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THE EFFECTS OF REDUCING RAINGAUGE NETWORK DENSITY ON GOODNESS OF CONCEPTUAL MODEL FIT AND PREDICTION

by

D. Richards

ABSTRACT

Reducing the density of the raingauge network has been shown to have very little effect on the efficiency of the three-store model used by the Institute to simulate hydrological response in some experimental catchments.

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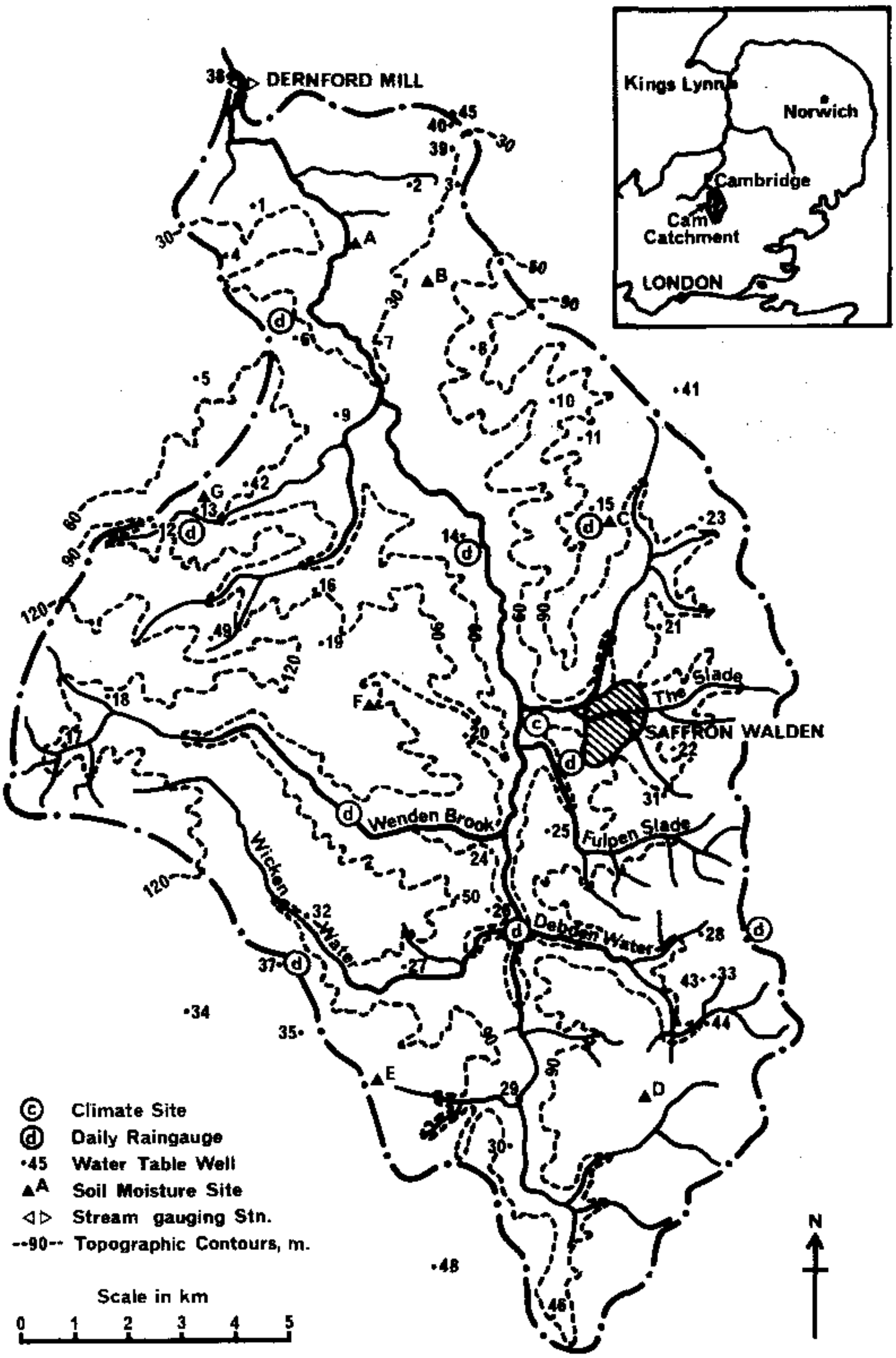


