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Derivation of long-term natural daily flows for the
North Calder River at Calderbank and Hillend gauging stations

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1 Background

In June 1997 the Institute of Hydrology (IH) were commissioned by PowerGen to assist with a joint study being undertaken by British Waterways and PowerGen aimed at assessing the potential water resources for a proposed CCGT power station at Gartcosh. Water would be drawn from British Waterway's Monklands canal, which is fed by the North Calder river, which has three small regulating reservoirs in its headwaters operated by British Waterways.

This early work was undertaken as part of a preliminary assessment of the hydrology and water resources of the catchment, and involved derivation of 'naturalised' flows, where an attempt was made to account for the effects of the three headwater reservoirs. However, the available river flow and reservoir data were not of the highest quality, and hence reference was made both to flow data from adjacent small catchments and also to synthetic flow estimates from the Institute's microLowFlows software. This earlier work was reported on by IH in June 1997.

Despite these attempts to derive reliable estimates of naturalised flows as inputs to water resource assessment modelling, IH subsequently recommended to PowerGen that additional studies be undertaken in an attempt to derive long-term (greater than 30 year) sequences of daily flows for input to a water resource assessment model which would use simulation of the system behaviour over many years. This report presents the results of these additional hydrological studies.

2 Study requirements

The study aim was to produce a long record of naturalised daily flows for the North Calder river at Calderbank and Hillend gauging stations (see Figure 1). By 'naturalised' flows we mean flows that would have occurred on the catchment without the existence of the three headwater reservoirs. No data are readily available on other abstractions or effluent returns within the catchment, and hence no account has been taken of such factors. A literal sense of 'natural' would imply taking account of other anthropogenic factors, such as changes in land use brought about by farming and forestry, but not only are such changes very difficult to quantify, their impacts are implicitly incorporated into existing flow records and are unlikely to have a major impact in the future; most of the change has taken place some time ago and future changes are likely to be relatively small. There is also a small natural lake, Rough Rigg, within the North Calder catchment which will have some effect on the flow regime of the catchment. However, outflows from the lake are not regulated and there is no information on how this lake might effect flows. It would only be possible to quantify the effects of this natural lake by undertaking a fairly large modelling study, which is neither justified, nor strictly necessary. Hence, no attempts were made to examine what impact Rough Rigg might have on the flow regime, and its effects are likely to be small in comparison with other unknowns within the system.

In our earlier June 1997 report, naturalised flows were derived for a six year period, 1990-1995. The requirement in the present study was to extend the limited gauged flow series to at least a 30 year period.

3 Runoff data extension

Although gauged flows exist on the North Calder at Calderbank from 1968 to date and at Hillend from 1972 to date, flow data for stations on the Monklands canal exist only from 1990 to the present. IH holds data for both Calderbank and Hillend up to the end of 1995, and so currently only six years of naturalised flow, 1990-95, were available from our previous studies for Calderbank (station number 84/27, grid reference NS765624). To derive estimates of the total natural flow, and hence water resources potential, of the North Calder catchment account must be taken of diversions into the Monklands canal, and also of the effects of the regulated headwater reservoirs. Suitable data exist only since 1990.

To obtain a longer flow time series, flow can be related to rainfall using an appropriate model, and available long-term rainfall records used to generate historic flow series. However, the naturalised six year flow record at Calderbank included 158 days of missing data which were infilled using Hillend flows, and 58 days of negative flows, which are probably caused primarily by inaccuracies in the reservoir water balance calculations. There is concern therefore over the accuracy of the North Calder naturalised flow due to the problems of accounting reliably for the artificial disturbances of the headwater reservoirs.

3.1 Rainfall-runoff modelling for the North Calder at Calderbank

As explained above, a naturalised flow series for the six years 1990-95 was available for the Calderbank gauging station. Catchment rainfall was calculated from IH databases for the same six year period. An attempt was made to calibrate a rainfall-runoff model for this period of the six years when concurrent flow and rainfall data are available. The parameters obtained could then be used to simulate the flow for the entire period 1961-1990 for which we have daily rainfall data. IHACRES (Littlewood *et al*, 1997), an IH rainfall and streamflow modelling package was used to try and generate flows at Calderbank for this earlier period.

A catchment average daily rainfall, CADR, is required as an input to the rainfall and flow model. CADR was calculated using the triangle method described by Jones (1983). The triangle method is an averaging process which assigns a weight to each of the raingauges within the appropriate area. The effects of an irregular density and distribution of raingauges is removed as much as possible using this procedure.

To find the relevant raingauges the catchment boundary to the flow gauging stations has to be known. The catchment boundary was derived from the IH Digital Terrain Model (DTM). The search for relevant raingauges was not just confined to within the catchment boundary, normally an equidistant buffer zone around the true catchment of area 2.25 times that of the true catchment boundary is set up. Any raingauges that fall within this area are used for the CADR calculations (Jones, 1983).

Figure 2 shows the catchment boundary, buffer zones and raingauge locations used in modelling the North Calder at Calderbank. Although, there are only two raingauges within the catchment, there are sufficient gauges within the buffer zone to permit derivation of satisfactory catchment rainfalls.

Temperature data is also required by the IHACRES model to estimate rainfall losses. No readily available temperature data exists on the IH databases for the recent period, 1991-1996, so temperature data for the previous five years, 1990-1995 was using data from the MORECS database held by IH. Such substitution of temperature data is generally acceptable as temperature varies relatively little from year to year, and the evaporation losses required by the model are even more conservative from year to year. What is important is the seasonal variations in temperature and evaporation losses, and simple substitution of data from one year to another should adequately represent this seasonality.

However, the quality of the North Calder naturalised flow proved to be too poor to permit calibration of a sensible hydrological model, probably due to difficulties in accounting adequately for effects of artificial influences in the catchment due to lack of suitable data. Classical rainfall-runoff modelling involves calibrating, or fitting, the model to only part of the period having concurrent rainfall and runoff records. The fitted model is then validated against another gauged period which was not used for model calibration. The calibration period used was a 15 month period having complete data, 18/6/92-11/9/93. The best fit obtained with IHACRES was a first order model, but this tends to give poor representation of low flows. Figure 3 shows the resultant simulated flows plotted against the observed, naturalised North Calder flows for the validation period, March 1994 to December 1995, which has relatively complete data. The figure highlights the poor model fit, with the performance being particularly poor in 1994 and also during the summer of 1995, and modelled low flows generally being too high throughout. A number of other calibration trials with variations on the initial model were undertaken in an attempt to permit stable parameter estimates to be developed. However, it was not possible to derive convincing model calibrations for any model configuration for any of the trial periods studied.

Further examination of the North Calder flows suggested that runoff from this catchment might in fact be significantly underestimated (see following paragraph and Table 1), and implied that perhaps the proposed rainfall-runoff modelling exercise might not after all be the best way of estimating long-term flows for the North Calder.

Considering long-term rainfalls, evaporation losses and runoffs for a range of catchments in the Clyde basin, the North Calder appears anomalous. Table 1 shows data from a number of such catchments surrounding the North Calder, and having broadly similar annual rainfalls. The North Calder appears to have an annual rainfall slightly below the regional average, which may in part explain its low annual runoff. However, one of the most striking features of Table 1 is the high computed evaporation losses for the North Calder, these being markedly higher than for elsewhere throughout the region.

