107	0.000
Residual	26.096	34	0.768		

Table 5.5 Analysis of variance table for the Skirwith regression

Source	*Sum –of squares*	*df*	*Mean square*	*F-ratio*	*p*
Regression	1.008	3	0.336	8.146	0.001
Residual	0.825	20	0.041		

The R^2 statistics in *Tables 5.2* and *5.3* show that the models describe about 75 per cent of the variance in the observed data. As noted above, MLR models can be over-parameterised and cross-validation and related methods can be used to check for overfitting. A leave-one-out or jackknife cross-validation method has been used to investigate the sensitivity of the regression coefficients and the R^2 statistics to the data. This method consists of sequentially removing one case of the data (i.e., one year's data) and computing the regression coefficients and the R^2 statistics for the new input data. It was found that the jackknife coefficients (*Figures 36* and *37*) and jackknife R^2 statistic showed little variation. This indicates that the model was not over-parameterised, and that all the jackknife coefficients lay within the 90 per cent confidence bounds of the regression model for each site (compare *Figures 27* and *29* with *Figures 38* and *39*).

5.4.2 Groundwater level reconstruction

Figures 40 and *41* show the reconstructed annual minimum groundwater level time series for Washpit Farm and Skirwith, and *Tables 5.6* and *5.7* list the 12 most extreme groundwater droughts as predicted by the hindcast annual groundwater level minima for Washpit Farm and Skirwith, respectively. *Figures 40* and *41* have been annotated to show years that have been identified as major or other droughts based on the work of Cole and Marsh (2005).

Table 5.6 Severe groundwater droughts at Washpit Farm

Year	*Level (m OD)*
1909	39.58
1802	39.73
1952	39.76
1833	39.85
1905	39.98
1896	39.99
1863	40.04
1807	40.06
1826	40.08
1864	40.08
1813	40.09
1838	40.14

Table 5.7 Severe groundwater droughts at Skirwith

Year	*Level (m OD)*
1978	129.29
1997	129.35
1996	129.4
1878	129.63
1992	129.68
1984	129.72
1989	129.73
1904	129.73
1952	129.74
1982	129.78
2003	129.79
1990	129.8

6. Conclusions

River flow and groundwater levels have been reliably reconstructed from rainfall data for the Ely Ouse and Eden catchments back to 1800. A number of severe drought sequences have been reconstructed on both catchments prior to the period of instrumental gauging. On the Ely Ouse, there were five droughts more severe than those that occurred in 1944 and 1991. On the Eden, three of the four most severe droughts occurred in the past two decades, the one early event being 1826. An analogue method has been developed to produce daily inflow data at all the required abstraction points on the AW and UU water resource systems, using regression relationships between the monthly mean flows at the points and those reconstructed at the catchment outlets. These daily sequences have been supplied to AW and UU and will be used in reservoir yield assessments. Future work will consider potential changes in future climate from three simulations of regional climate models.

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Appendices

Appendix 1 Figures

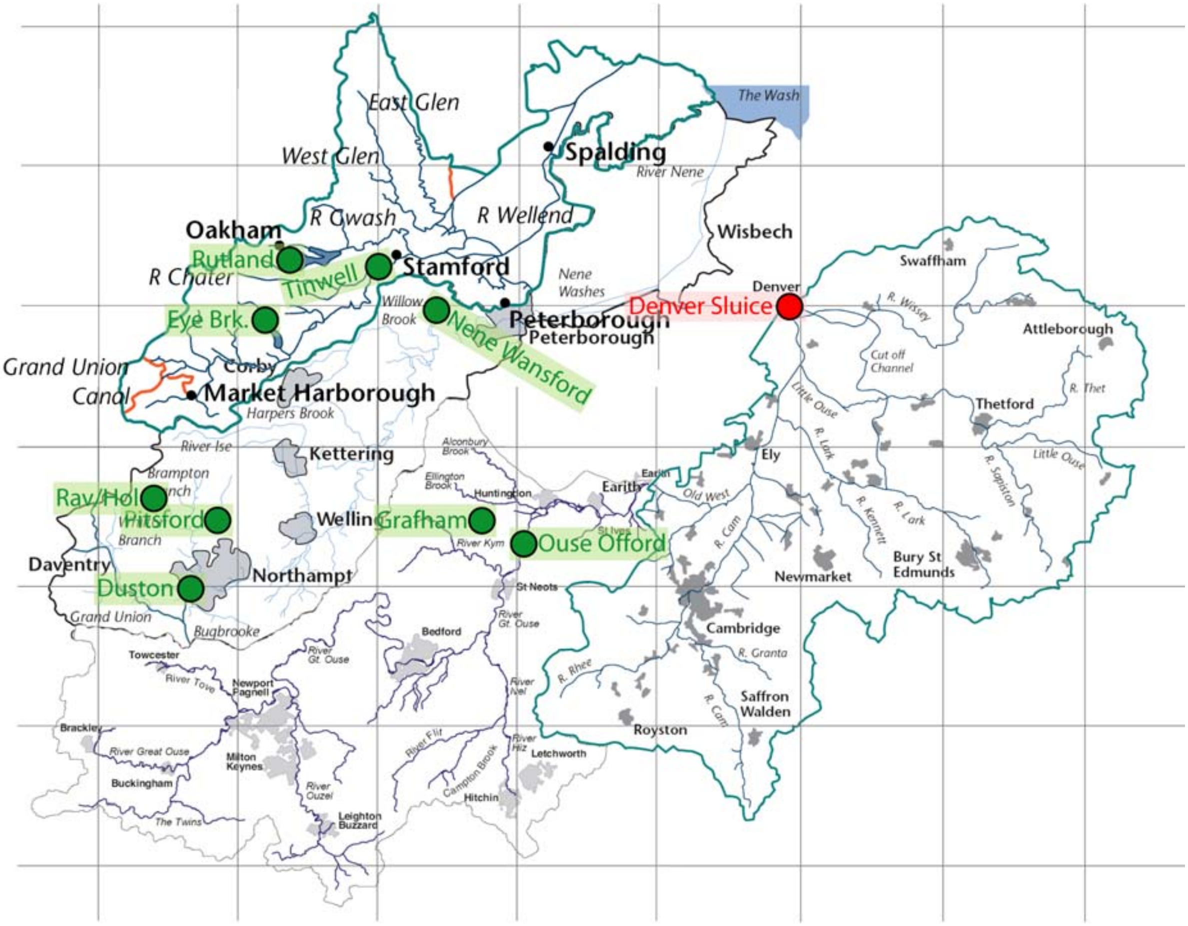


Figure 1 Ely Ouse, Nene and Welland catchments

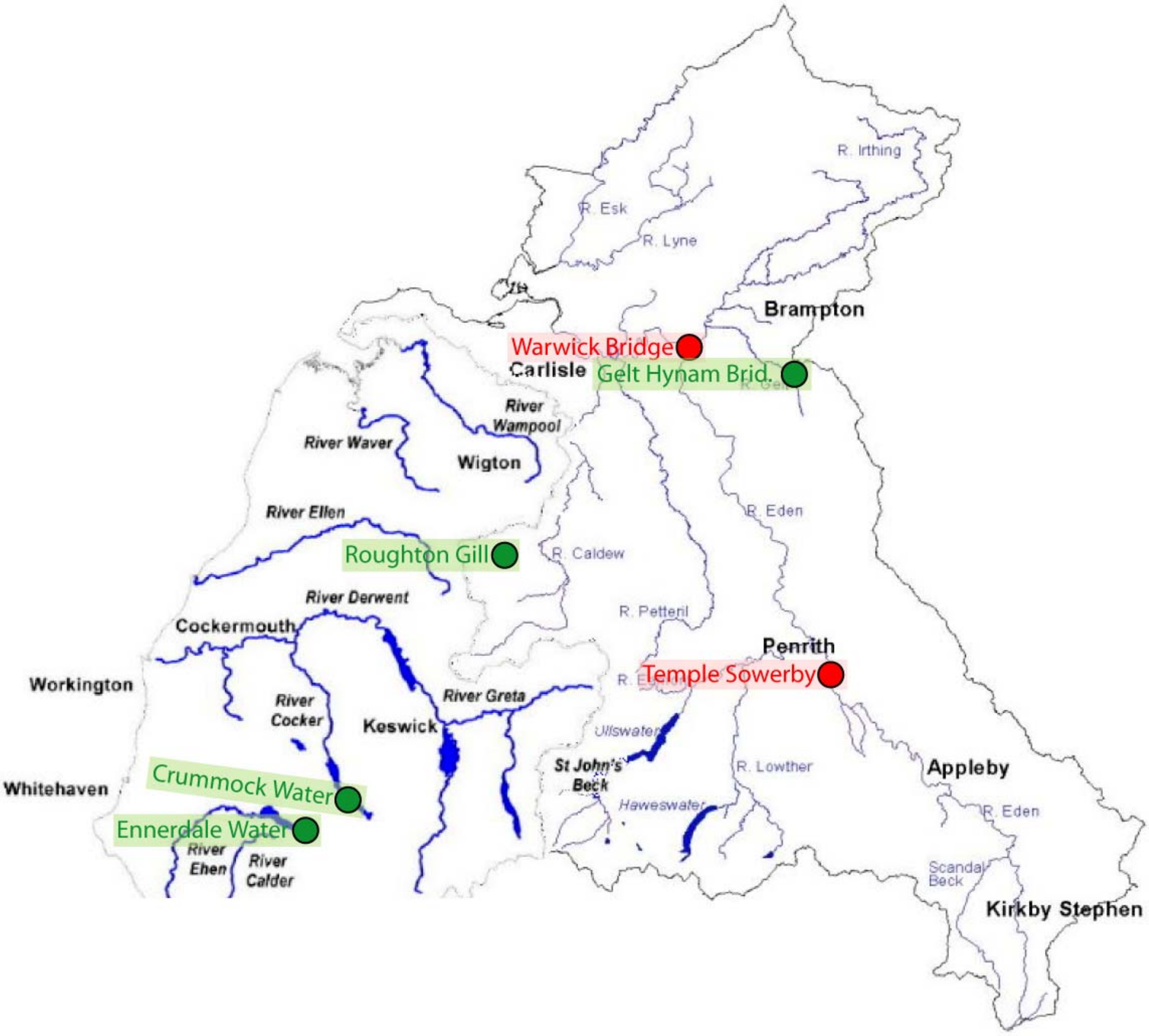
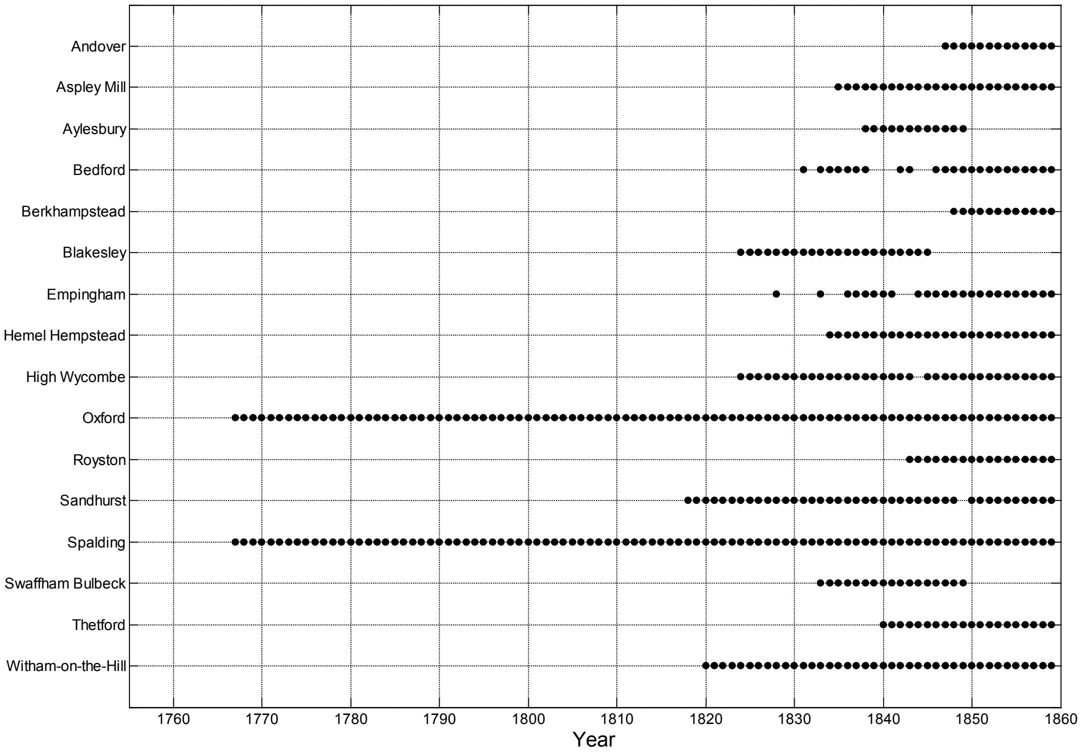


Figure 2 Eden and Derwent catchments



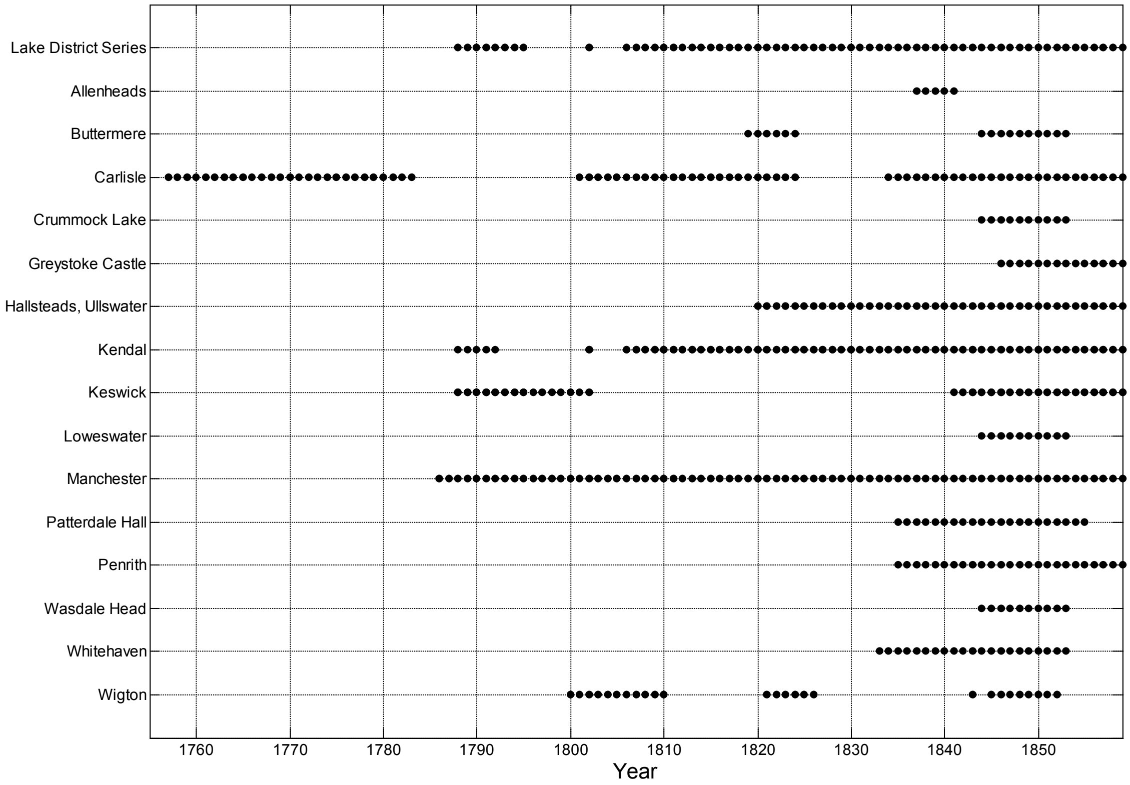


Figure 3 **Available records (complete years) for rain gauges in the Ely Ouse (top) and Eden (bottom) catchment areas**

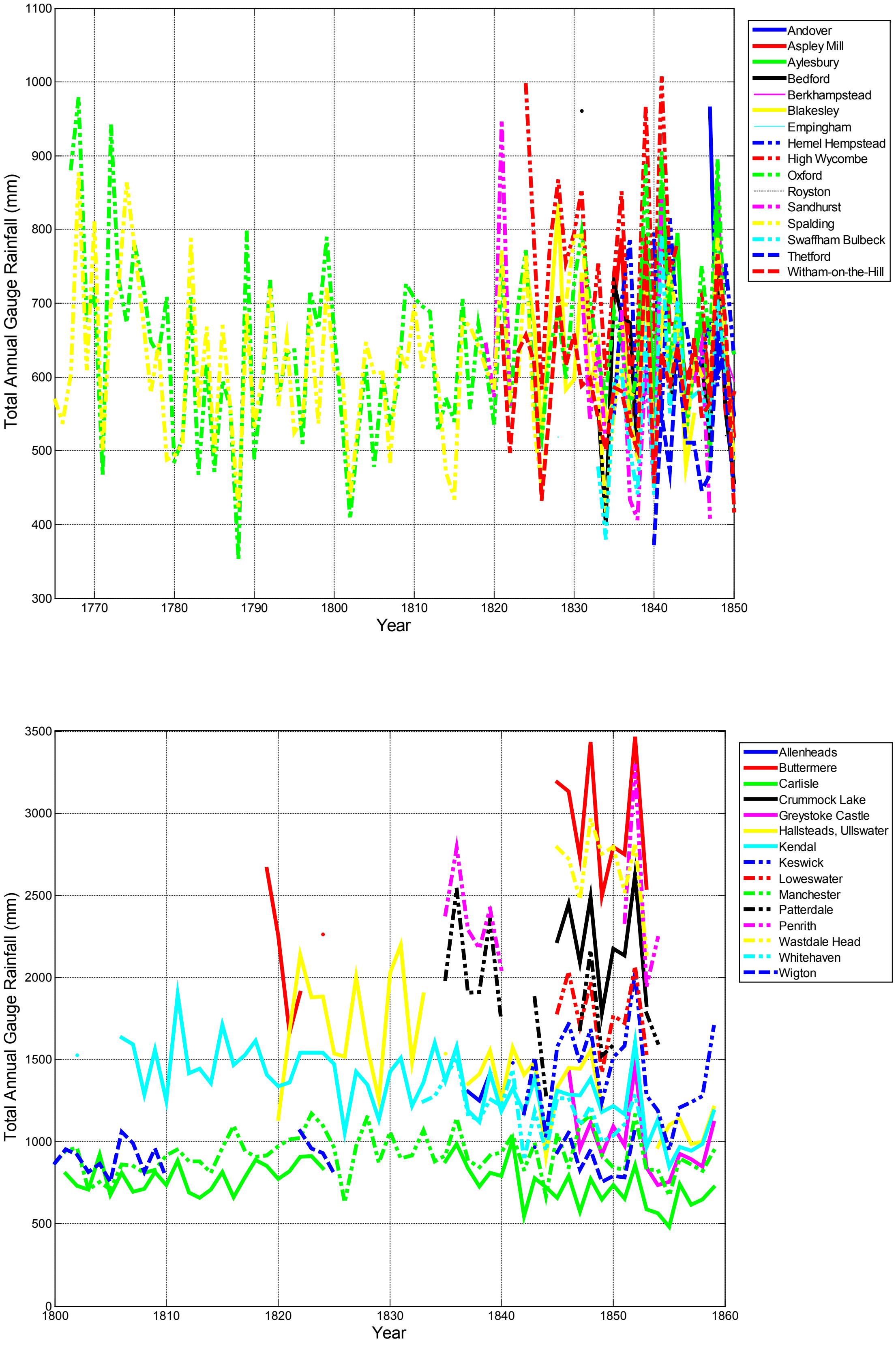


Figure 4 Annual rainfall records (mm) for individual rain gauges in the Ely Ouse (top) and Eden (bottom) catchments