Figure 1 The Cam catchment above Dernford Mill

INTRODUCTION

The conceptual catchment models used in this study contained three (sometimes two) storage elements: (a) an interception store, with contents depleted by evaporation and transfer to (b) a soil moisture store, depleted by transpiration, rapid runoff, and transfer of contents to (c) a groundwater store, with contents depleted by baseflow discharge This model, with a maximum of thirteen parameters, was fitted by calculating that set of parameter values which minimized the sum of squared deviations from the observed streamflow of the streamflow estimates given by the model.

Records of precipitation, potential evapotranspiration and streamflow were available for three experimental catchments: the Cam down to Dernford Mill; Coalburn; and the Ray at Grendon Underwood. The available record from each catchment was divided into two. The first part was used to fit model parameters, while the second - together with the parameter estimates - was used to transform the precipitation and potential evapotranspiration sequences into a 'predicted' streamflow sequence for comparison with that observed during the period.

In each of the three catchments studied, precipitation was measured by a network of monthly storage gauges together with one or more recording gauges. The purpose of the study was to examine the effect of reducing the density of the storage gauge network on (a) the goodness of fit obtained in the first part of each record and (b) the agreement of predicted streamflow with that observed in the second part. The results suggest that changes in the precipitation estimates resulting from reducing network density were compensated during the fitting stage by adjustment of the parameters, principally those controlling the part of the model governing evaporation. The differences between observed and predicted streamflow increased, however, as network densities decreased.

THE CATCHMENTS

The Cam Catchment

Full details of the physiography of this catchment are given by Dickinson and Douglas (1972). It lies approximately ten miles south of Cambridge and comprises 197 km^2 of predominantly agricultural land on the margin of the Fens; the central branch of the river rises in the chalk uplands south of Saffron Walden and flows slightly west of north to the gauging station near Dernford Mill, as shown in Figure 1. Geologically, the catchment consists of boulder clay on chalk, which lies in turn on Cambridge Greensand.

Figure 1 also shows the networks of hydrological instruments located in and around the Cam catchment. The data collected by them was checked and used to calculate river discharge, mean basin precipitation, potent-