The evaporation figure is computed as the difference between recorded mean annual rainfall and mean annual runoff, and such high losses are more typical of south eastern England than south west Scotland. The contrast with the south Calder catchment located immediately to the south is particularly striking.

Table 1 Mean annual rainfall, evaporation losses and runoff from selected catchments in the Clyde basin

Stn. No.	Catchment	Area (km^2)	Mean annual Rainfall (mm)	Mean annual Evaporation (mm)	Mean annual Runoff (mm)
84/24	North Calder at Hillend	19.9	1042	521	521
84/27	North Calder at Calderbank	60.6	955	545	410
84/7	South Calder at Forgewood	92.0	952	291	661
84/8	Rotten Calder at Redlees	51.3	1197	280	917
84/16	Luggie Water at Condorrat	33.9	1086	289	797
84/23	Bothlin Burn at Auchengeich	35.7	1042	351	691

Source: Hydrometric Register and Statistics, 1986-90. Institute of Hydrology and British Geological Survey, 1993

The anomalous gauged runoff behaviour of the North Calder is probably largely a reflection of the high degree of artificial influences within the catchment. In view of this apparent anomalous runoff pattern, and since it had not been possible to model the North Calder flow data with sufficient accuracy, an attempt was made to substitute a different flow gauge from an analogue catchment having similar rainfall, soil, and land use characteristics to the North Calder but one which is less affected by artificial influences.

3.2 Rainfall-runoff modelling of the South Calder at Forgewood

Flows from the South Calder Water at Forgewood gauging station (station number 84/7, grid reference NS 751585) were selected as an appropriate substitute for the North Calder flows at Calderbank. It is assumed the flow regimes should be similar as the catchments are adjacent and they both receive similar rainfalls; mean annual rainfall for the North Calder at Calderbank and the South Calder at Forgewood are 955mm and 952mm respectively. The two catchments also have similar topographies, land use and geology. Figure 1 shows the locations and catchment boundaries of the North Calder at Calderbank and the South Calder at Forgewood.

The South Calder catchment has an area of $92km^2$ which is just over 1.5 times larger than the North Calder catchment. The South Calder already has a long gauged flow record, and flows exist on the IH database from 1/2/66-31/12/96. There are some periods with missing data from 21/1/91-23/1/91, 26/2/91-28/2/91, 29/1/93-3/2/93, 1/5/93-26/5/93, 31/7/94-3/8/94, and 13/7/95-27/7/95, although these amount to a total of only 57 days missing out of the 31 year period of record.

Given that there are already 31 years of almost complete gauged daily flows for the South Calder at Forgewood, it was only necessary to use the IHACRES model to generate simulated flows for the early years, 1/1/1961-31/1/66 and also to infill the limited flow record gaps in the 1990s. This was possible as the South Calder catchment rainfall could be calculated for the period 1961-1966 to extend the observed flow record. Validated daily rainfall data are readily available from the Meteorological Office from 1961 to date.

Figure 5 shows the catchment boundary, buffer zones and raingauge locations used in modelling the South Calder at Forgewood. Although there is only one raingauge within the catchment, as with the North Calder, there are sufficient gauges within the buffer zone to permit derivation of satisfactory catchment rainfalls.

The IHACRES model was calibrated over a 26 month period, 20/8/81-23/10/83, which gave a sufficient model fit. When the model was run to simulate flows from the rainfall and temperature data a good fit was obtained between modelled flow and actual flow. An example of the model fit for the South Calder at Forgewood, is shown in Figure 4. This can be compared with the North Calder model fit at Calderbank for the same period, Figure 3. In all cases, the following discussions concern naturalised flows for the North Calder catchment at Calderbank gauging station, with the effects of the three headwater reservoirs and diversions to the Monklands canal having been accounted for as far as the available data permitted.

The model fit for the South Calder is better than that for the North Calder, particularly during the early years, and for low flows. Comparison of Figures 3 and 4 confirms the earlier statements in Section 3.1 that the North Calder flows are not well measured and strengthens the case for using the South Calder flows as a surrogate data series.

Flows for the South Calder could thus be generated using the fitted IHACRES model for the period 1/1/1961-31/1/66 to extend the gauged flow record. In addition, modelled flows were used to infill the short periods of missing flow data for the Forgewood gauge. However, for some periods of missing data, such as 21/1/91-23/1/91, the naturalised North Calder flows derived in our earlier study were used to infill gaps when it was considered that the Calderbank flows were correct (i.e. the Calderbank flows were non negative, and agreed well with observed South Calder flows for dates immediately preceding and following the data gap).

4 Comparisons of North Calder flow with South Calder flow

The infilled and extended South Calder flows were divided by 1.5 to give a surrogate flow series for the North Calder at Calderbank (the North Calder has a catchment area approximately 1.5 times smaller than South Calder, see Table 1). Figure 6 shows the South Calder flow, adjusted to allow for the difference in area, and the original naturalised North Calder flows from our earlier June 1997 study. As stated above, all references to North Calder flows in the following comparisons are to naturalised flows at Calderbank gauging station, with the effects of upstream reservoirs and Monklands canal flows being accounted for as far as possible.

Figures 6 and 7 show comparisons between the two sets of flows. These show that there is a tendency for the South Calder flows to be lower than those of the North Calder, particularly for low and medium flows. The primary reason for the marked difference is probably the uncertainties introduced by the flow naturalisation exercise. However, as pointed out earlier in section 3.1, gauged flows on the North Calder catchment are anomalously low when compared with surrounding catchments, and it appears that they do not realistically represent the water resources potential of the region as a whole. The naturalisation attempted in our earlier report was an attempt to return gauged flows to their 'normal' state, but with the relatively poor data available, confidence in these naturalised flows must be low.

5 Flows for Hillend gauging station

The same uncertainties that exist over the reliability of the naturalised flows for Calderbank apply to the Hillend gauging station upstream. Therefore we recommend that for water resource assessment purposes, a series based on flows of the South Calder at Forgewood be used.

The Hillend gauge has a catchment area of 19.9 km^2 compared with 60.6 km^2 at Calderbank. The simple area ratio is 0.328. However, being a headwater gauge, the Hillend catchment generates a higher proportion of the total North Calder flow than does the intervening area between the two gauges. The long-term mean annual flow for Hillend is 10.37 $m^3 \times 10^6$, whereas that for Calderbank is 24.85 $m^3 \times 10^6$. Thus the Hillend catchment generates 10.37/24.85, or 42 percent of the Calderbank runoff, rather than the 33 percent implied by the simple area ratio.

To derive Hillend flows from those at Forgewood, it is therefore recommended that Forgewood flows be multiplied by 0.667 x 0.42, that is 0.28. Thus Hillend flows should be taken as 28 percent of those at Forgewood.

6 Conclusions

The attempt to extend the six year series of naturalised flows derived for Calderbank in the earlier study (IH, 1997) proved to be difficult. A satisfactory model calibration could not be produced, in part because of the many periods of negative flow which resulted from the previous naturalisation process. Such anomalies are an inevitable result of reservoir water balance corrections, and are not surprising.

In view of the poor fit of the rainfall-runoff model, and because of the doubts expressed in Section 3.1 over the reliability of the gauged flows within the North Calder catchment, it is recommended that a surrogate data series, flows from the adjacent South Calder catchment be used to estimate water resources for the proposed Gartcosh power station.