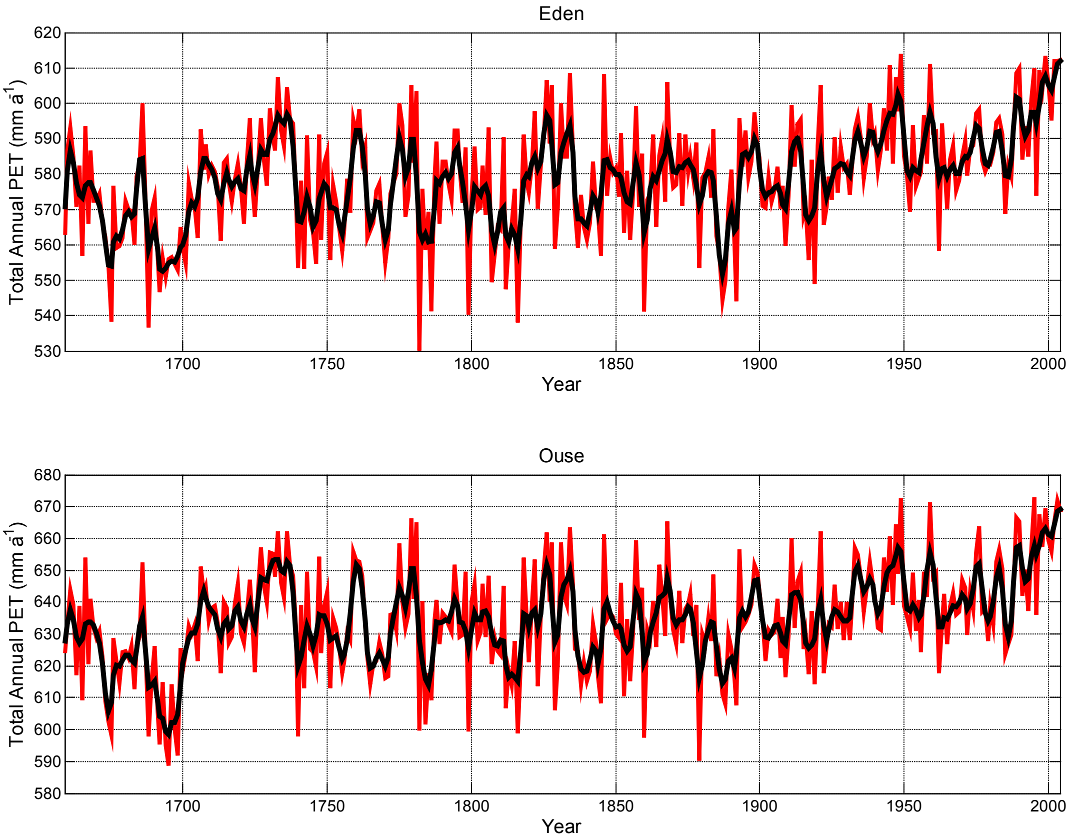
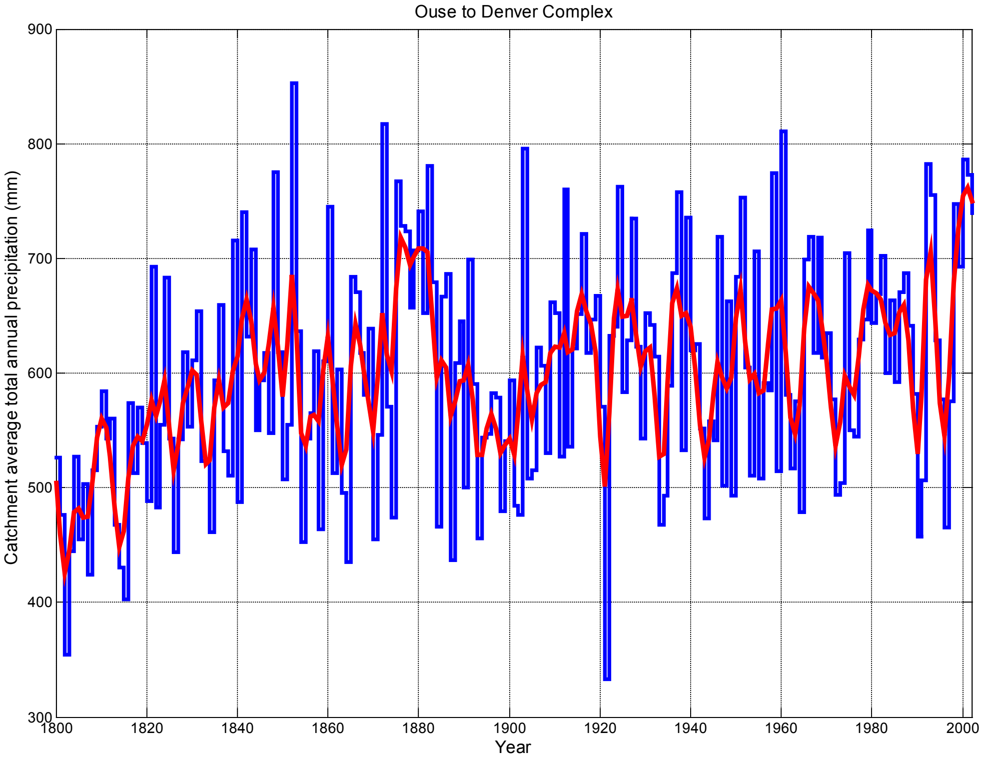


Figure 5 **Potential evapotranspiration (mm) estimated using the Thornthwaite method, annual totals (red) and decadal means (black)**



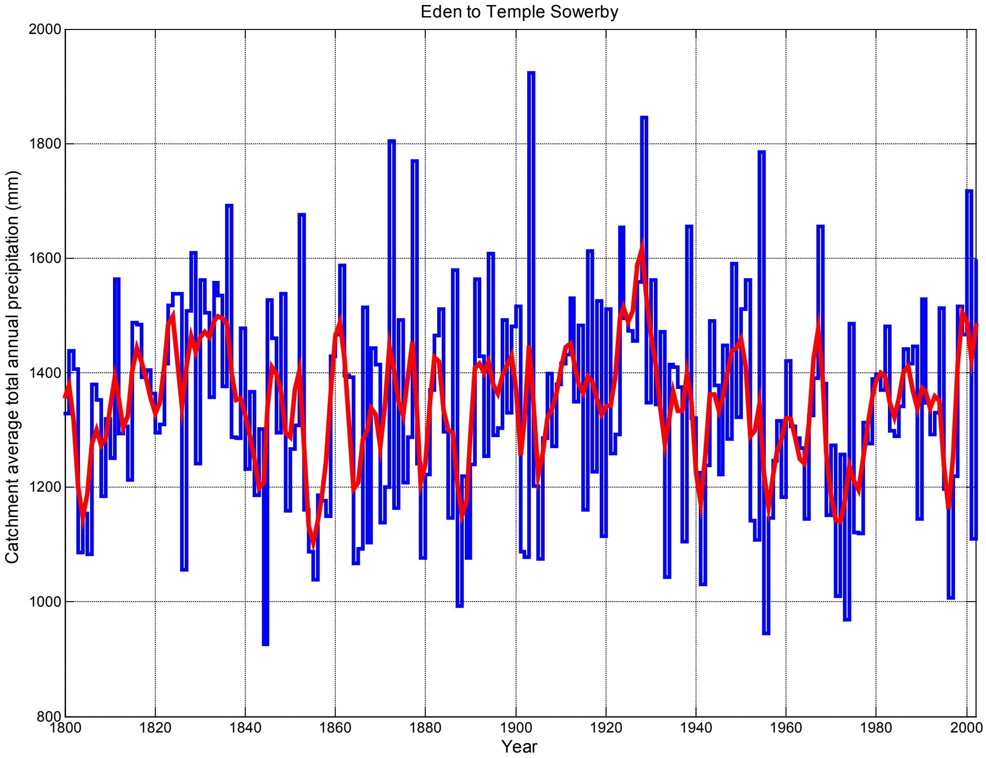


Figure 6 Reconstructed catchment-average total annual rainfall (mm) for Ely Ouse (top), southern Eden (bottom) and northern Eden (next page) catchments, annual totals (blue) and decadal means (red)

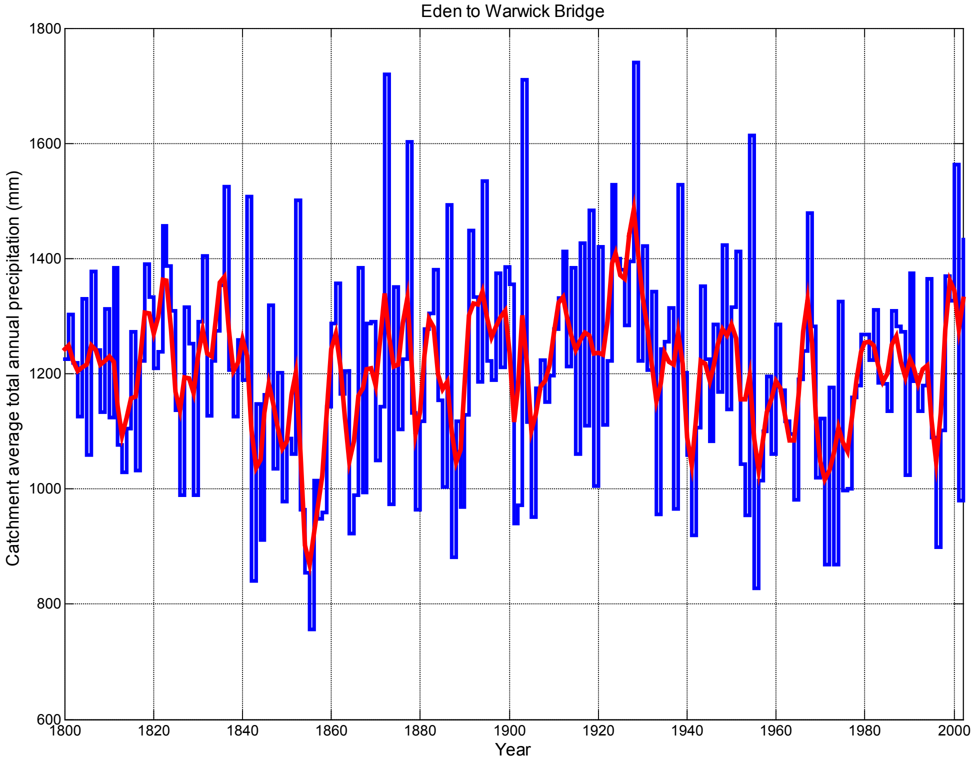


Figure 6 (cont…) **northern Eden catchment**

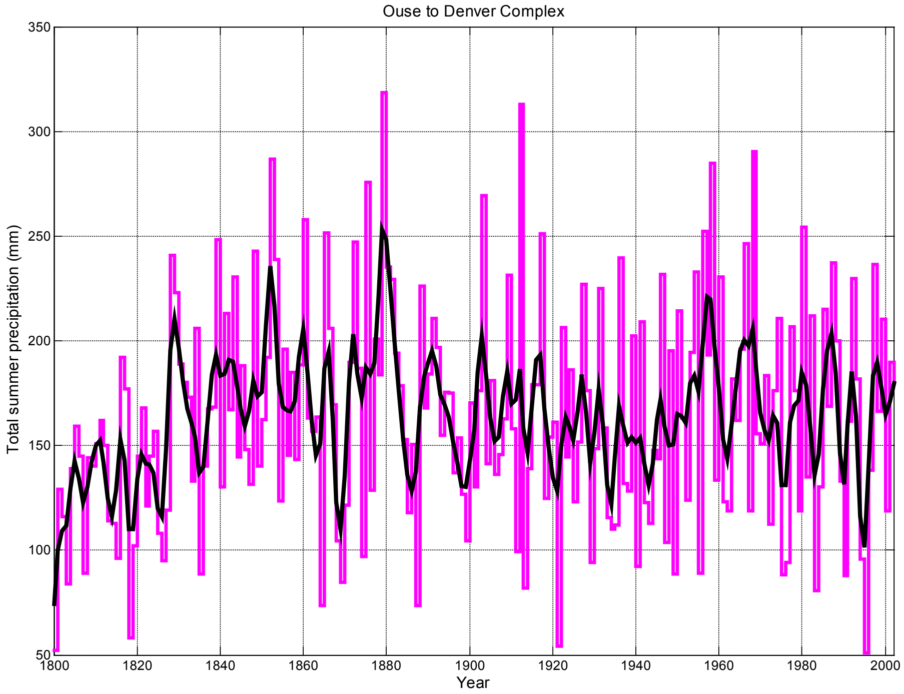
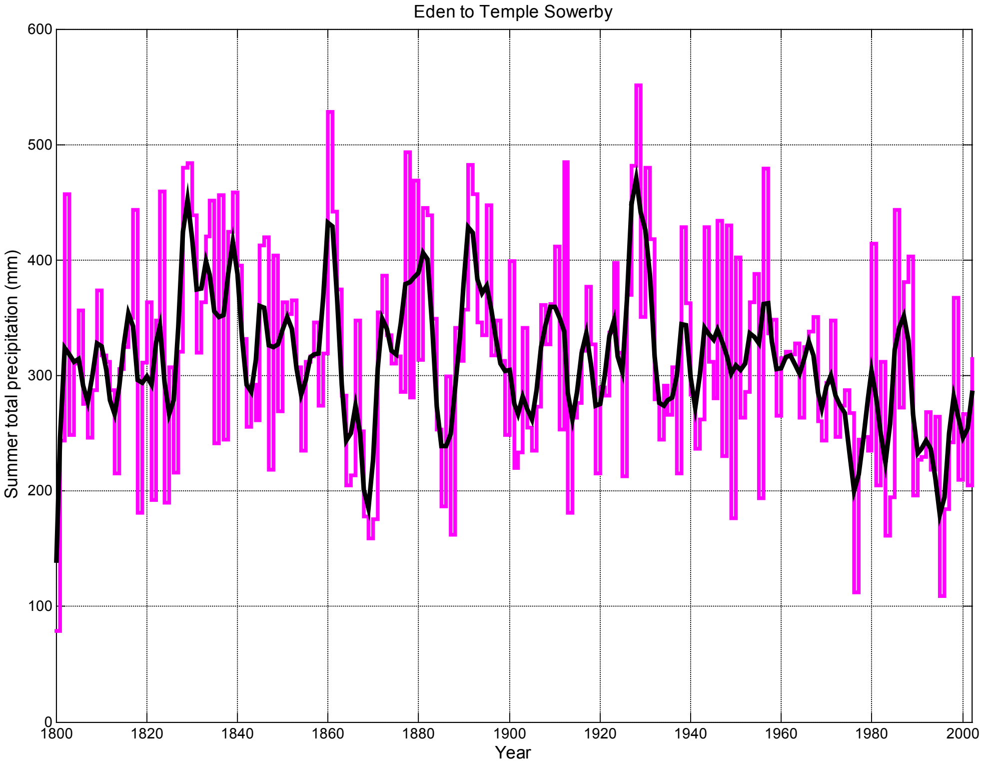


Figure 7 **Reconstructed catchment average total summer (June, July, August) rainfall (mm) for Ely Ouse (this page), southern Eden (next page, top) and northern Eden (next page, bottom) catchments, summer totals (pink) and decadal means (black)**