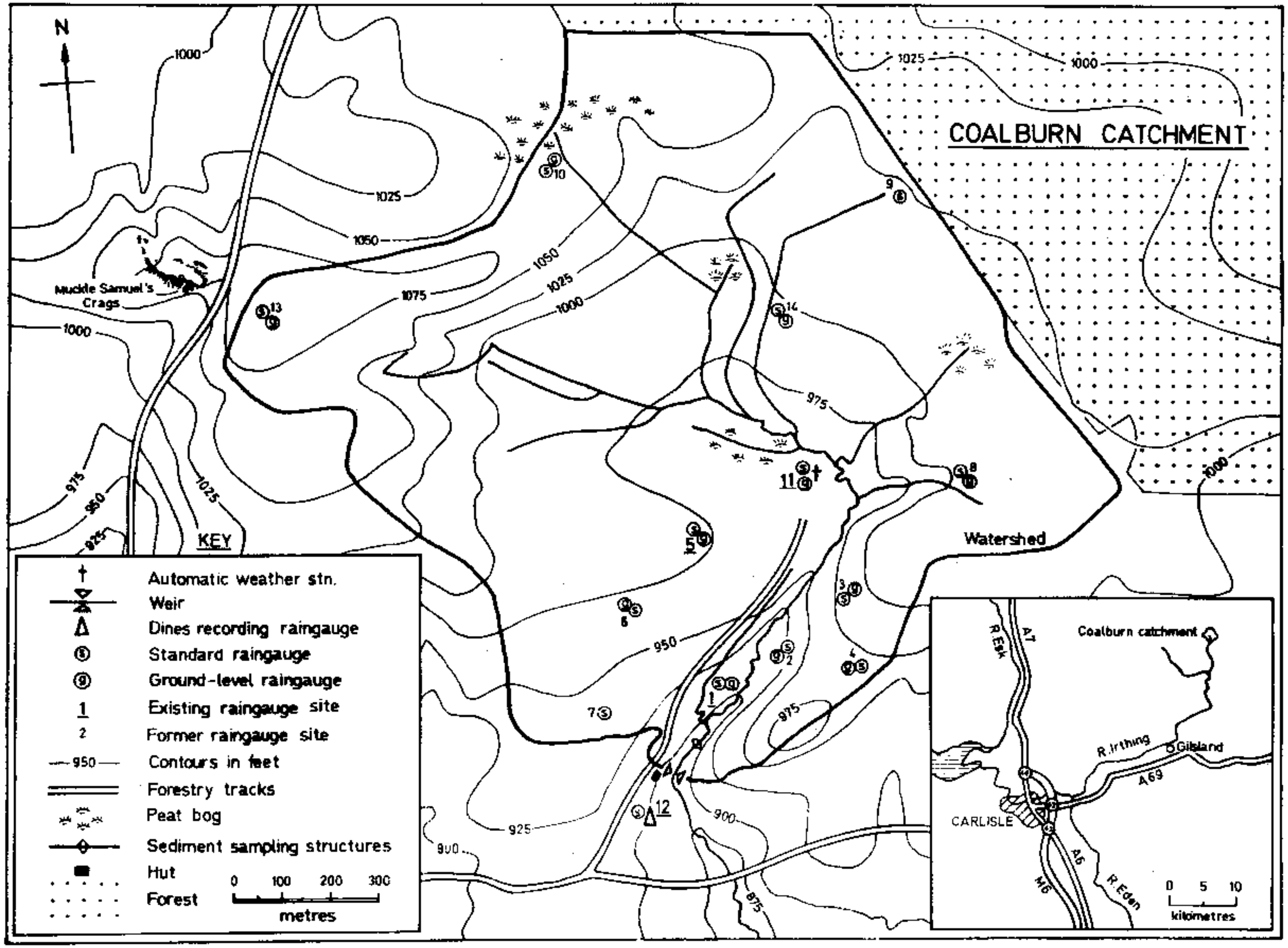


Figure 2 The Coalburn catchment

ial evapotranspiration and mean basin soil moisture status. For the purpose of the modelling studies described below, discharge and precipitation were accumulated over six-hour intervals; discharge was calculated from a continuous river stage record and a stage-discharge relation derived by the Anglian Water Authority, while mean basin precipitation was calculated by subdividing the daily catches by the ten gauges around the catchment into hourly components, the proportion allocated to each hour being determined from the continuous rainfall record obtained at the meteorological site. Hourly estimates so obtained were combined to give Thiessen estimates of mean areal rainfall hour by hour, and these were used to derive six-hourly estimates of mean areal rainfall. Using measurements collected at the meteorological site (daily maximum and minimum air temperatures, 0900 GMT wet and dry bulb readings, hours of sunshine, and 0900 GMT wind run) daily potential evaporation was calculated using the Penman formula (1948); this daily estimate was subdivided into six-hour estimates by use of the factors 0.697, 0.138, 0.0 and 0.165 for the periods 0900-1500, 1500-2100, 2100-0300 and 0300-0900 hours respectively.

For the Cam catchment, 4½ years of record (January 1968 - June 1972) of six-hourly cumulative streamflow, precipitation and potential evapotranspiration estimates were used in the analysis. The soil moisture record, mentioned above, was not used explicitly in this study.

Coalburn

The stream draining this small upland catchment (1.52 km^2) is a tributary of the River Irthing, Cumberland. The Coalburn experiment was set up to study the hydrological effects of ploughing rough grassland and subsequent afforestation, and the Institute has been collecting rainfall and runoff records since 1966. The Forestry Commission ploughed the catchment in July 1972 and trees were planted in 1973.

Figure 2 shows the network of instruments located in the catchment. River stage is recorded at a conventional Crump Weir maintained by the North-West Water Authority, and stage is converted to discharge by means of a theoretical calibration curve. Precipitation was recorded, during the period for which the record was used in the analysis below, by a network of 12 storage gauges read weekly; one sample recording gauge sited a little below the weir was used to distribute the weekly total catch at each gauge into three-hourly components. These were used to compute three-hourly Thiessen estimates of mean areal precipitation. No meteorological station is sited in the catchment, but readings of daily maximum and minimum air temperatures, 0900 GMT wet and dry bulb recordings, and 0900 hr wind run from a station at Spadeadam some 13 km away, are used to calculate a Penman estimate of daily potential evapotranspiration. This is divided into three-hourly components by the proportions 0.341, 0.356, 0.138, 0.0, 0.0, 0.0, 0.0, 0.165. Since ploughing, an automatic weather station has been sited in the catchment to provide data for the estimation of potential evapotranspiration; the record used below, however, extended from October 1967 to September 1970, i.e., before ploughing began.