It is suggested that the adjusted South Calder flows at Forgewood should give the best indication of natural flows in the North Calder catchment at Calderbank rather than data available from either of the North Calder gauging stations. This is because these South Calder flows are not as significantly influenced by artificial water abstractions and effluent returns as those of the North Calder. The Calderbank flows should be taken as

66.7 percent of those at Forgewood flows, and similarly, Hillend flows should be taken as 28 percent of those at Forgewood.

The derived daily flow series are plotted and given in Appendix 1.

It is recommended that these long daily flow series be applied to a suitable water resources simulation model of the north Calder catchment whereby these flows provide the input to a long-term behavioural analysis of the catchment. Thus, the daily flows for Hillend should be apportioned according to proportional catchment area and mean annual rainfall and input to the three headwater reservoirs. Releases should be made from these reservoirs as necessary in order to meet the existing, and increased Monklands canal water demands (i.e. 'increased demands' means the existing water requirement for navigation and amenity plus the additional demands of the proposed CCGT power station at Gartcosh). Releases should also be made to ensure that the minimum flow requirement to the lower North Calder catchment are maintained, that is, there should be no diversions to the Monklands canal when the gauged flow at Calderbank is less than the Q95 value of 0.195 m^3s^{-1}. The simulation model should be run with a range of potential transfer rates along the Monklands canal and months and years of failure to meet this full demand counted. It is necessary to run a range of demands through the simulation model, as the simple counting failure technique provides only a discrete approximation to a continuous process. Results of a number of trials with varying demands are normally plotted and a smooth curve drawn through the results in order to estimate demands which can be met with, say, a 1 in 20 or 1 in 40 year risk of failure.

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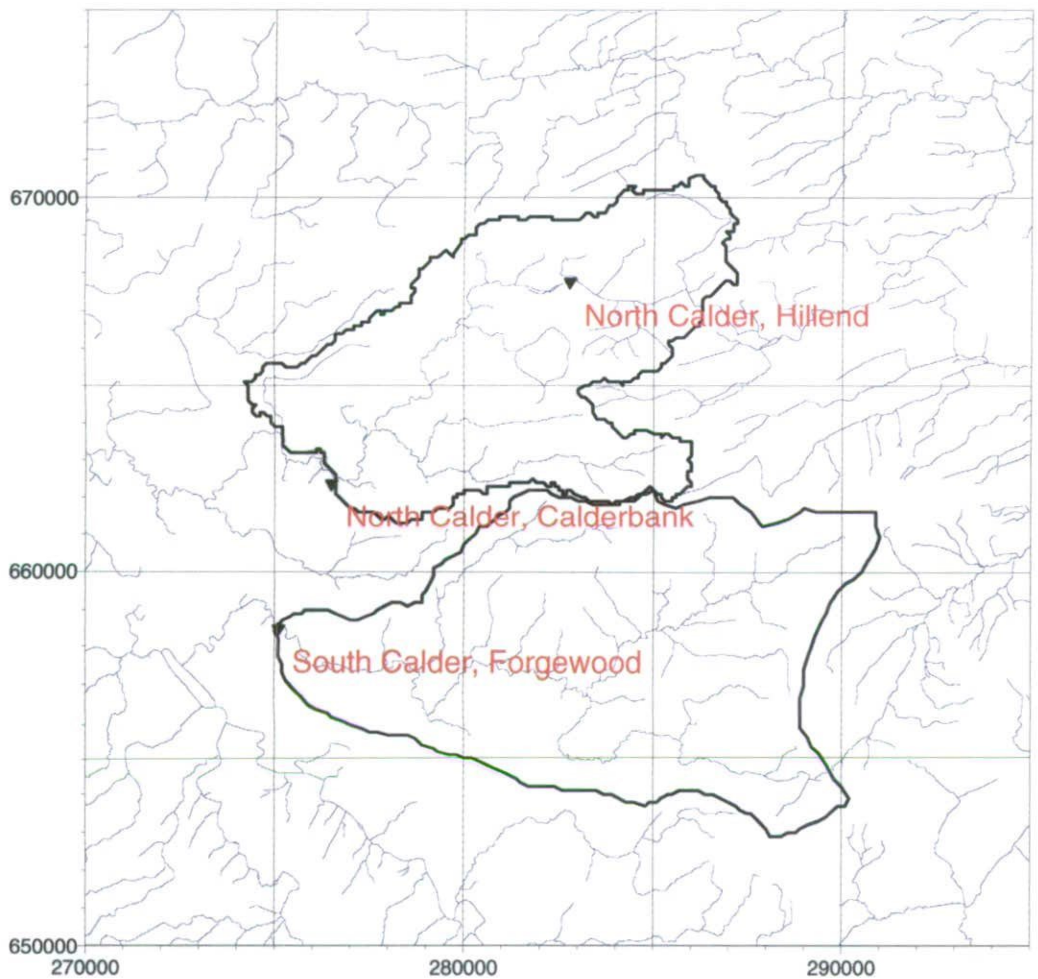

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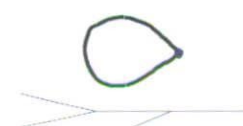