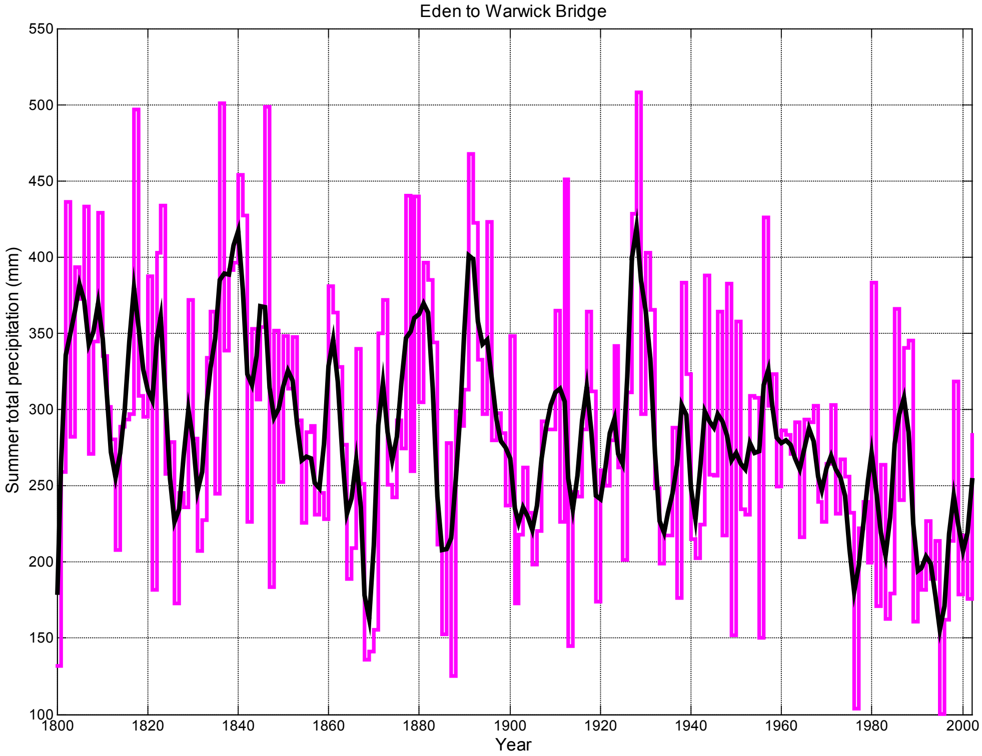
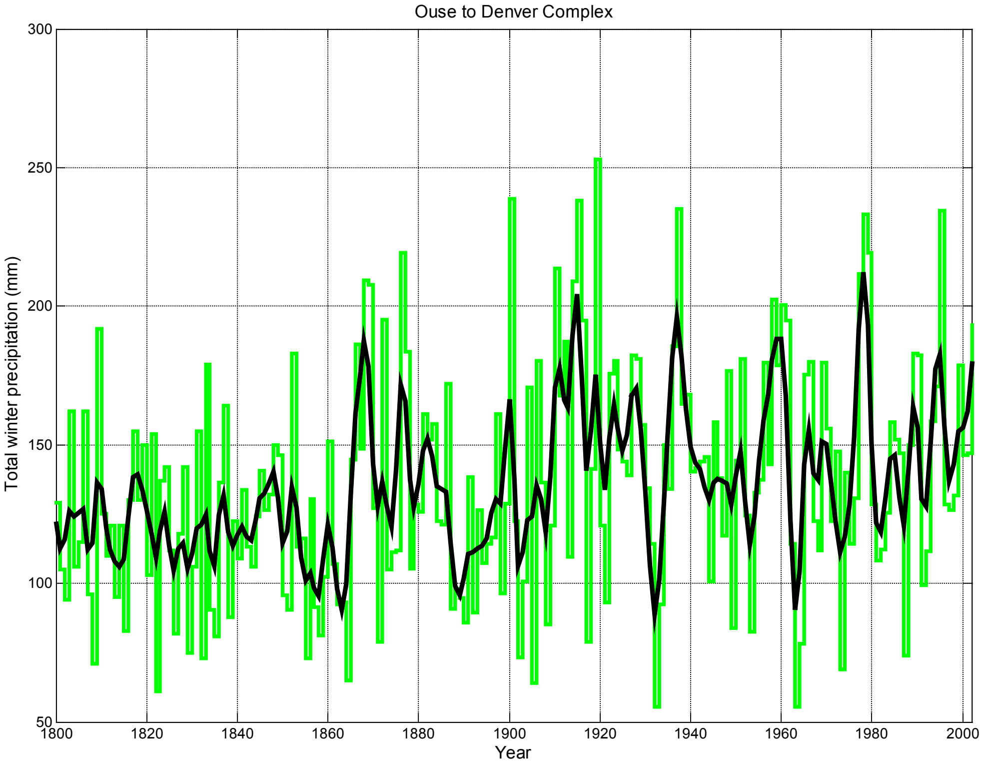


Figure 7 (cont…) **southern Eden (top) and northern Eden (bottom) catchments**



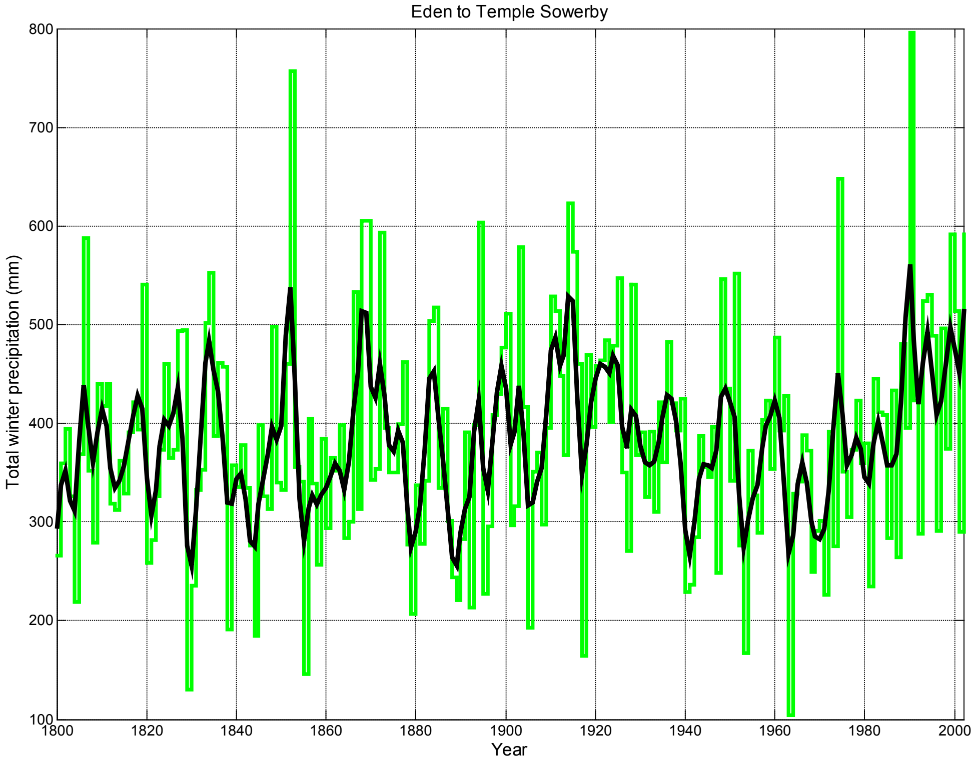


Figure 8 Reconstructed catchment-average total winter (December, January, February) rainfall (mm) for Ely Ouse (top), southern Eden (bottom) and northern Eden (next page) catchments, annual totals (green) and decadal means (red)

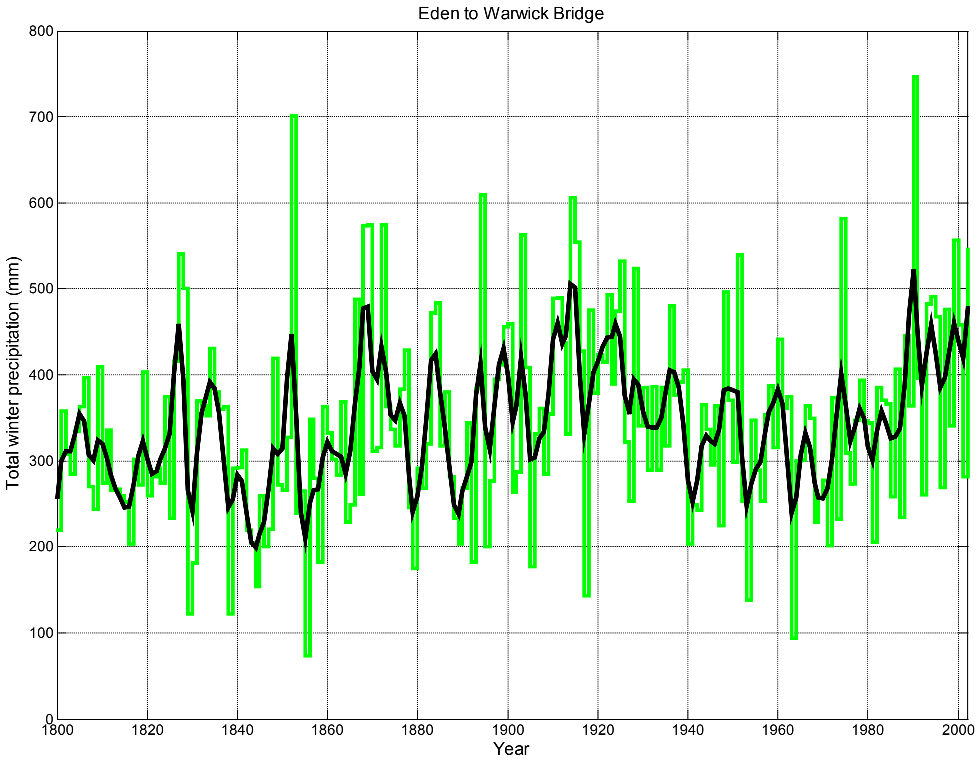


Figure 8 (cont…) **northern Eden catchment**

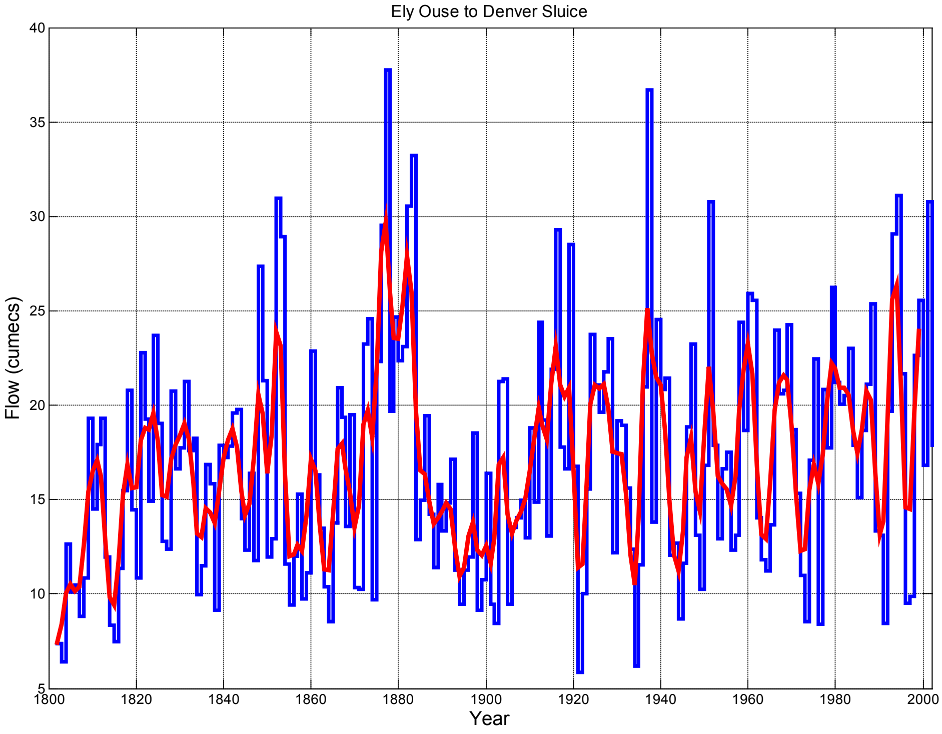
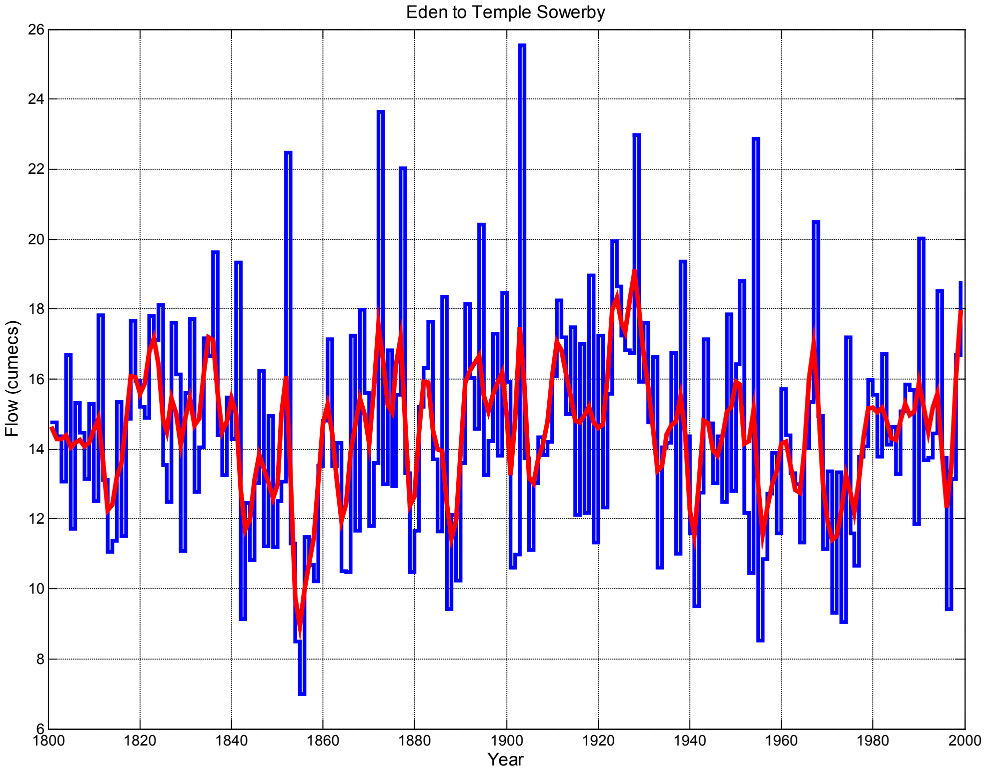


Figure 9 **Reconstructed annual average river flow (cumecs) for Ely Ouse (this page), southern Eden (next page, top) and northern Eden (next page, bottom), annual (blue) and decadal means (red)**



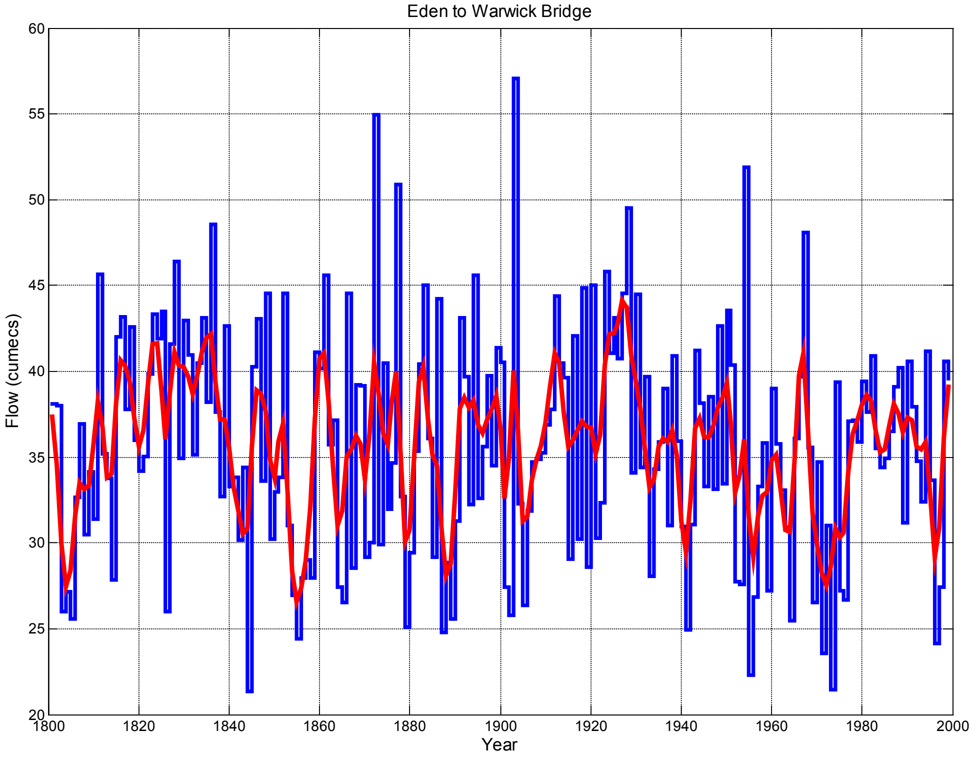
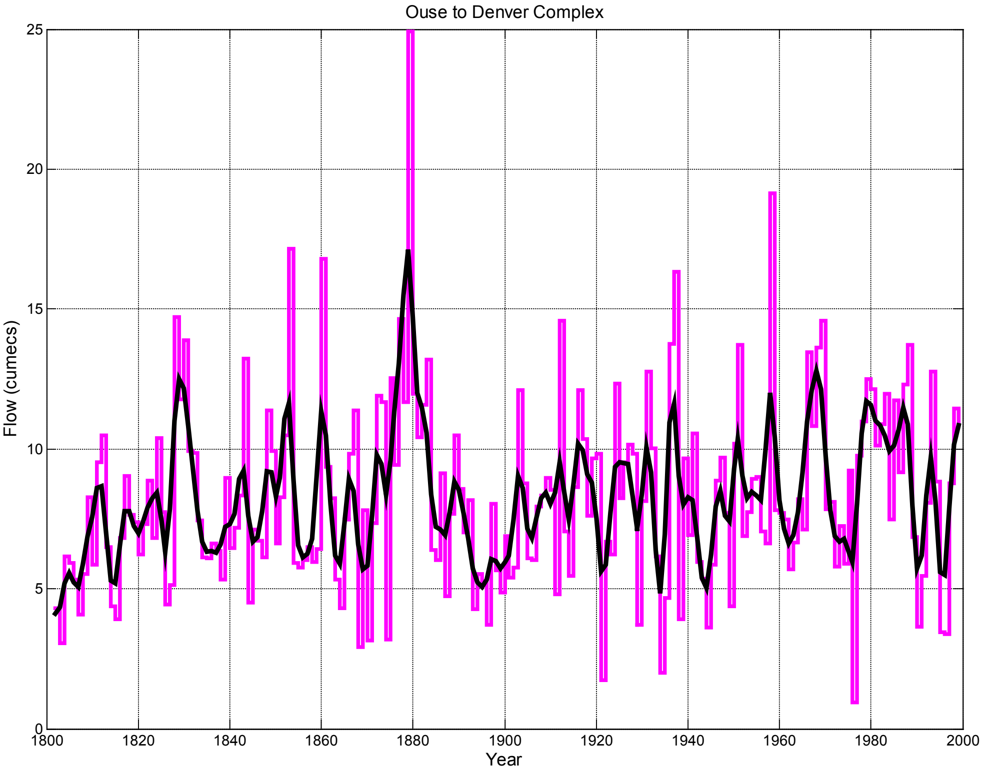