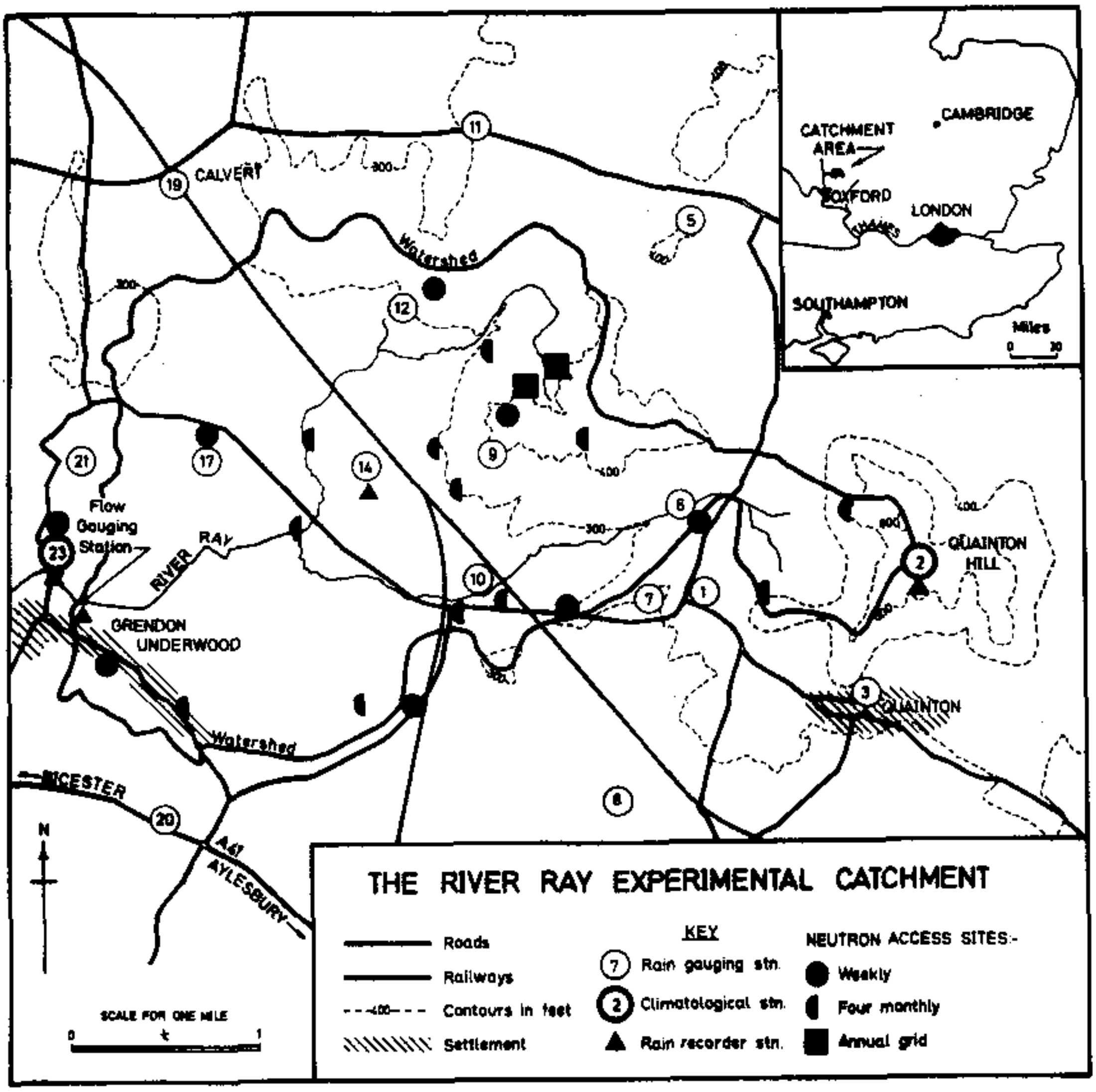


Figure 3 The Grendon Underwood catchment

The Ray at Grendon Underwood

Earlier modelling studies of the Ray catchment have been described by Mandeville *et al* (1970) who describe the basin as follows:

"This experimental basin of 19 km^2 is a tributary of the Thames, lies almost entirely on deep impervious clay. There is no groundwater table in the usual sense; the soil layer is thin and the main storage occurs in the upper 30 cm of the profile; temporary storage also occurs in the form of surface and ditch retention. Some storage also occurs in thin limestone and sandy strata in the upper part of the basin. The topography is gently rolling, rising from 67 to 186 m. About 19% of the basin is wooded, and the remainder is mainly grassland, with some root and cereal crops; periodic surveys have shown that the land use is relatively constant. River flow is measured continuously by a critical depth flume, and daily estimates of open water evaporation are derived from observations at a single meteorological site. The evaporation estimates have been distributed throughout the day to provide a comparable record. The records have been subjected to quality control checks and are stored on magnetic tape in three-hourly values of areal mean rainfall, open water evaporation and runoff".

The period used in the study was of three year's duration (May 1970 to April 1973); throughout this time there were 14 daily gauges and 3 recording gauges. Records from the latter were used to distribute the total catch by the former into the three-hourly components, from which Thiessen estimates of mean areal precipitation were deduced.

THE MODEL

The model used for all three catchments was that described by Dickinson and Douglas (1972). Essentially, it regards each catchment as a lumped system represented by three storages: (1) an interception store, with contents augmented by precipitation, depleted by evaporation at a rate proportional to that from open water, and depleted by transfer of excess to (2) a soil moisture store, with contents depleted by transpiration (at a rate that is a monotonic decreasing function of the soil moisture deficit below an upper limit imposed on soil moisture content), depleted by rapid runoff (at a rate that is again a monotonic decreasing function of soil moisture deficit) and depleted by transfer of water to (3) a groundwater store, with contents depleted by baseflow at a rate that is a monotonic increasing function of groundwater store contents. Figure 4, copied from Dickinson and Douglas, illustrates the model structure, and Table 1 lists the parameters which, when known, determine model behaviour.

The rapid runoff from the soil moisture store and the baseflow from the groundwater store are combined to give estimated streamflow. Rapid runoff is subjected in the model to a constant time delay, the magnitude of which is treated as a parameter to be estimated from data; baseflow is delayed and attenuated by routing through a linear or non-linear reservoir. For the Coalburn and Ray catchments, which have no appreciable groundwater component, the third groundwater storage was omitted.