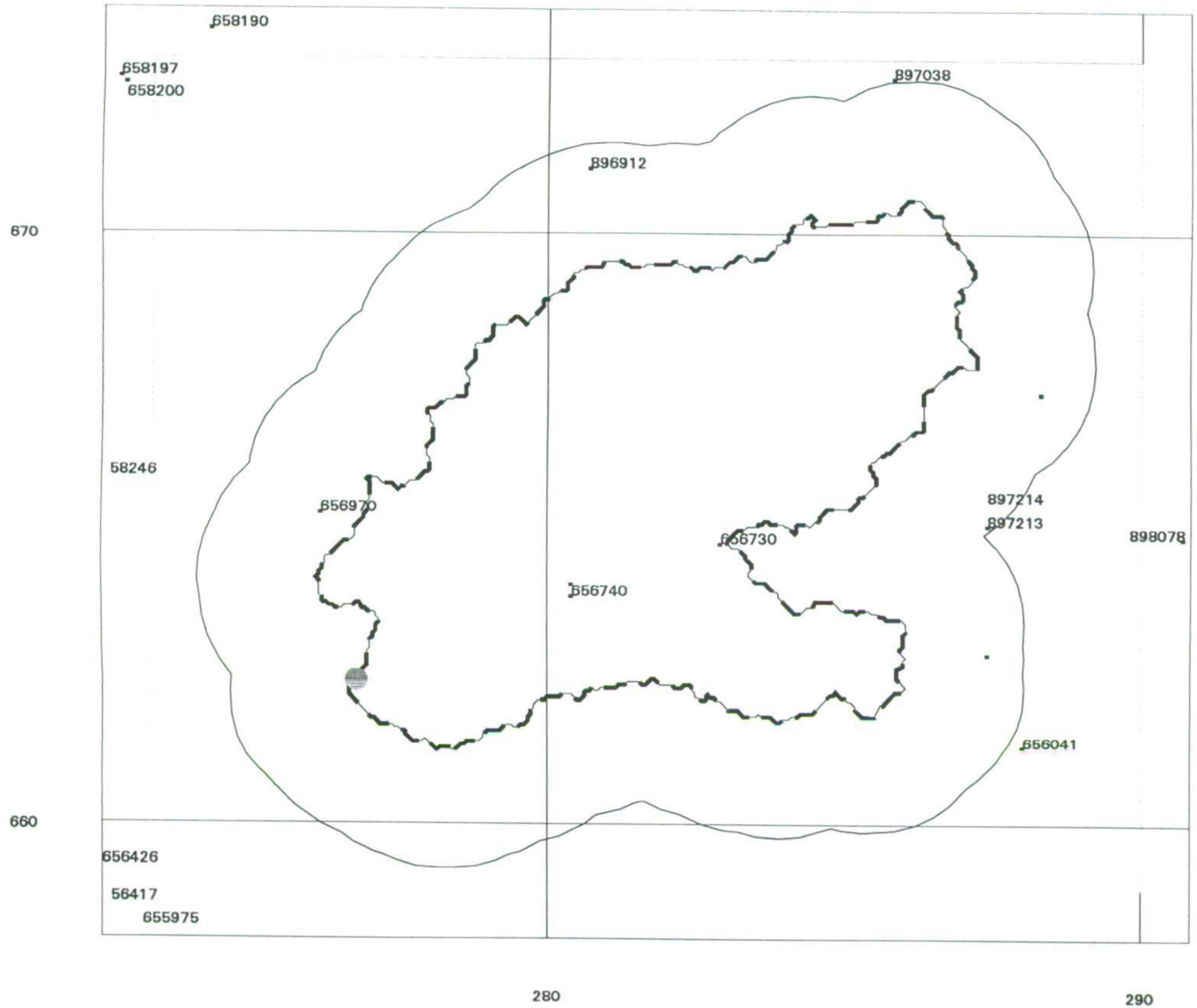
catchment boundary

rivers

Map produced at 16:50 on 9 Jun 1998

Figure 1

Daily and Recording Raingauges - Catchment derived from DTM at (276800,662450)



61.76 sqkm catchment area
970.88 SAAR 1941-70
1025.05 SAAR 1961-90
150.13 sqkm buffer area
2000 m buffer distance