Figure 9 (cont…)   southern Eden (top) and northern Eden (bottom)



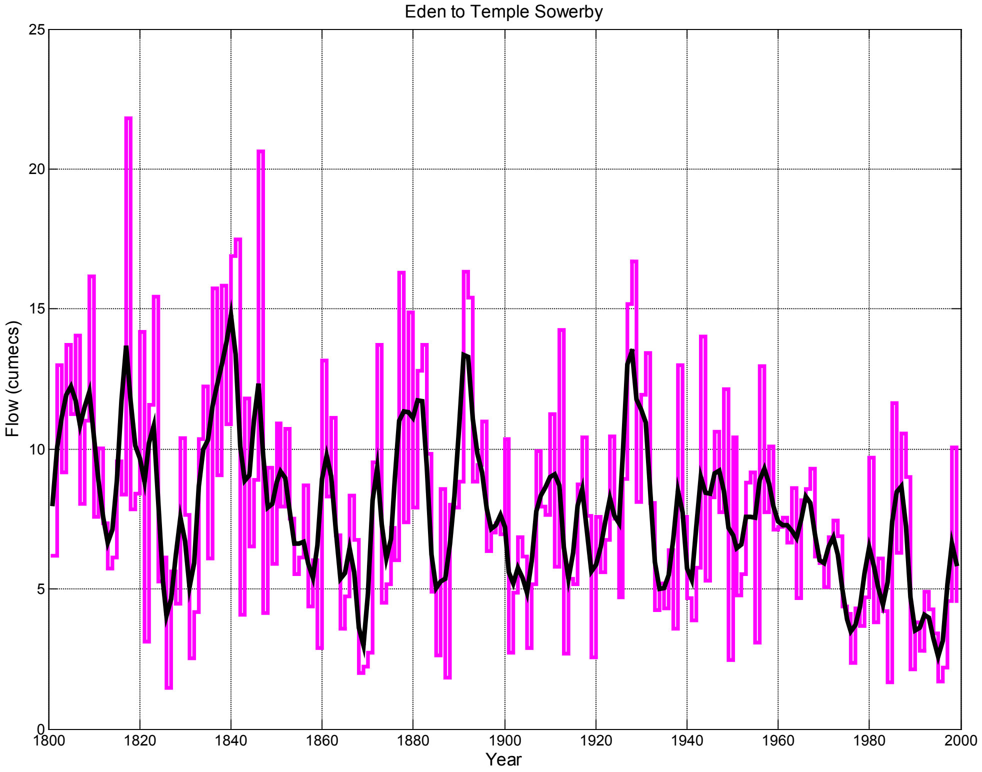


Figure 10 **Reconstructed summer (June, July, August) average river flow (cumecs) for Ely Ouse (top), southern Eden (bottom) and northern Eden (next page), summer (pink) and decadal means (black)**

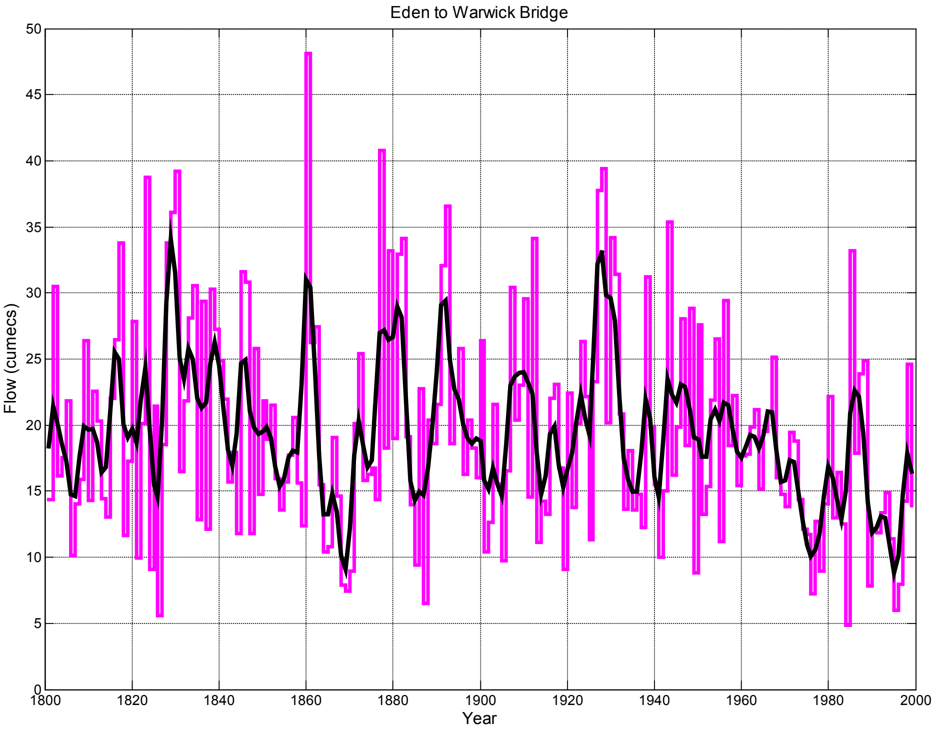


Figure 10 (cont…)   northern Eden catchment

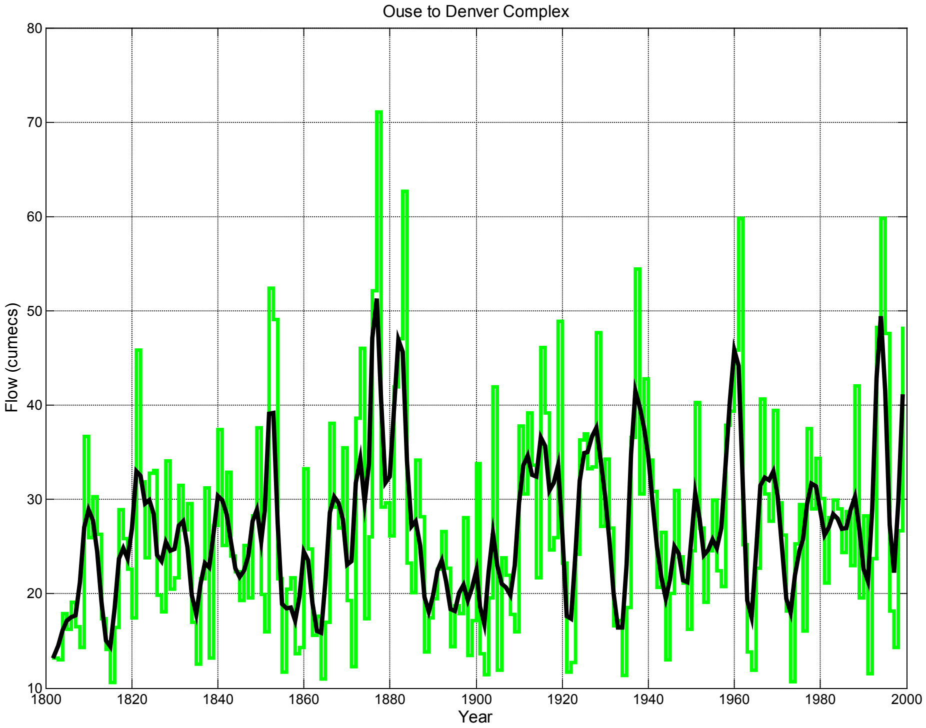
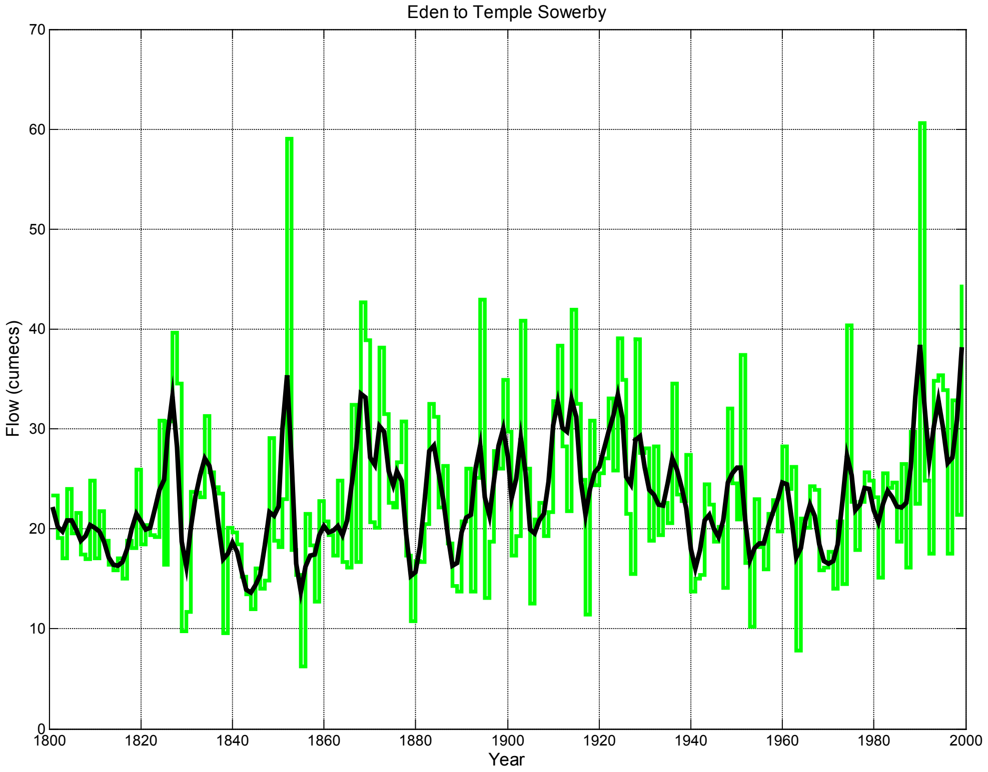


Figure 11   Reconstructed winter (December, January, February) average river flow (cumecs) for Ely Ouse (this page), southern Eden (next page, top) and northern Eden (next page, bottom), winter (green) and decadal means (black)



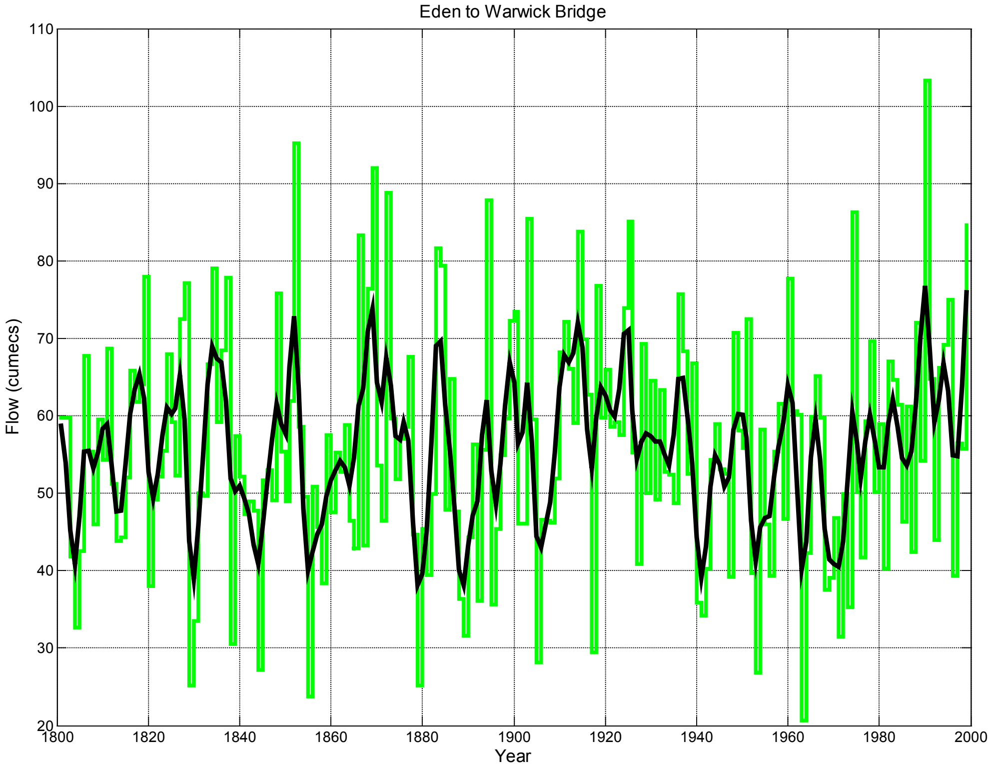


Figure 11 (cont…) southern Eden (top) and northern Eden (bottom)

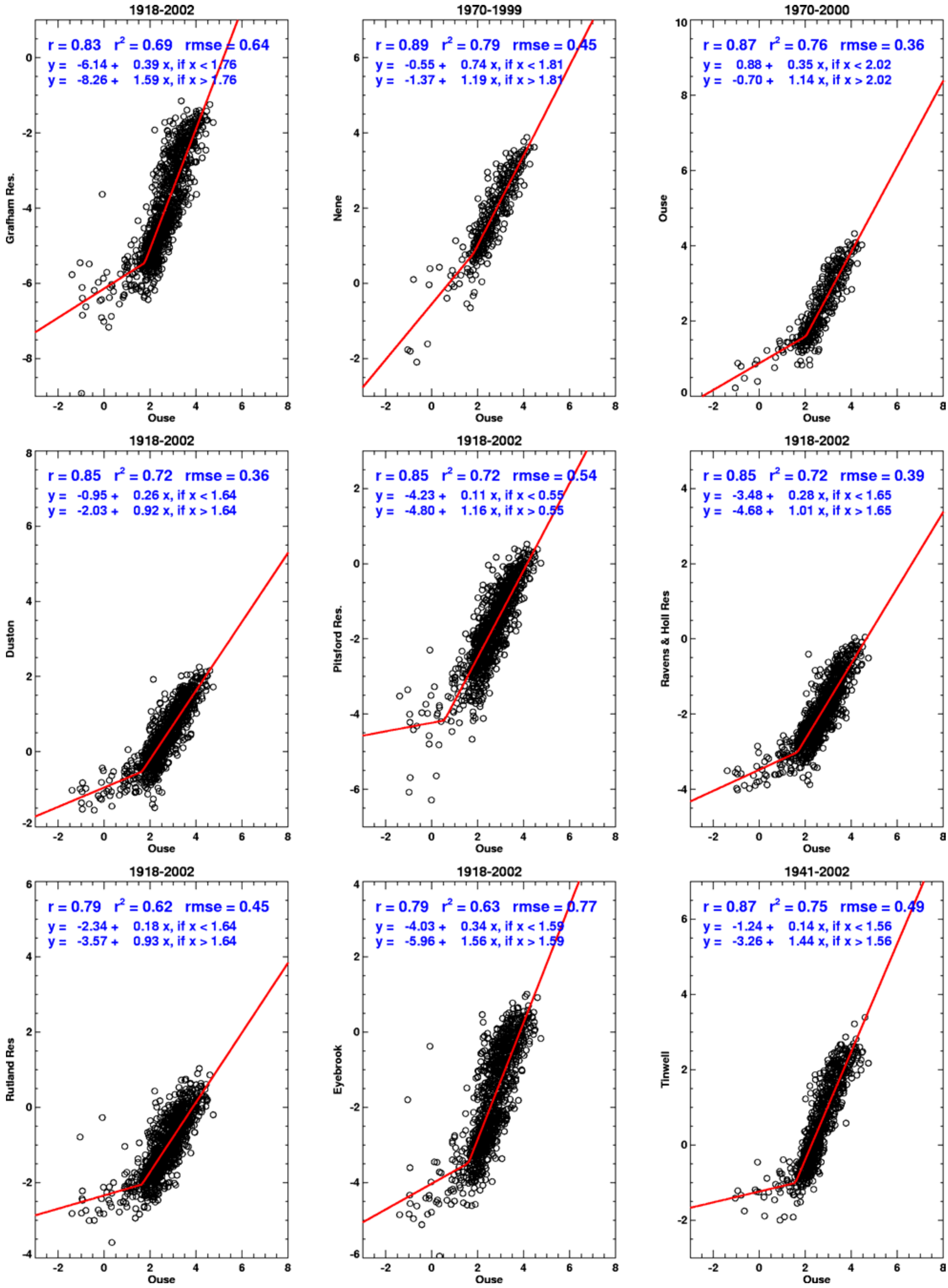


Figure 12 Regression lines for creating the Ely Ouse analogue series. Natural logarithm of reconstructed monthly Ouse flows on *x*-axis; natural logarithm of target series on *y*-axis. Red lines indicate two-piece relationship used.