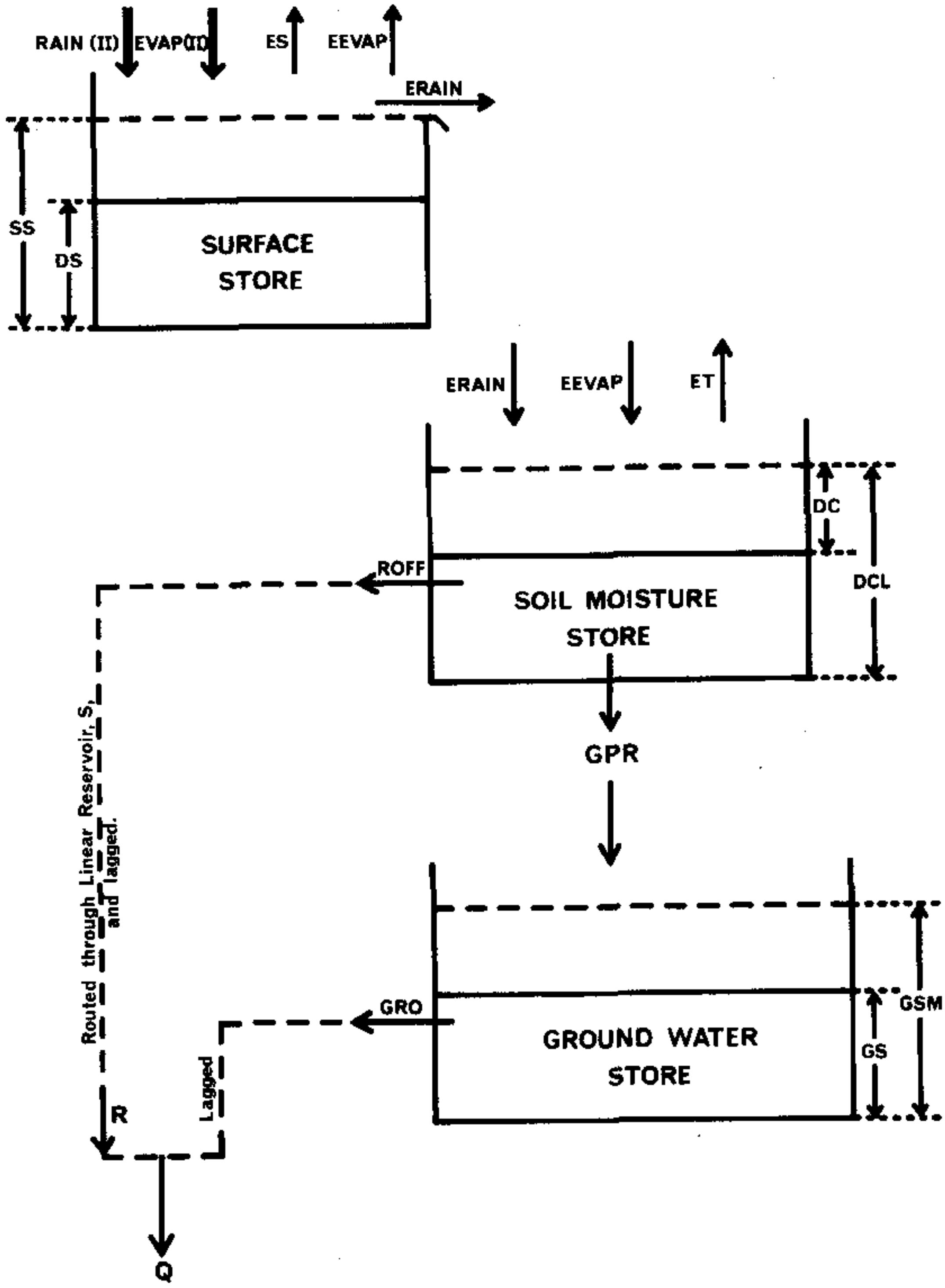
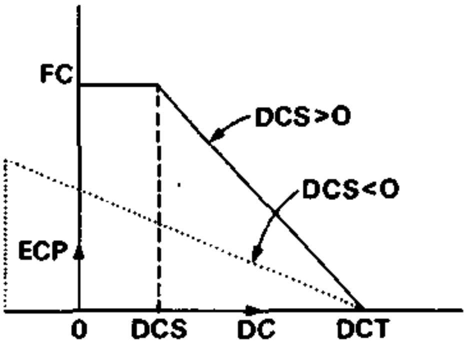
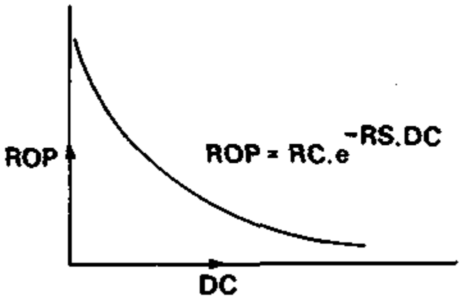


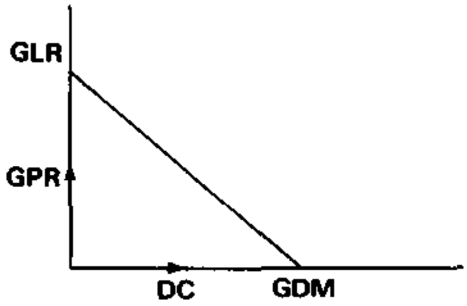
Figure 4 Three store conceptual model

Table 1.