Figure 2 North Calder catchment at Calderbank

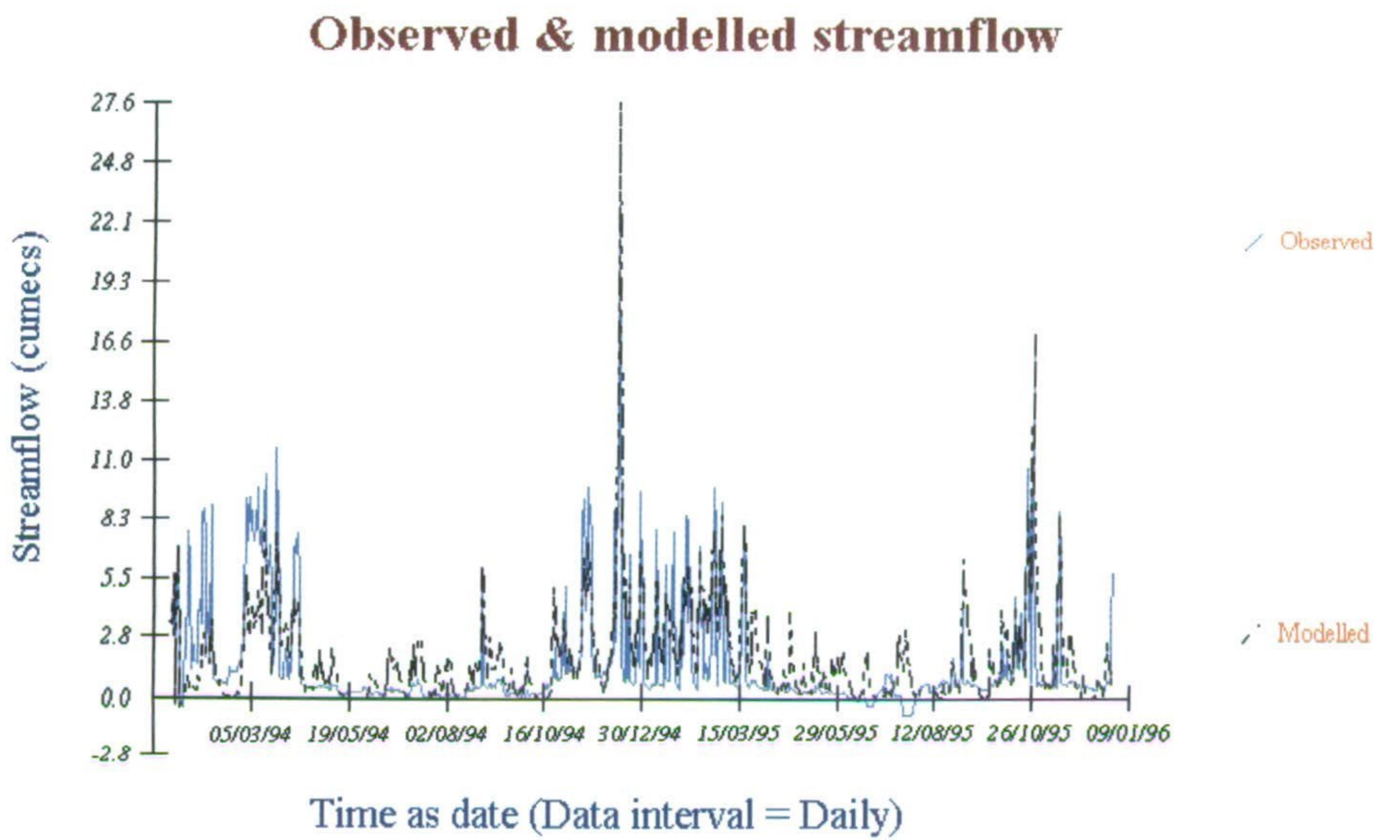


Figure 3 North Calder at Calderbank

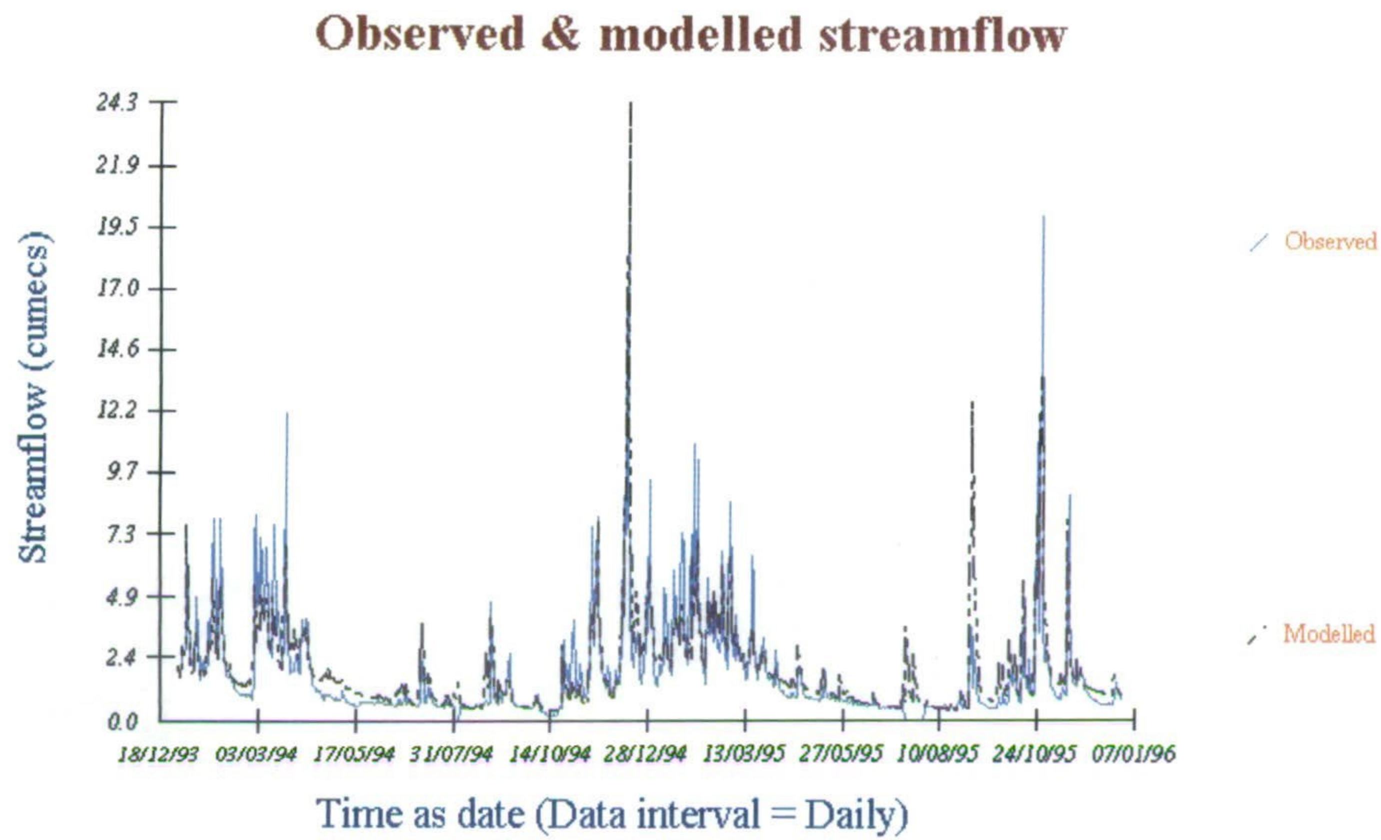
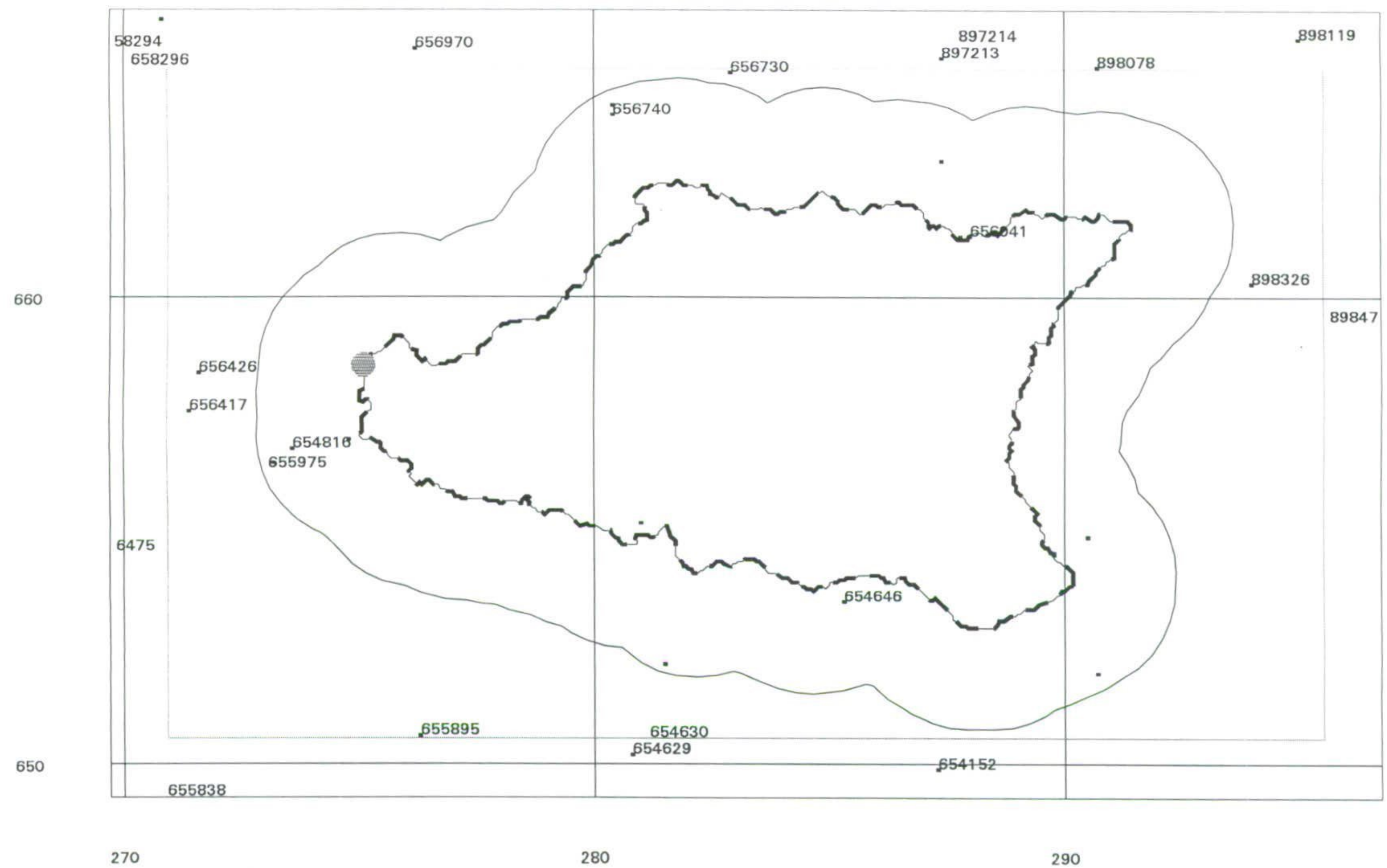


Figure 4 South Calder at Forgewood

Daily and Recording Raingauges - Catchment derived from DTM at (275100,658550)



92.47 sqkm catchment area
911.59 SAAR 1941-70
928.96 SAAR 1961-90
211.21 sqkm buffer area
2200 m buffer distance

Figure 5 South Calder catchment at Forgewood

Naturalised flows at North Calder, Calderbank and area adjusted flows at South Calder, Forgewood 1990-1995