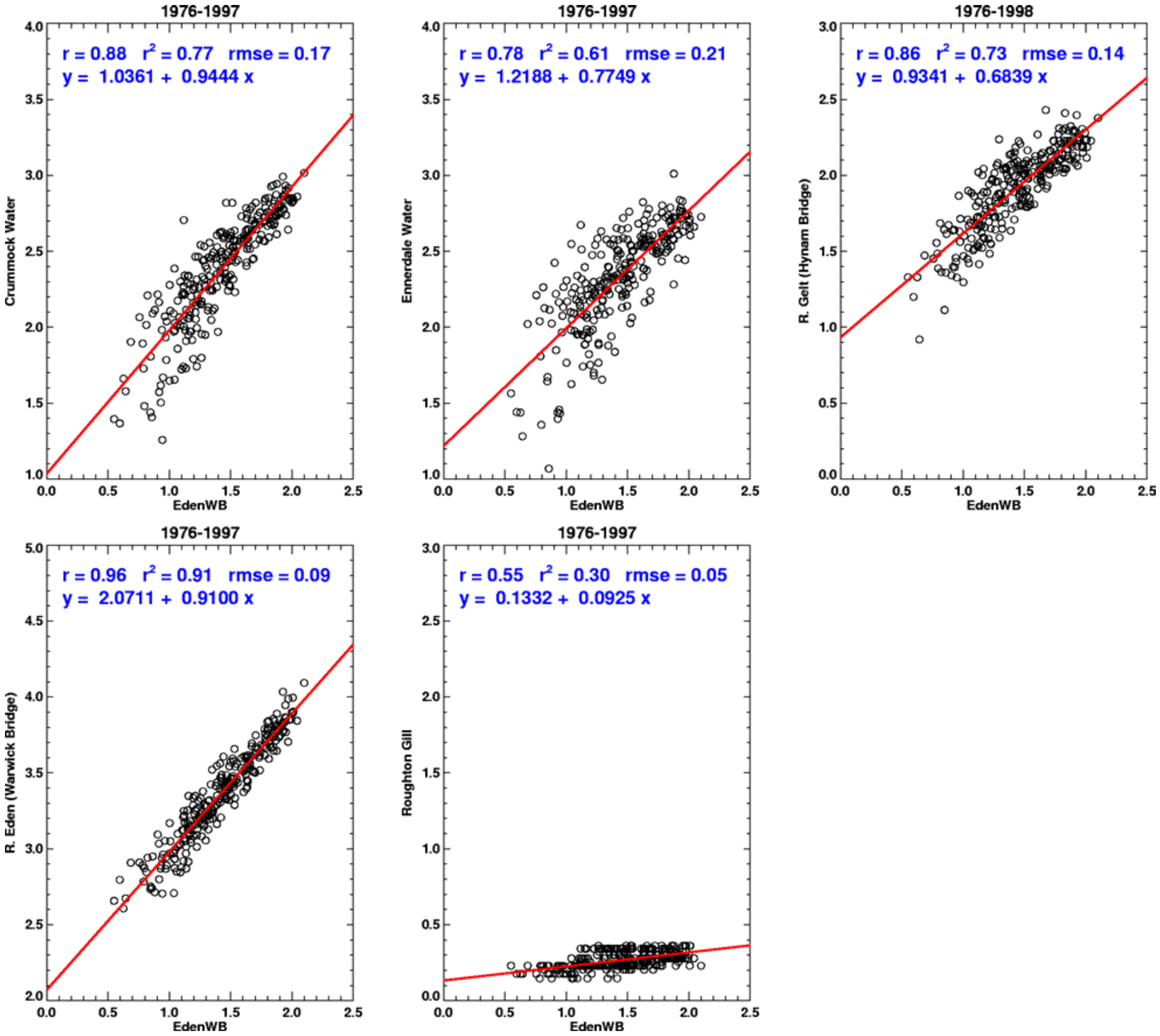


Figure 13 Regression lines for creating the Eden analogue series. Logarithm of reconstructed monthly Eden (Warwick Bridge) flows on *x*-axis; logarithm of target series on *y*-axis. Red lines indicate one-piece relationship used.

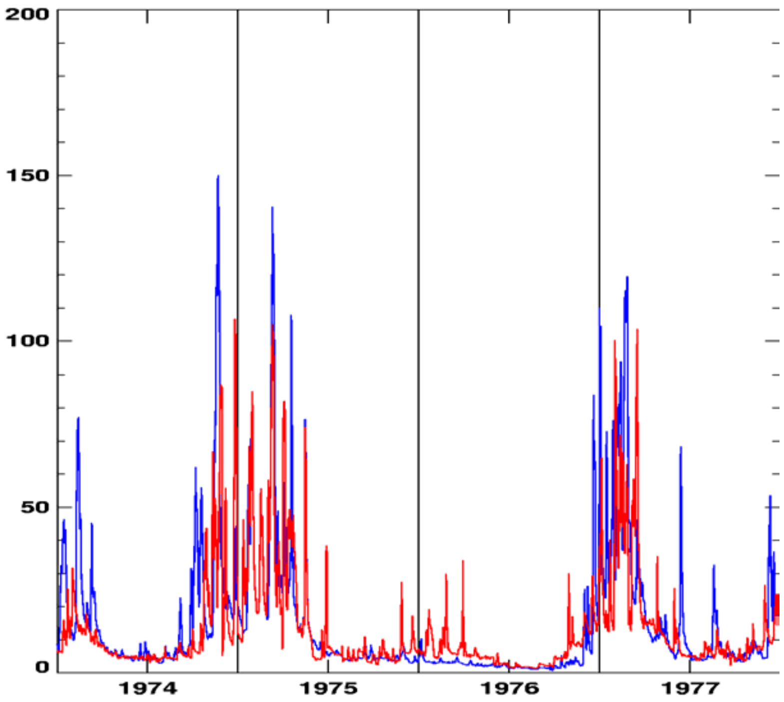


Figure 14 Ely Ouse analogue flow series (red) and observed flows (blue) for 1974-1977

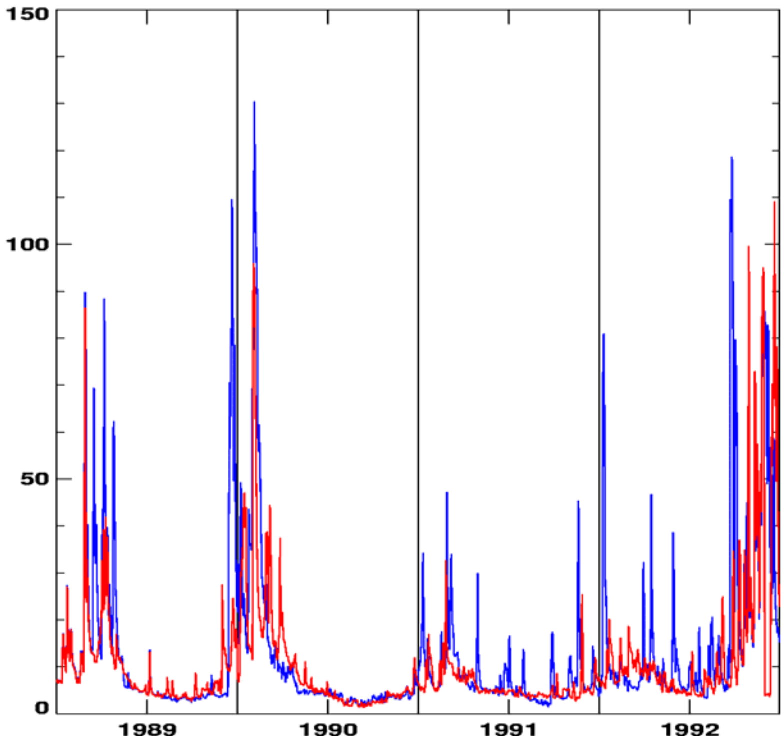


Figure 15 Ely Ouse analogue flow series (red) and observed flows (blue) for 1989-1992

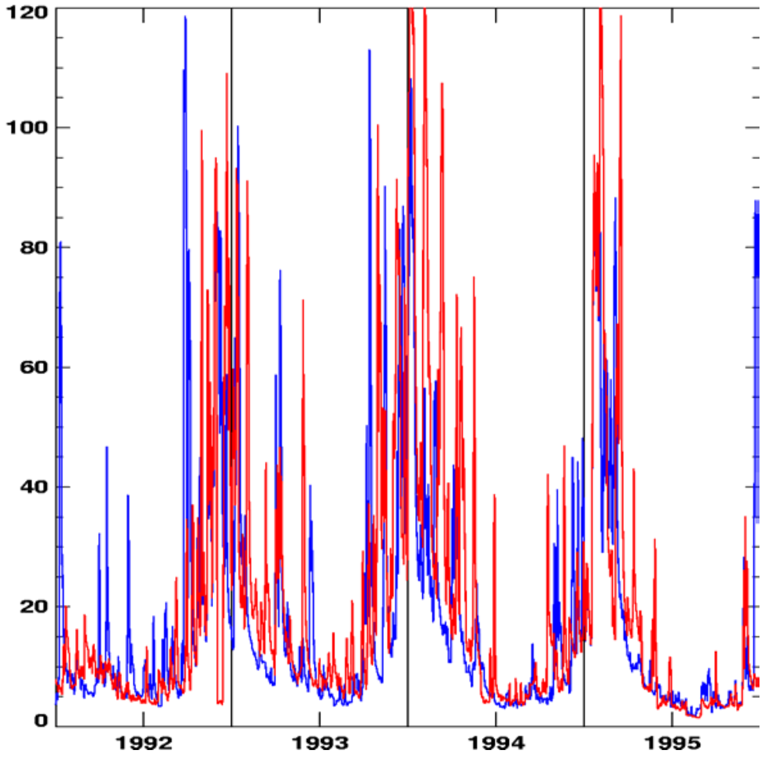


Figure 16 Ely Ouse analogue flow series (red) and observed flows (blue) for 1992-1995

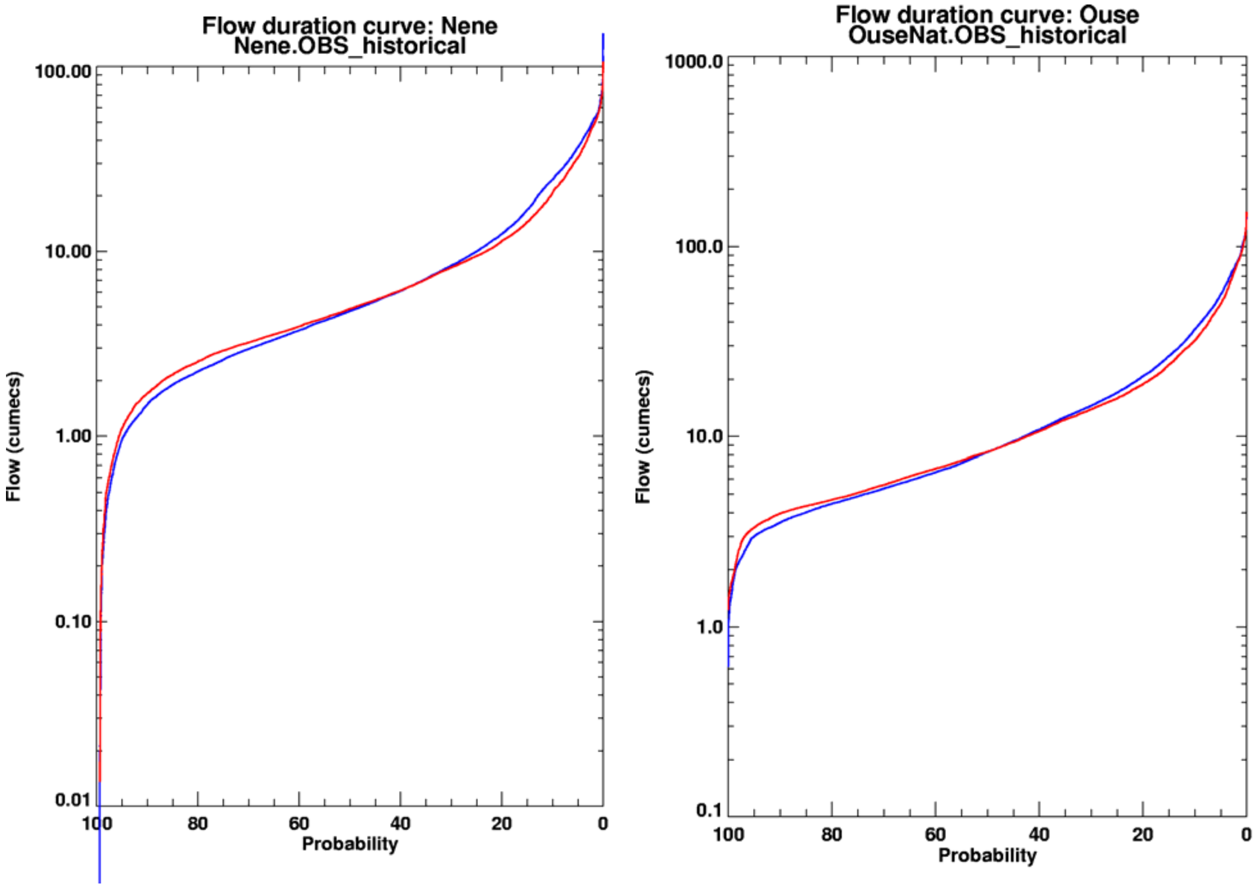


Figure 17 Flow duration curves for Nene and Ouse abstraction points on the AW system (blue="observations"; red=daily analogues).

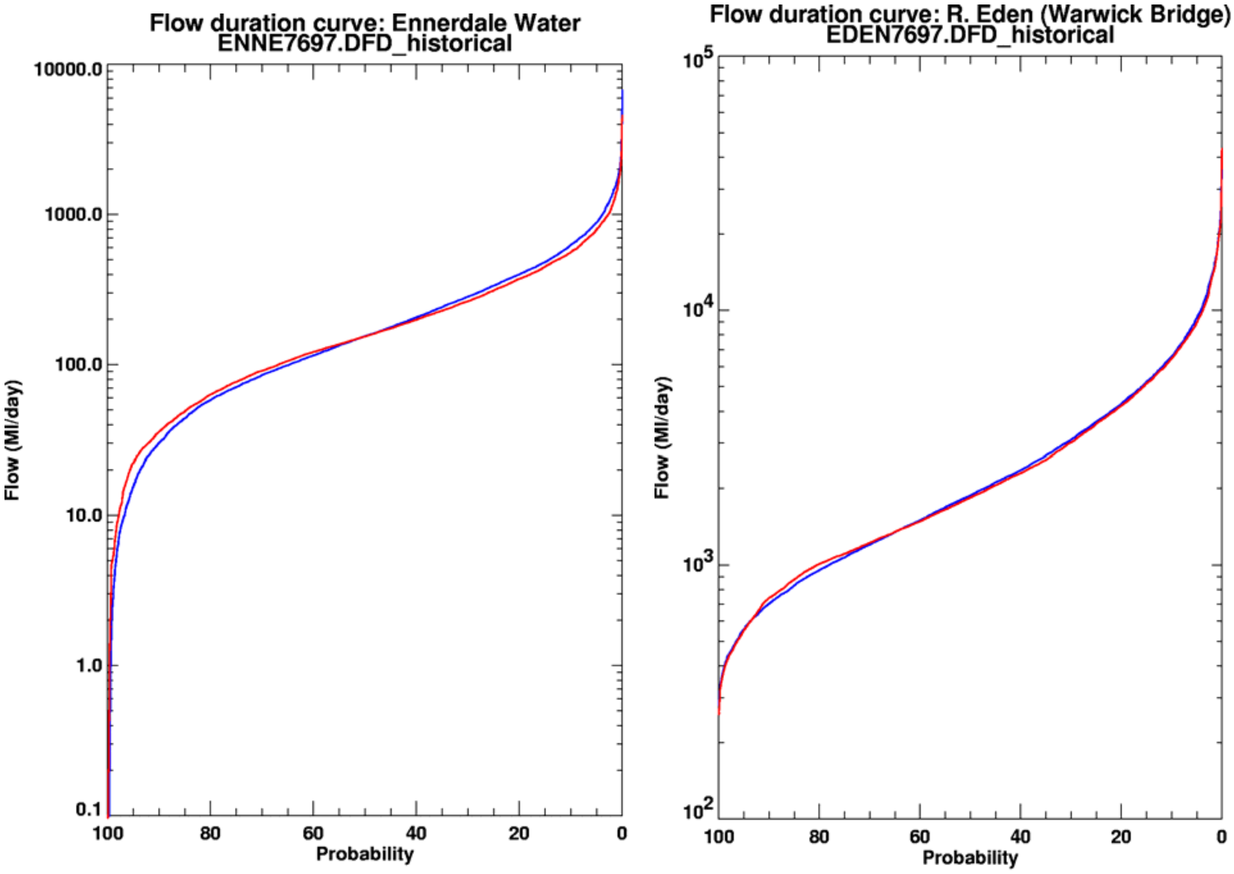


Figure 18 Flow duration curves for the Ennerdale and Eden abstraction points on the UU system (blue="observations"; red=daily analogues)