MODEL
1. Effective rainfall $ERAIN = RAIN(II)-(SS-DS)$ 2. Surface evaporation $ES = FS.EVAP(II)$ 3. Residual evap. demand $EEVAP = EVAP(II)-ES$ Parameters: FS, SS Opt. constraint: $FS = 1.0$
4. Actual transpiration $ET = ECP.EEVAP$ where $ECP = FC.\frac{(DCT-DC)}{(DCT-DCS)}$ 5. Direct runoff $ROFF = ROP.ERAIN$ where $ROP = RC.\exp(-RS.DC)$ 6. Percolation to groundwater $GPR = GLR.(1.0-DC/GDM)$ Parameters: FC, DCT, DCS, RC, RS, GLR, GDM
7. Groundwater flow $GS = GSM.(GF.GPR+(1-GF).GRO)$ Parameters: GSM, GF
8. $S = DRK.R^{A}$ with R delayed by DEL Parameters: DRK, DEL, A Opt. constraint: $A = 1.0$







The parameters in the model were estimated by least squares; parameter values were calculated which minimized the sum of squared differences between the observed and 'fitted' three-hourly streamflows. Denoting the observed streamflow sequence by $q_1, q_2, \ldots\ldots q_N$ and the fitted flows that correspond to a particular set of parameter values by $\hat{q}_1, \hat{q}_2 \ldots\ldots \hat{q}_N$, the parameter values were calculated by minimizing F^2, given by

$$F^2 = \sum_{i=1}^{N} (q_i - \hat{q}_i)^2$$

with suitable assumptions about the starting values of the contents of the three storages.

It is customary to base a measure of goodness of fit of a model on the values of F^2 and F_0^2, where F_0^2 is the sum of squared differences between the observed streamflows and their arithmetic mean, i.e.

$$F_0^2 = \sum_{i=1}^{N} (q_i - \bar{q})^2$$

where $\bar{q} = \sum_{i=1}^{N} q_i/N$. Following linear regression theory, in which the coefficient of determination (expressed as a percentage)

$$R^2 = (1 - F^2/F_0^2) \times 100$$

is taken as a measure of the goodness of fit of a linear statistical model, this same quantity R^2 is often taken as a measure of the goodness of fit of a non-linear hydrological model. It is essentially one statistic that is used to summarize the sequence of residuals $q_i - \hat{q}$. In linear statistical theory, however, R^2 must be between 0 and 100 on a percentage scale, a restriction which does not apply with non-linear models (since the values of F^2 may exceed F_0^2, although it would be a poor model indeed where this occurred!). A value of R^2 near to 100 gives some confidence that the fit is good, but must not allow complacency: an oft-quoted example of the danger resulting from a too easy acceptance of a high R^2 is that given when a straight line is fitted to points lying on a parabola, for which R^2 exceeds 90.

It must also be understood that the optimised parameter values do not imply physical exactitudes. It is the values taken by DC, the soil moisture deficit, which determine the functional relationship between the parameters in the soil moisture store, and these DC values are very dependent on the assumed initial value. The dominant feature in achieving balance between the model input and output is the interdependence of the parameters in this store.

METHOD OF STUDYING THE EFFECTS OF VARYING RAINGAUGE NETWORK DENSITIES

The number of storage gauges and recording gauges on each of the three catchments were as shown in Table 2.

Table 2. Number of storage and recording gauges in each catchment

	No. of storage gauges	No. of recording gauges
Cam	10 (read daily)	1
Coalburn	13 (read weekly)	1
Ray	14 (read daily)	3

For each catchment, subsets of storage gauges from the complete network were taken; for each subset, the Thiessen polygon areas were measured by planimeter and a Thiessen estimate of mean areal precipitation computed. The single recording gauge on each of the Cam and Coalburn catchments was included in every subset: the three recording gauges on the Ray catchment were also included. The number of gauges in each subset were as shown in Table 3.