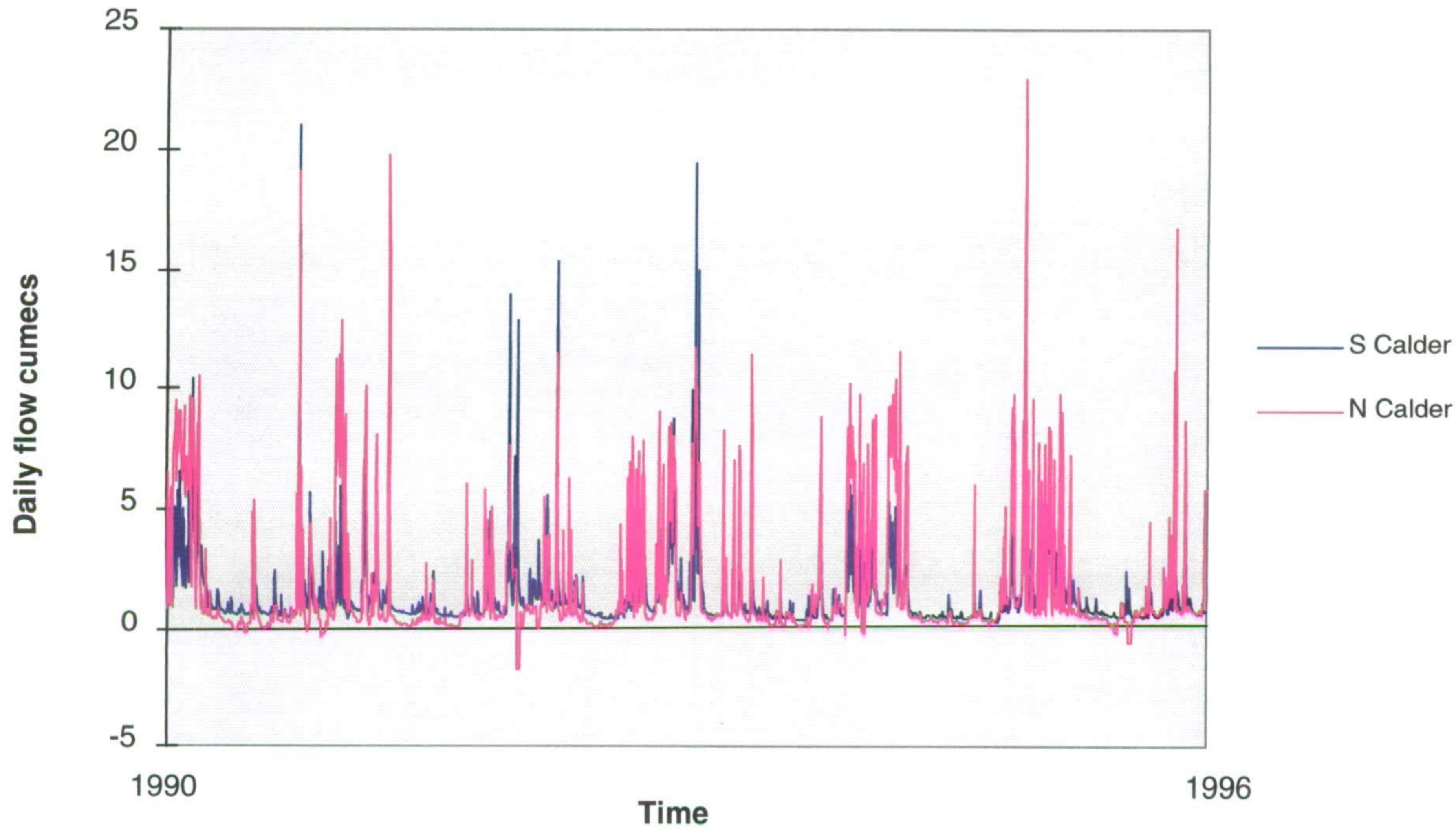


Figure 6

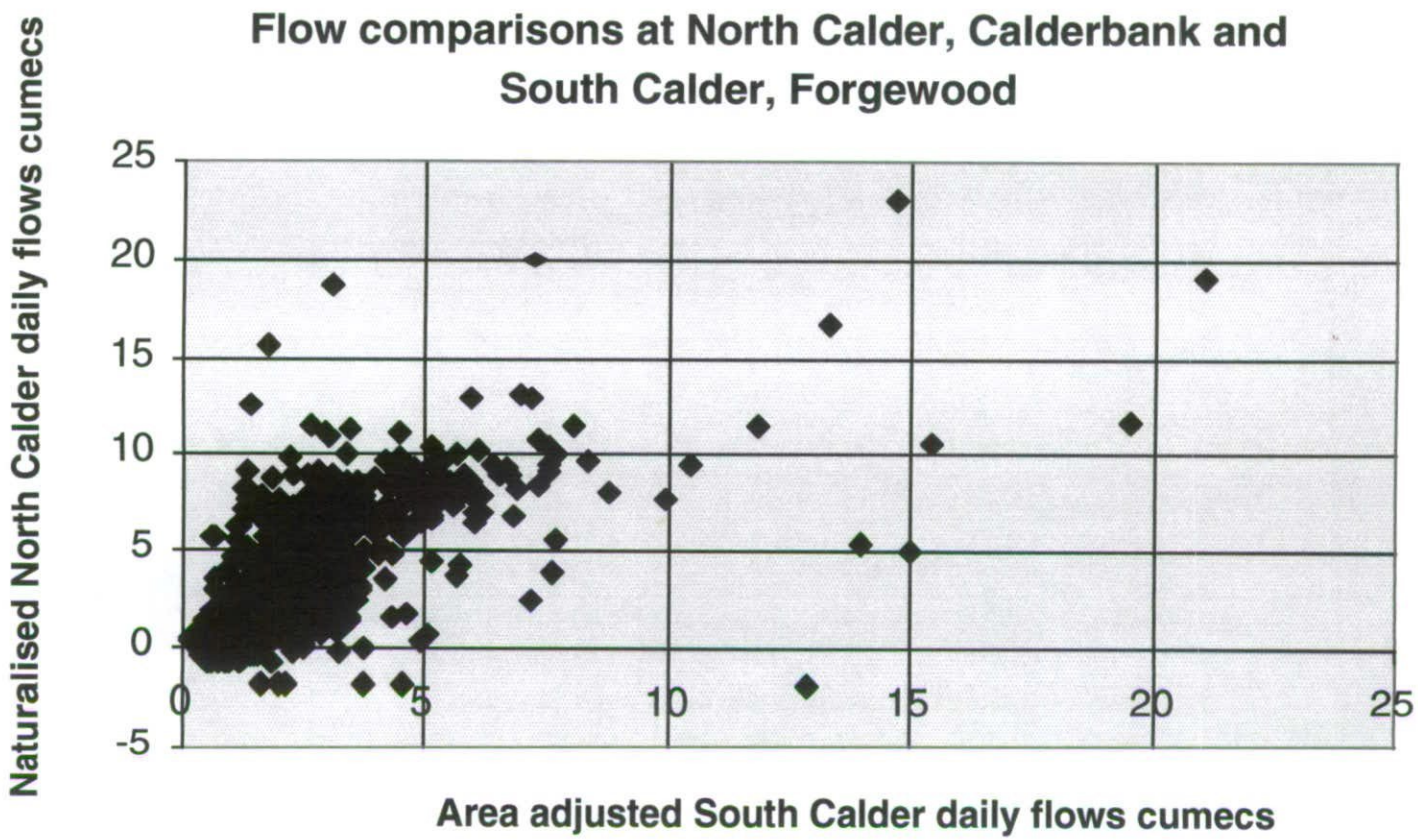

Flow comparisons at North Calder, Calderbank and
South Calder, Forgewood
Naturalised North Calder daily flows cumecs
25
20
15
10
5
0
-5
0
5
10
15
20
25
Area adjusted South Calder daily flows cumecs