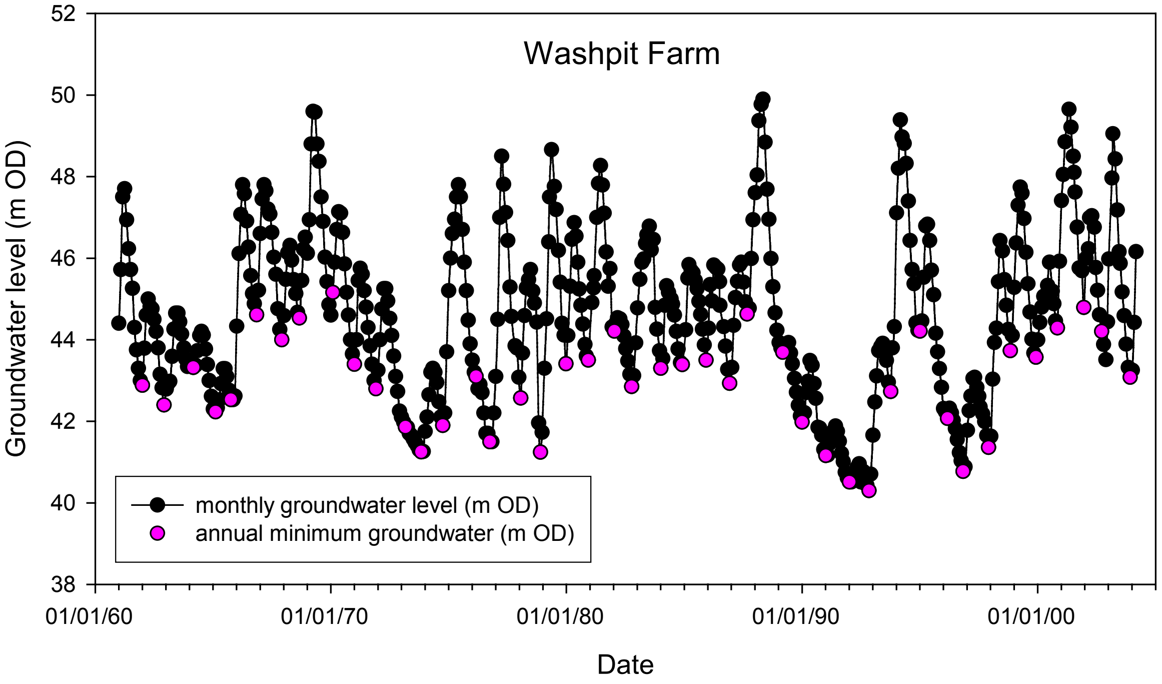


Figure 19 **Monthly groundwater levels and annual minima at Washpit Farm**

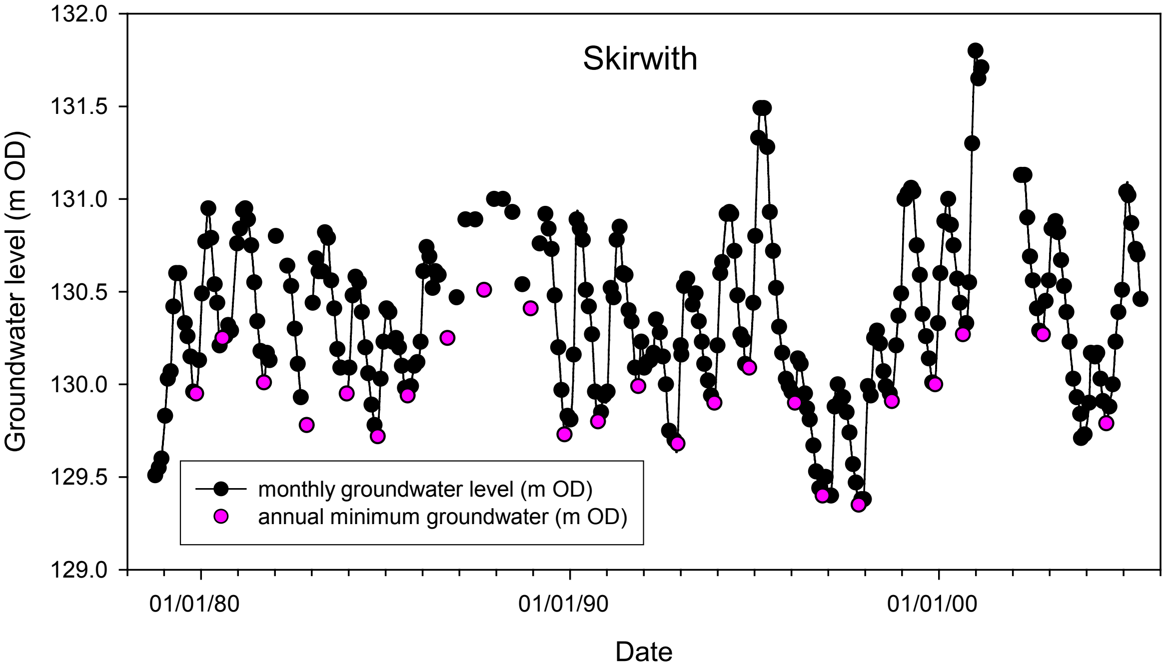


Figure 20 **Monthly groundwater levels and annual minima at Skirwith**

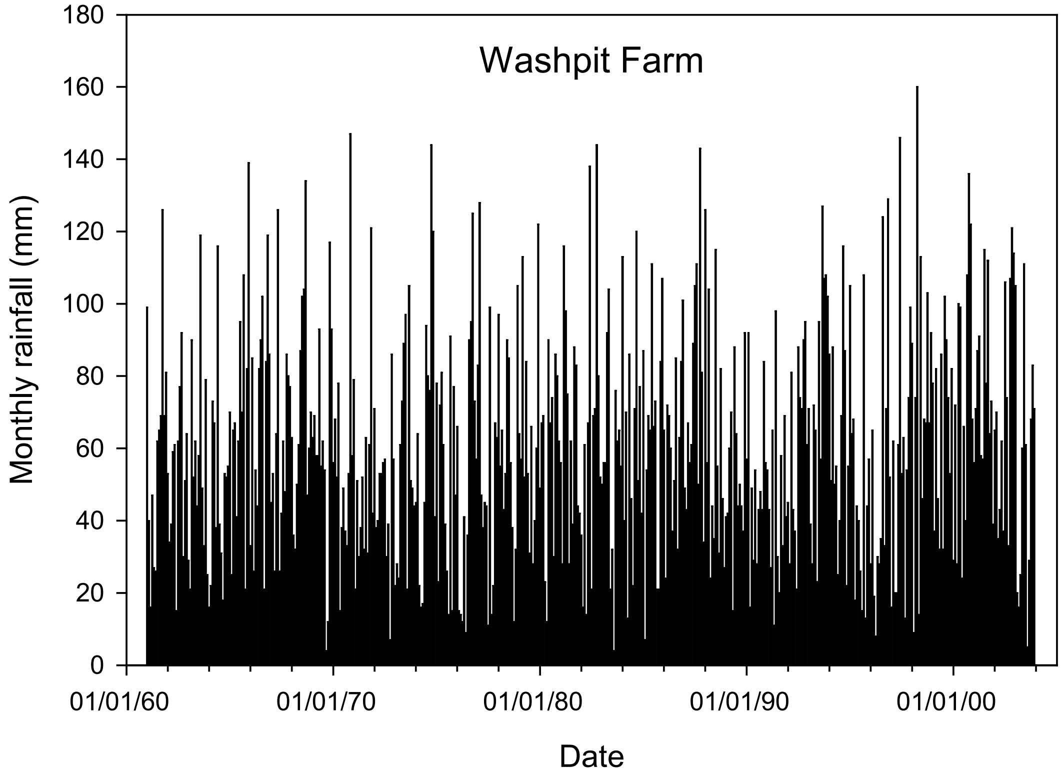


Figure 21 CEH 1 km gridded rainfall for Washpit Farm

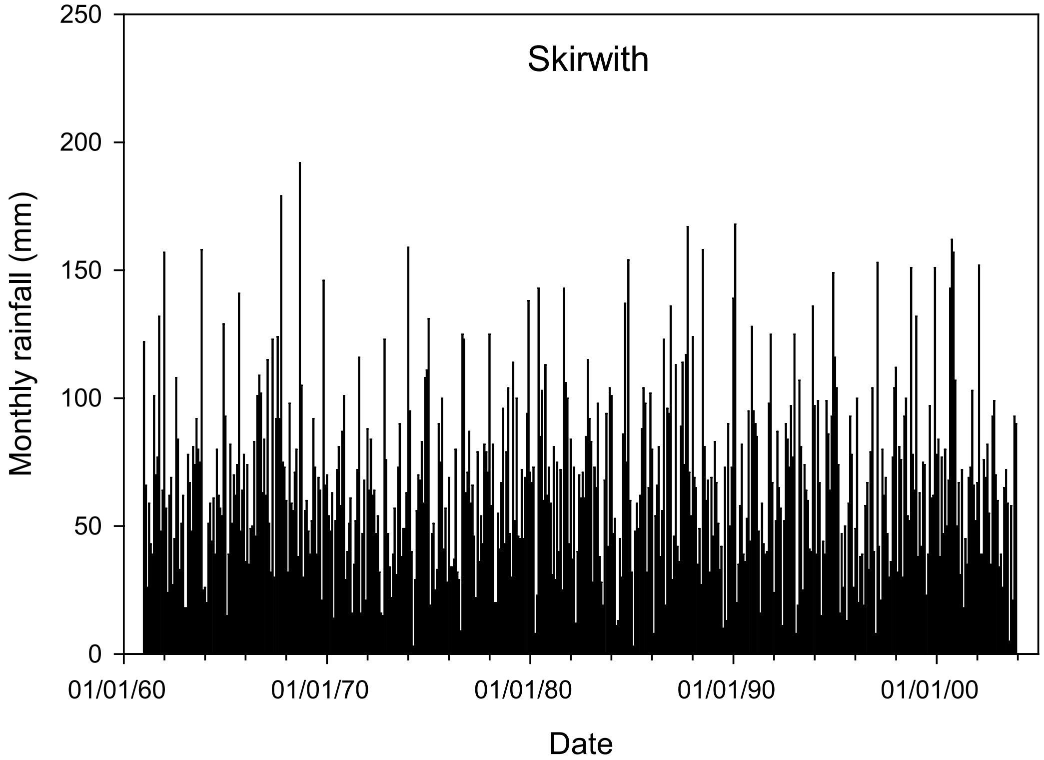


Figure 22 CEH 1 km gridded rainfall for Skirwith

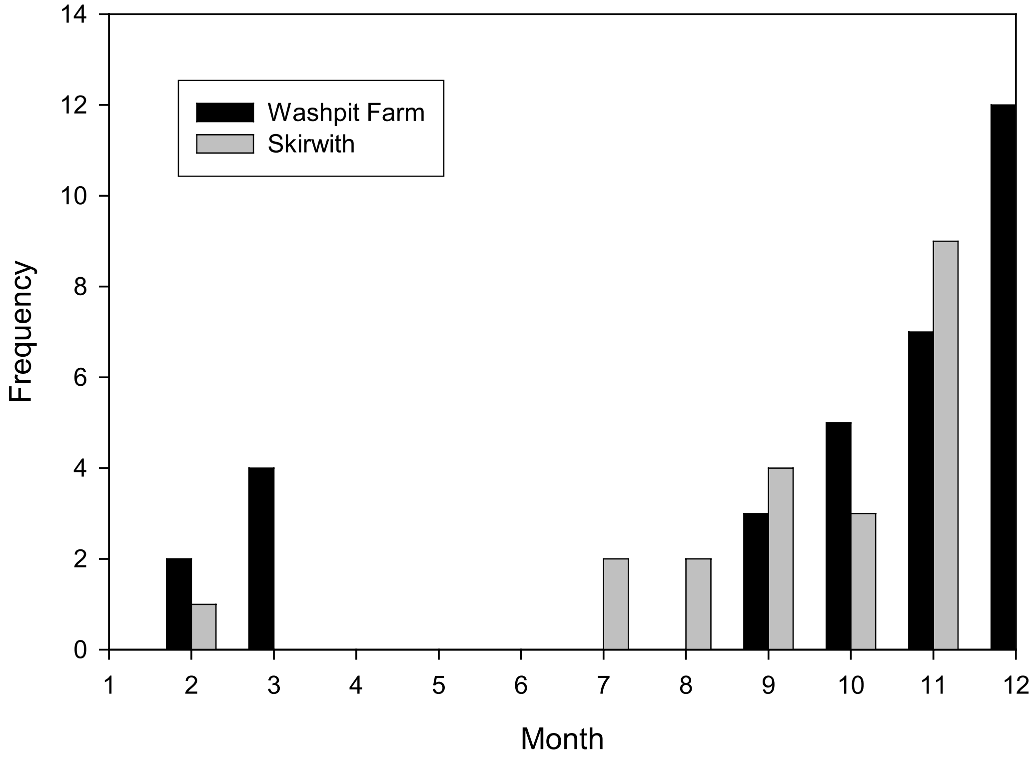


Figure 23 **Frequency histogram showing the months in which annual groundwater level minima occur for the two sites**

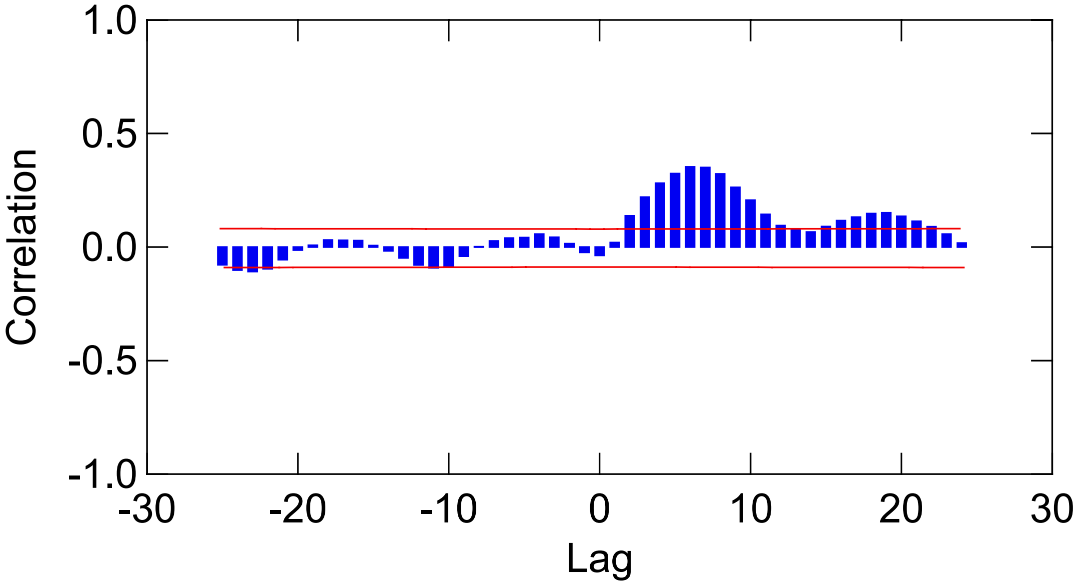


Figure 24 **Rainfall–groundwater level cross-correlation plot for Washpit Farm**

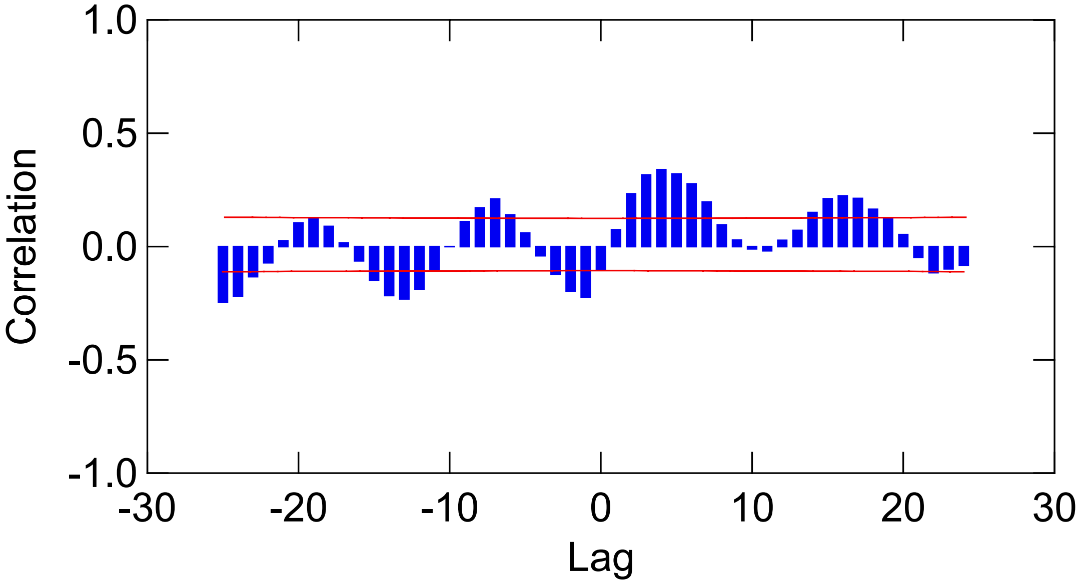


Figure 25 **Rainfall–groundwater level cross-correlation plot for Skirwith**

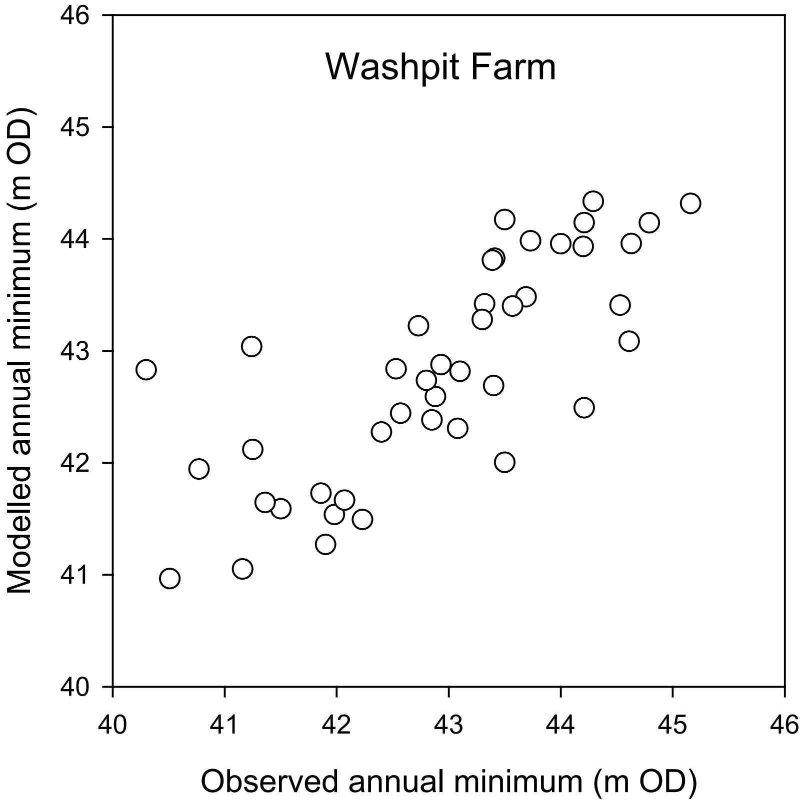


Figure 26 Modelled against observed groundwater levels at Washpit Farm

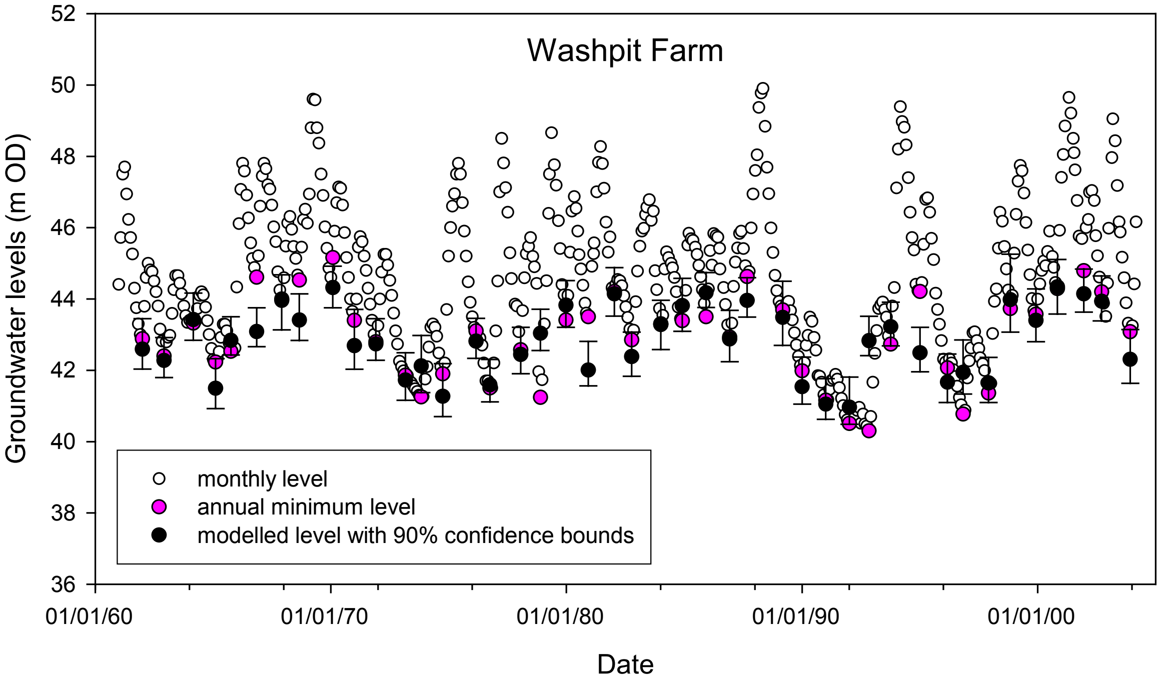


Figure 27 Modelled annual groundwater level minima with 90 per cent confidence bounds plotted against the Washpit Farm groundwater level time series

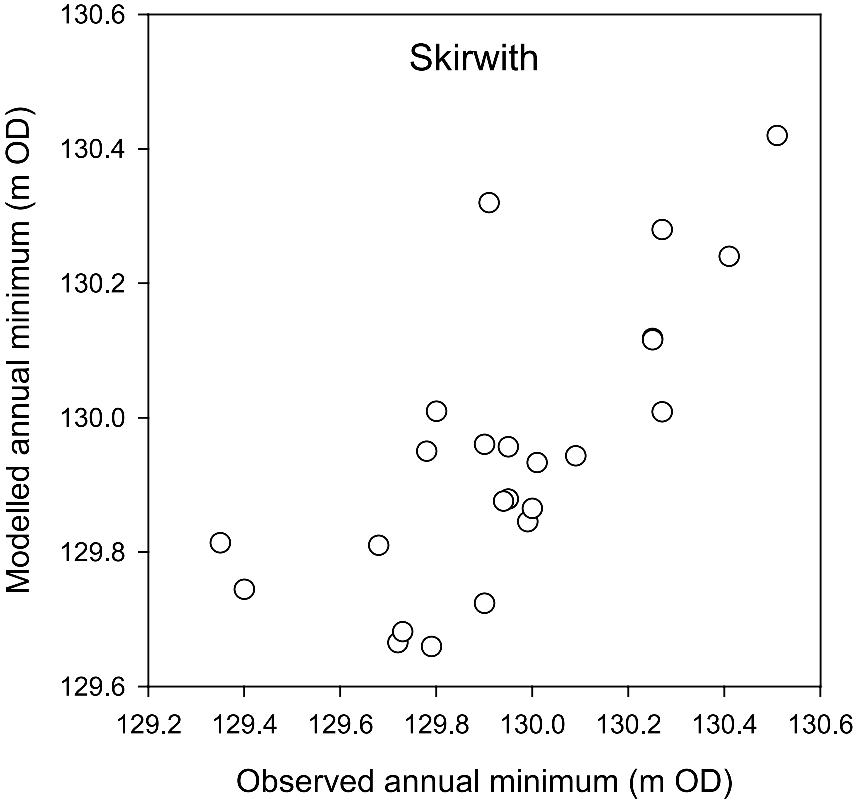


Figure 28 **Modelled against observed groundwater levels at Skirwith**

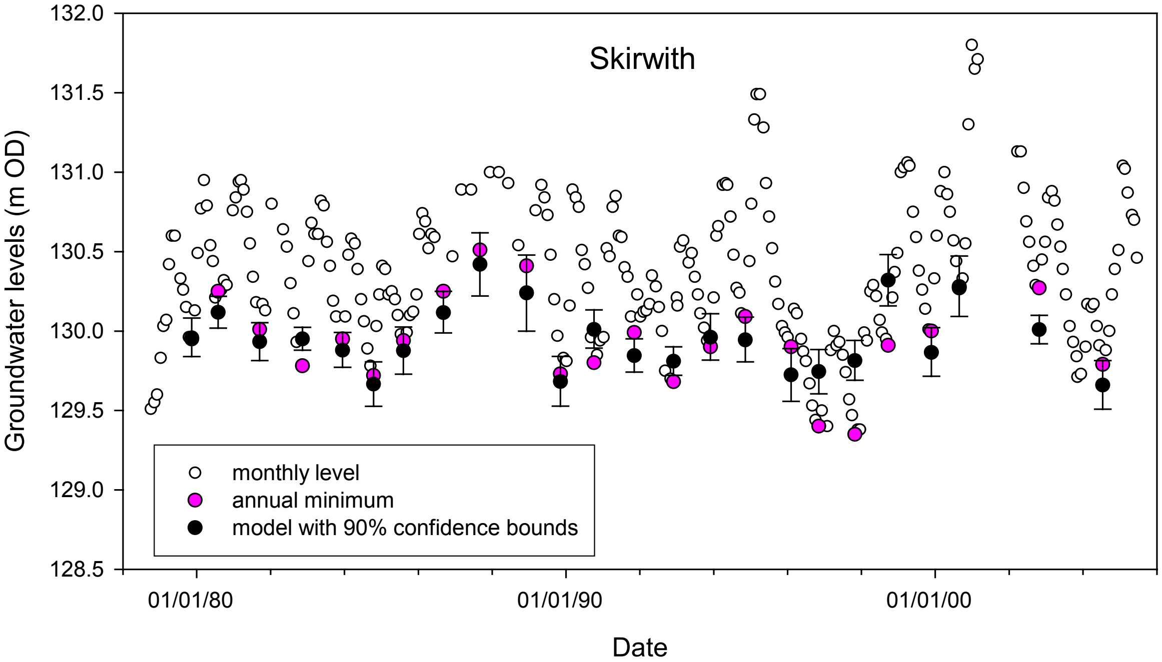


Figure 29 **Modelled annual groundwater level minima with 90 per cent confidence bounds plotted against the Skirwith groundwater level time series**