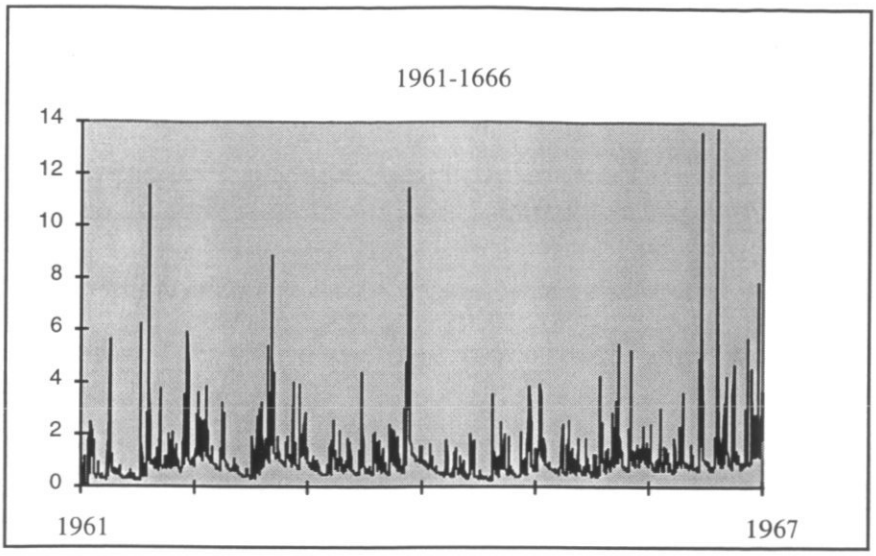
Figure 7

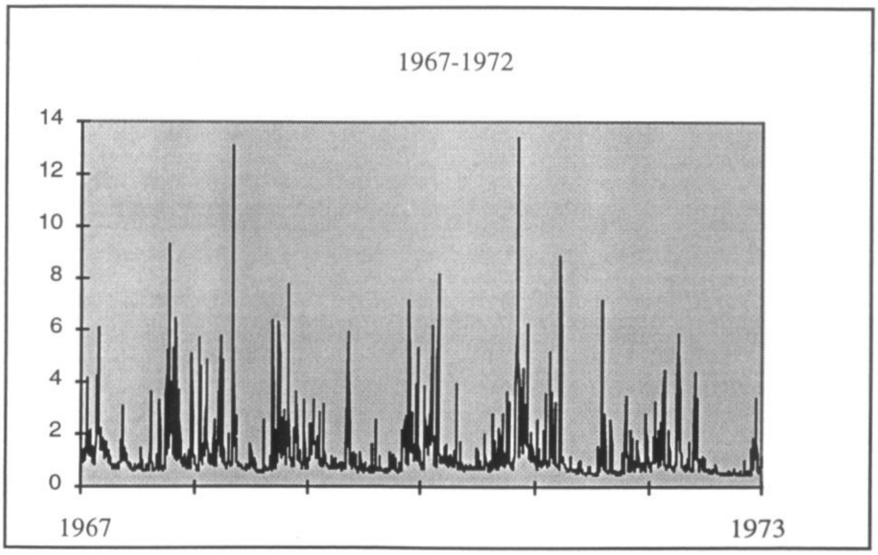
APPENDIX 1

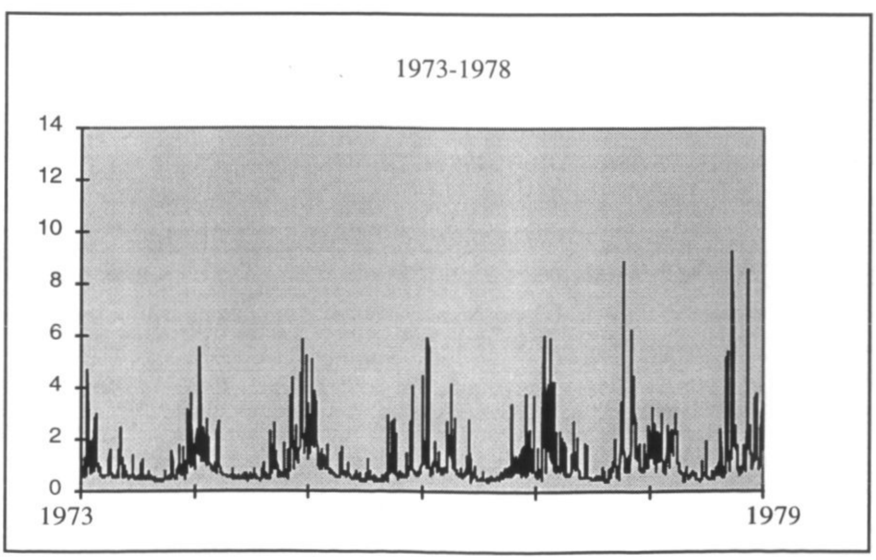
Hydrographs of estimated daily flows for the North Calder at Calderbank and Hillend gauging stations

Adjusted South Calder, Forgewood flows to give the best indication of North Calder, Calderbank flows