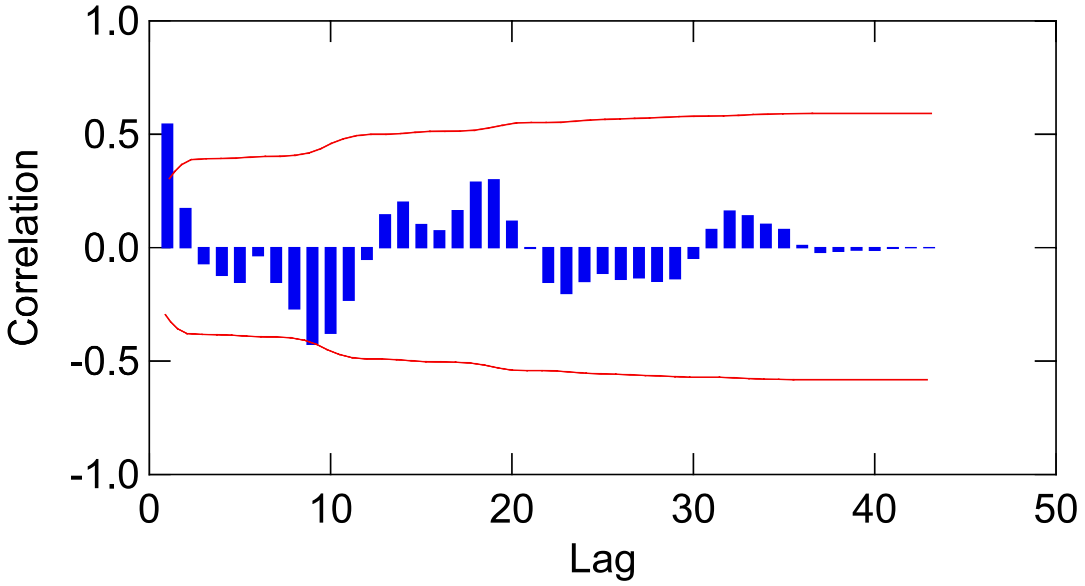


Figure 30 Autocorrelation plot of groundwater minima for Washpit Farm

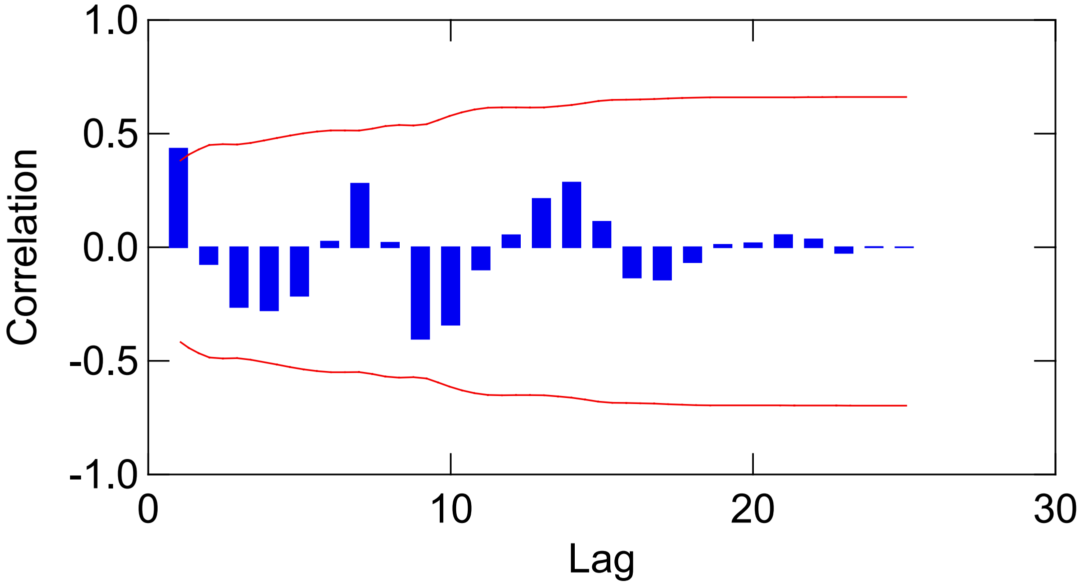


Figure 31 Autocorrelation plot for groundwater minima for Skirwith

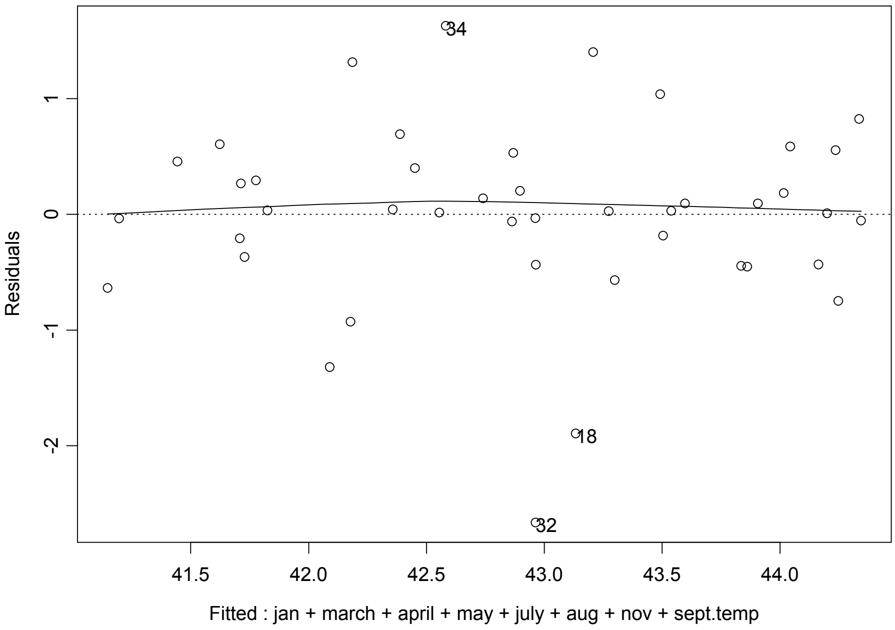


Figure 32 Plot of residuals for the Washpit Farm regression

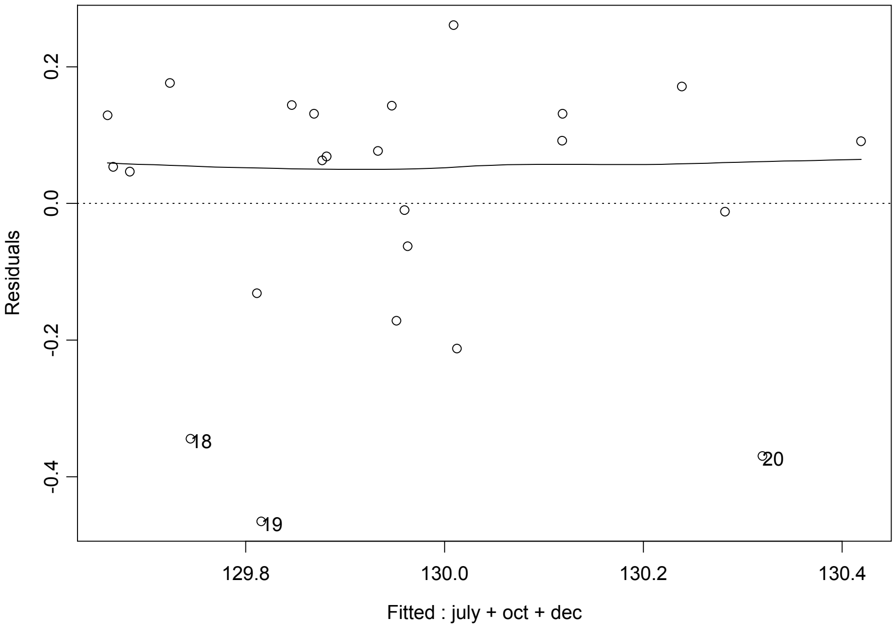


Figure 33 Plot of residuals for the Skirwith regression

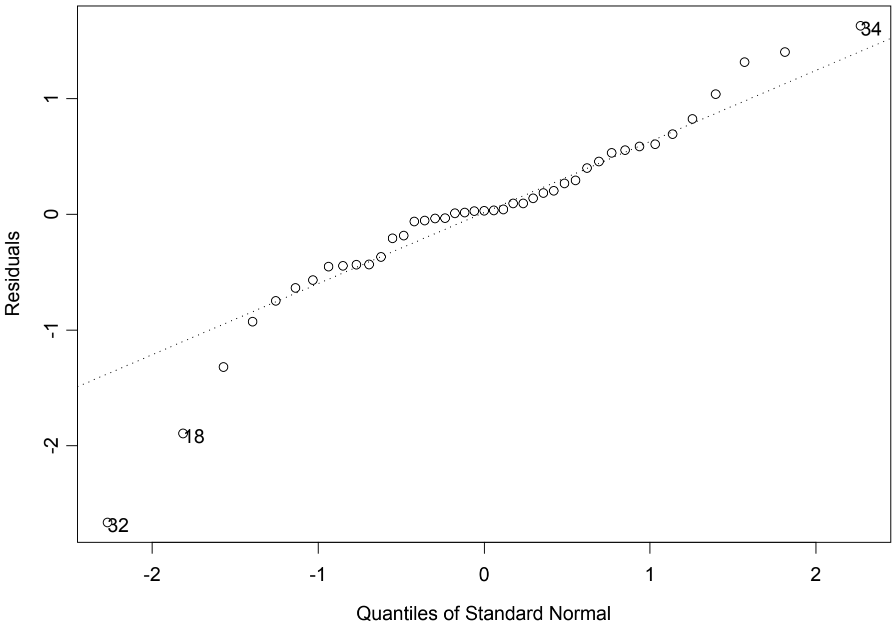


Figure 34 Normal probability plot of the residuals for the Washpit Farm model

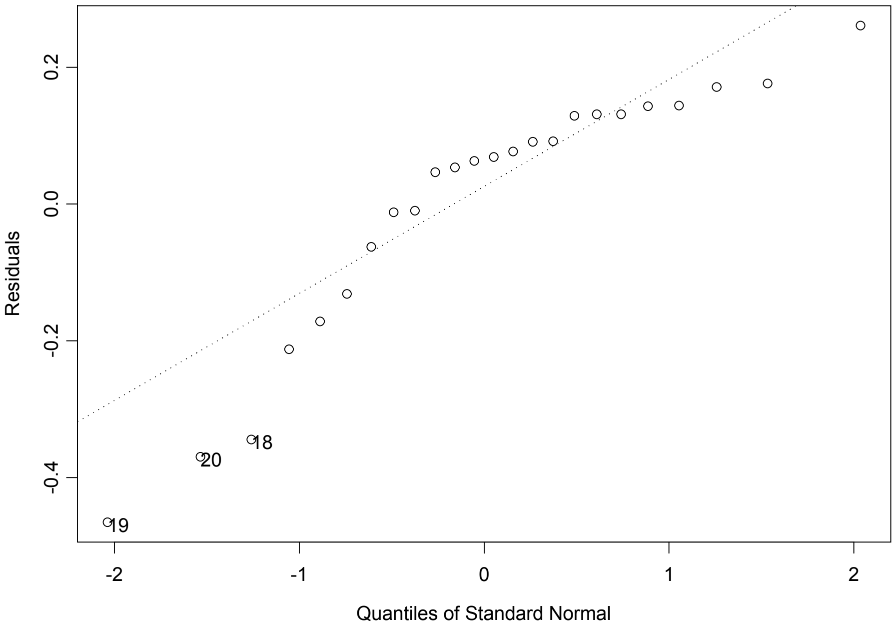


Figure 35 Normal probability plot of the residuals for the Skirwith model

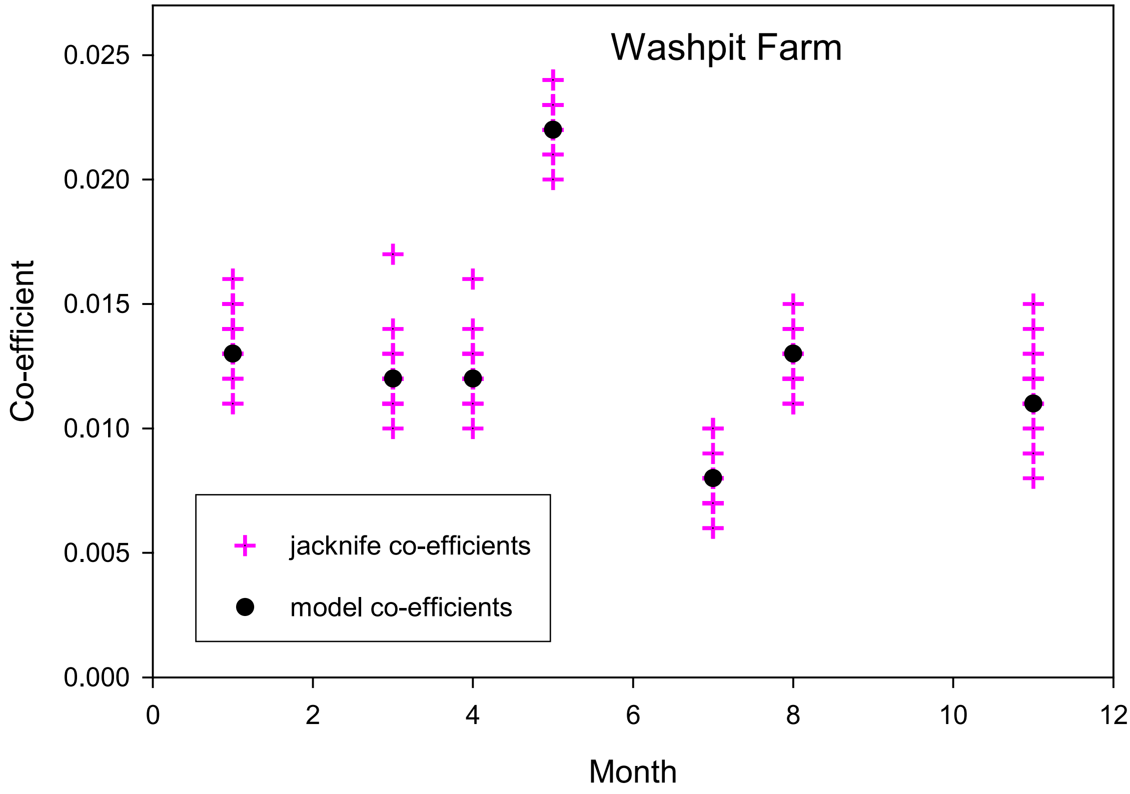


Figure 36 **Variation in jackknife coefficients for the Washpit Farm model**

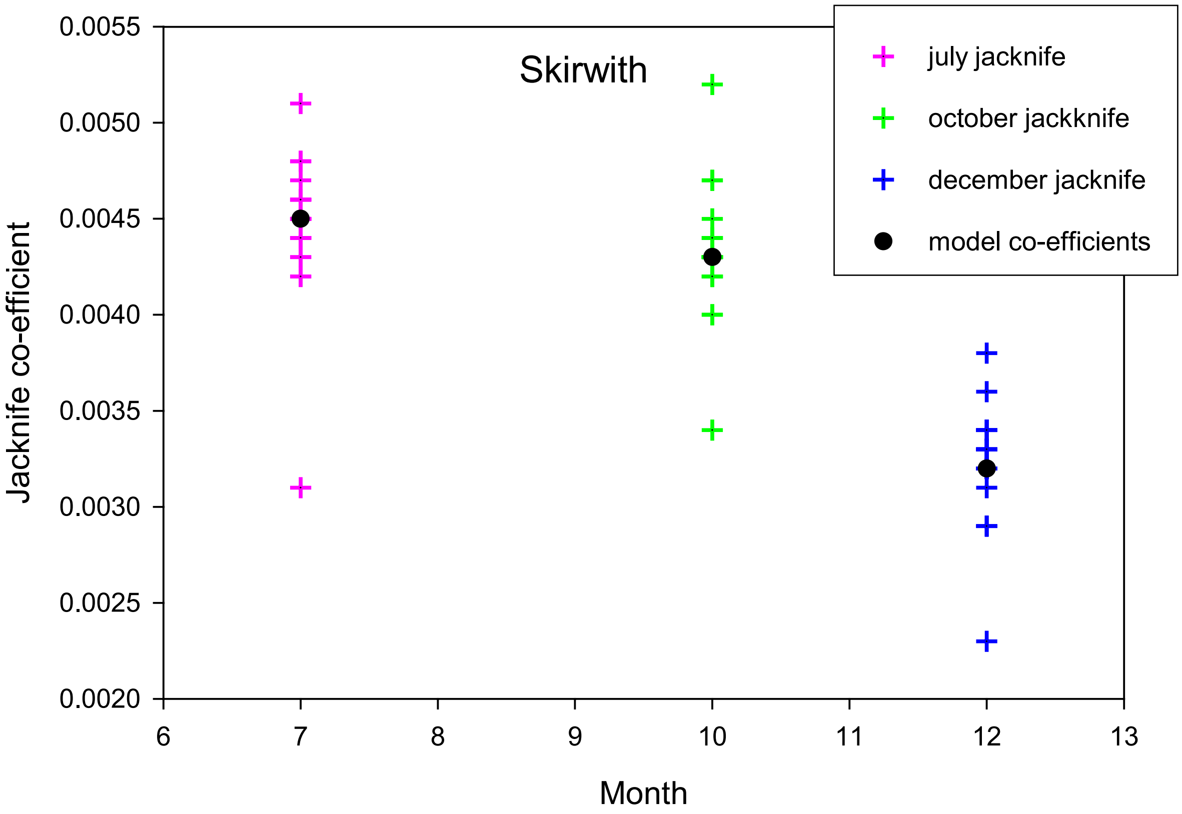


Figure 37 **Variation in the jackknife coefficients for the Skirwith model**

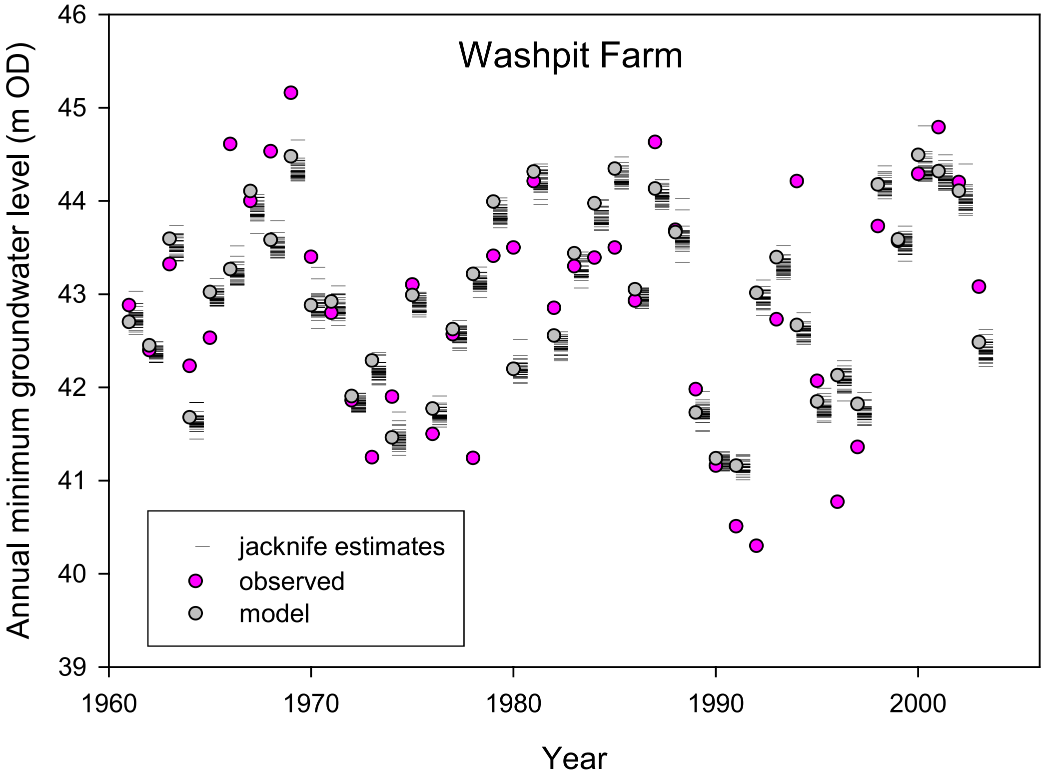


Figure 38 Estimates of annual groundwater level minima for the jackknife values compared with observed and modelled values for Washpit Farm

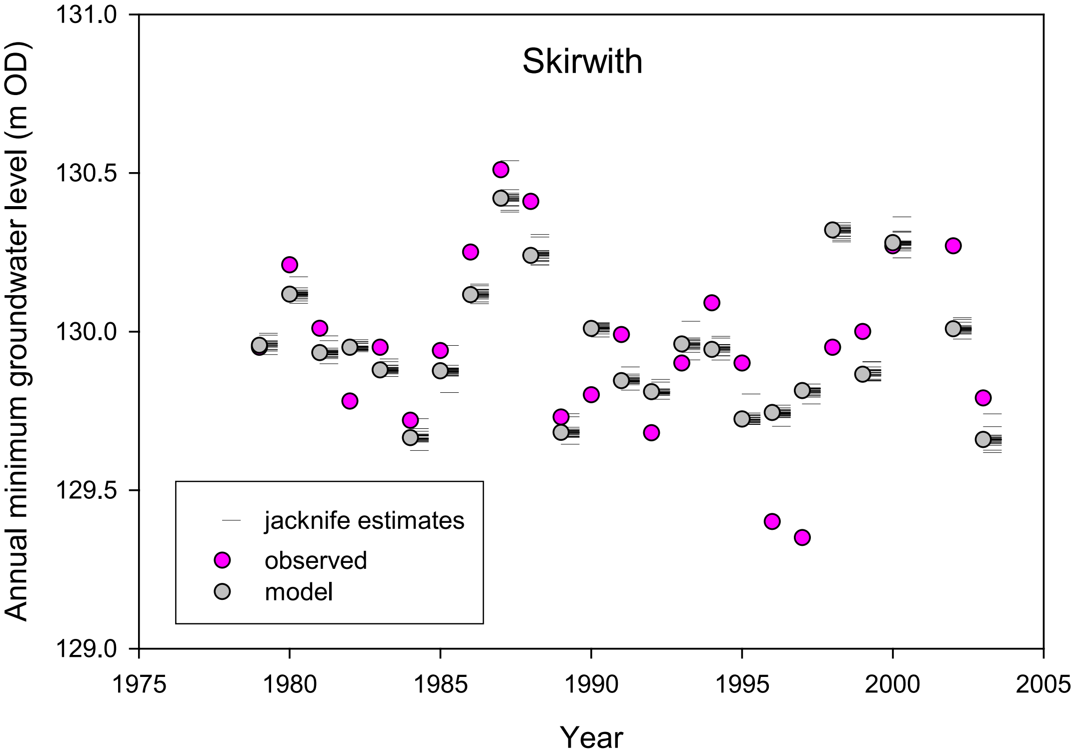


Figure 39 Estimates of annual groundwater level minima for the jackknife values compared with observed and modelled values for Skirwith

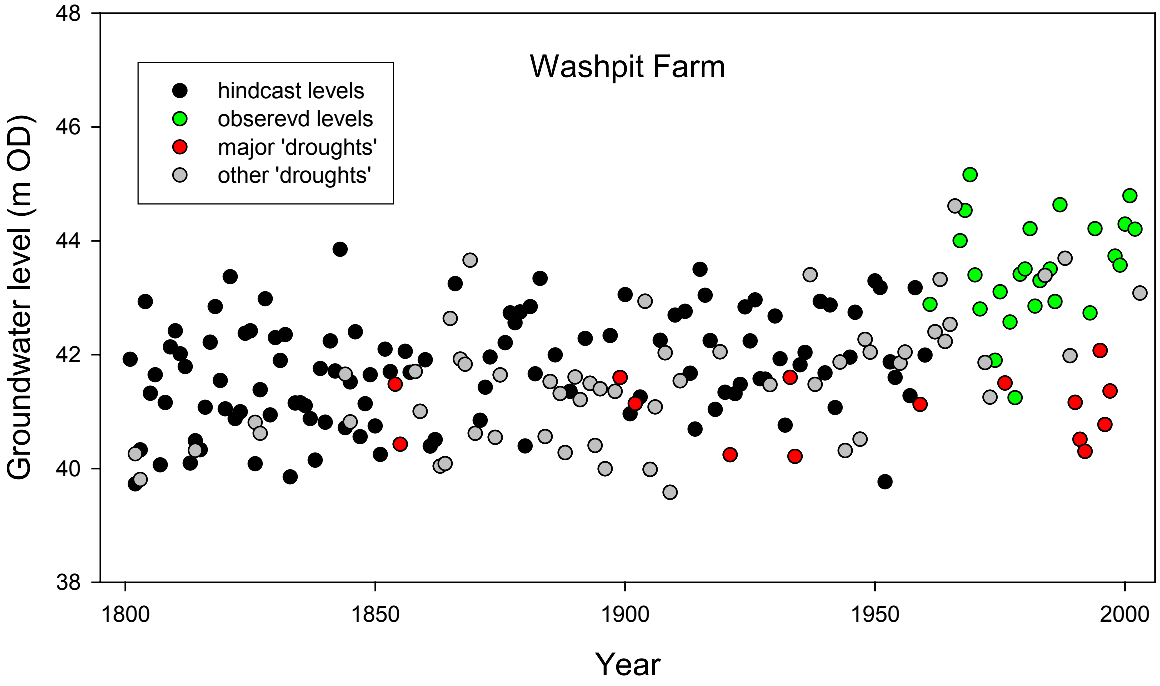


Figure 40 Hindcast annual minimum groundwater levels for Washpit Farm

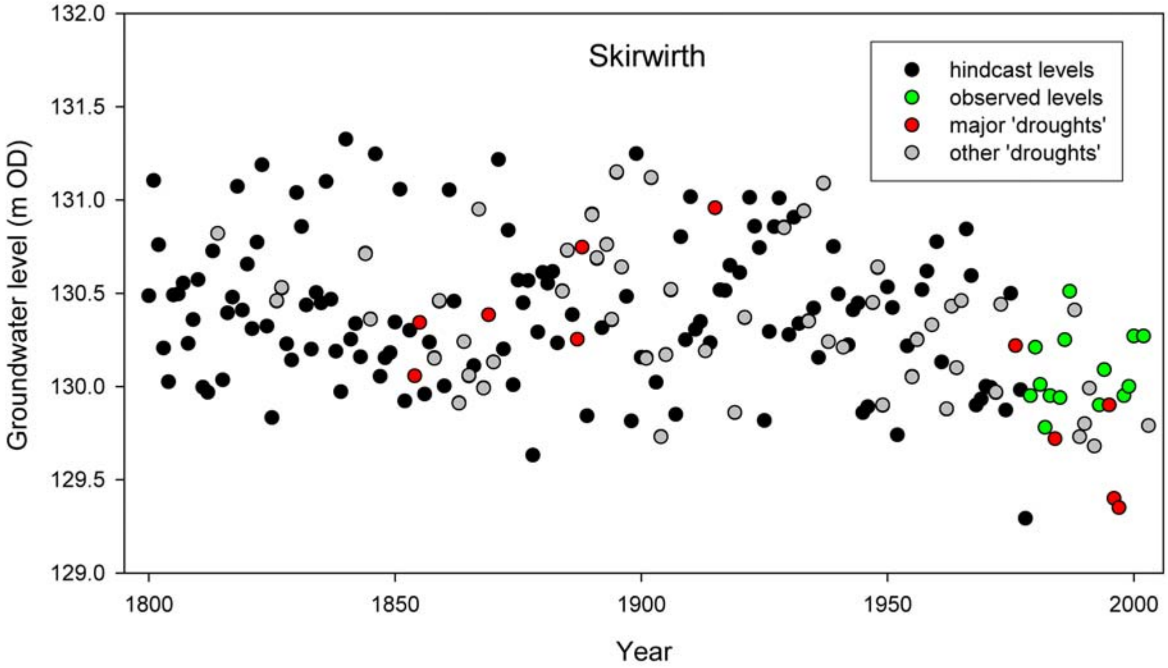


Figure 41 Hindcast annual minimum groundwater levels for Skirwith

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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