Daily flow cumecs

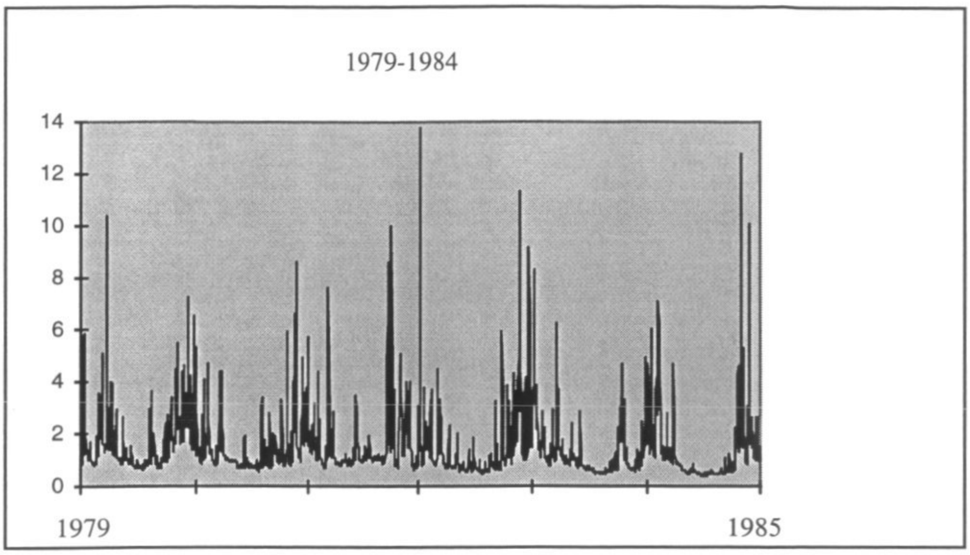


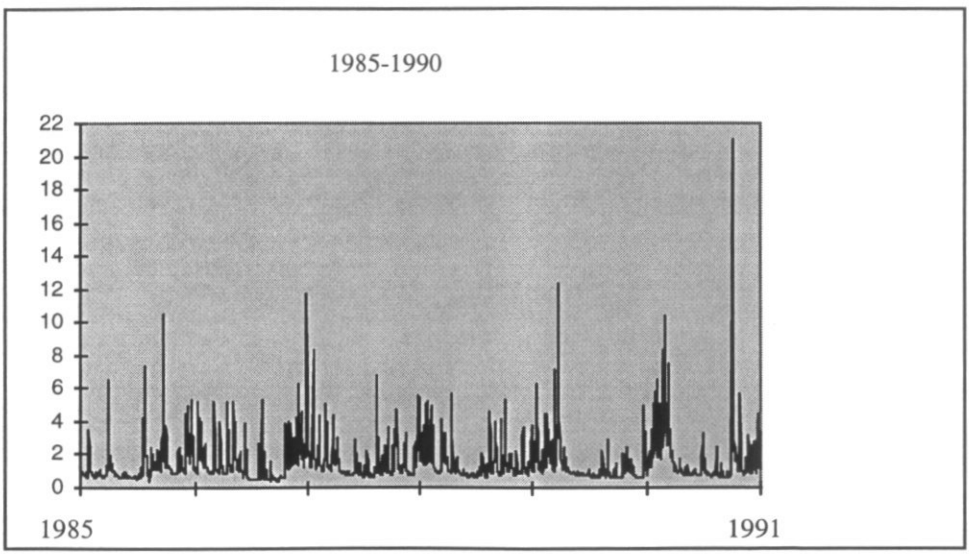


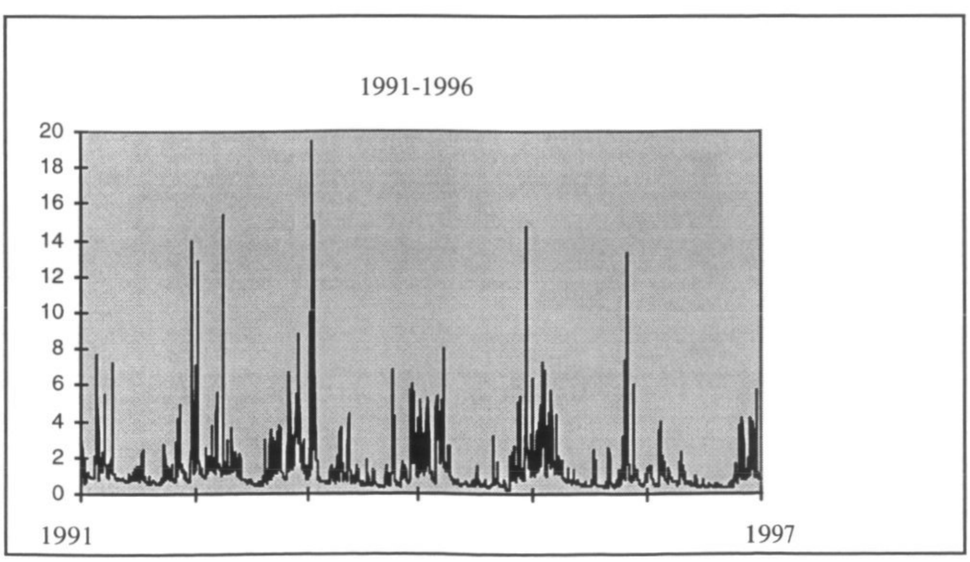


Adjusted South Calder, Forgewood flows to give the best indication of North Calder, Calderbank flows

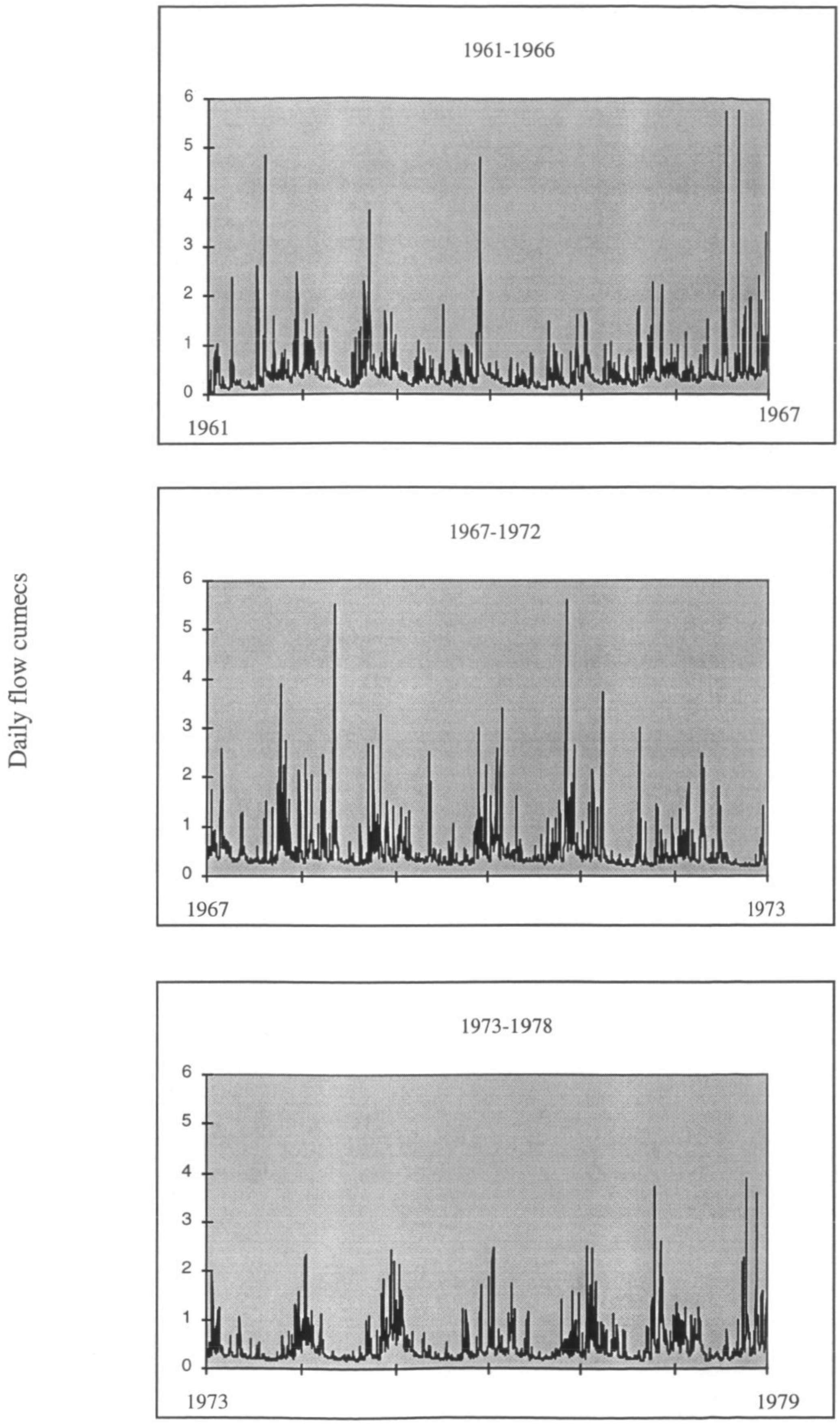
Daily flow cumecs







Adjusted South Calder, Forgewood flows to give the best indication of North Calder, Hillend flows



Adjusted South Calder, Forgewood flows to give the best indication of North Calder, Hillend flows

Daily flow cumecs