Table 3. Number of gauges in each subset of the total network

	Gauges in full network	Gauges in subsets of network				
Cam	10	8	6	4	2	1
Coalburn	13	10	8	5	3	1
Ray	14	11	8	6	3	2

For each subset, five spatial arrangements of that number of gauges were usually taken: thus, for the Cam, 5 arrangements, each of 8 gauges, were selected from the 10 in the total network, 5 arrangements each of 6 gauges, 5 of 4 and 5 of 2 were taken. (Only 1 arrangement of 1 gauge was taken). Similarly, for Coalburn, 5 spatial arrangements each of 10, 8, 5 and 3 gauges were taken, with 1 spatial arrangement of 1 gauge; for the Ray, 5 spatial arrangements each of 11, 8, 6, 3 and 2 gauges were taken. To each spatial arrangement of gauges there corresponded a unique mean areal precipitation sequence; the sequences of estimated open water evaporation and streamflow were the same for all subsets, and for all spatial arrangements within each subset.

The total duration of record of mean areal precipitation, open water evaporation and streamflow for each spatial arrangement was divided into two. The first half was used to estimate the model parameters by least squares, and to calculate a value of R^2; using these parameter values, the sequences of mean areal precipitation and open water evaporation in the second half of the record were transformed by the model into a sequence of 'predicted' streamflows. A value of R^2 was calculated from this sequence and taken as a measure of the value of the model for prediction purposes.

Table 4. Efficiency (R) for fitting and predicting stramflow in the Cam at Dernford Mill

No. of groups in subset	Efficiency: fitting (R^2)	Efficiency: prediction (R^2)
10	69.1	76.0
8	70.6	77.7
8	70.2	78.3
8	70.5	79.0
8	69.2	75.1
8	69.9	75.6
Mean	70.08	77.12
6	69.5	74.6
6	67.8	74.1
6	71.0	68.8
6	69.4	75.0
6	69.6	73.5
Mean	69.46	73.18
4	69.6	67.2
4	69.6	72.8
4	69.6	64.5
4	68.3	70.0
4	67.1	65.5
Mean	68.68	68.03
2	70.0	66.2
2	67.0	74.2
2	66.7	75.9
2	68.6	64.9
2	66.7	72.2
Mean	67.94	70.69
1	68.1	60.40

RESULTS

The Cam at Dernford Mill

Table 4 shows the efficiencies of the model, as measured by R^2, for fitting and predicting streamflow in the Cam at Dernford Mill. The most noticeable feature of this table is the general decline in the value of R^2 obtained in prediction as the gauge density decreases; with 8 gauges, the value of R^2 is 77% on average, falling to 60% where only one daily storage gauge is used. The latter value, being based upon one spatial arrangement only, may be misleading however. An analysis of the efficiencies of Table 4 is given in Table 5.

By contrast, the values of R^2 obtained during the fitting phase are very similar to each other whether mean areal precipitation is computed using 1 or 10 storage gauges. This suggests that errors in the estimate of mean areal precipitation due to unrepresentative networks may be largely 'absorbed' by the model parameters leaving the goodness of fit - as measured by the statistic R^2 - largely unchanged. Expressed in another way, the goodness of fit for the Cam catchment model is limited less by systematic errors due to network bias than by deficiencies in the model structure itself and the verisimilitude with which it describes the behaviour of the system it purports to represent. To support this contention, Table 6 shows the mean values, over the 5 spatial arrangements in each subset, of the 13 parameters in the Cam model. With the possible exceptions of DCS and GLR, the mean values over the 5 spatial arrangements tend not to be too dissimilar; the standard deviations tend to be much more variable however, particularly those for DCT, DCS and FC,

Table 5. Analysis of variance of R^2 values obtained by varying the raingauge network densities on the Cam catchment: R^2 computed for prediction

Source	df	MS	F
Between densities	5	75.237	6.707***
Single gauge v. rest	1	138.285	12.328***
10 gauges v. 8, 6, 4, and 2	1	13.712	1.222$^{n.s.}$
Linear trend amongst 8, 6, 4 and 2	1	149.548	13.33**
Remainder	2	74.640	6.65**
Within densities (residual)	16	11.217	

* Significant at the 5% level but not at 1% level.
** Significant at the 1% level but not at 0.1% level.
*** Significant at the 0.1% level.
n.s. Not significant (at the 5% level).

This convention will be used throughout the report.

Table 6. Means and standard deviations of 13 parameter estimates: Cam at Dernford Mill

(See Table 1 for meaning of parameter symbols)

No. of groups	Parameters:												
	FS	SS	FC	DCT	DCS	RG	RS	1/GLR	GDM	GSM	1/DRK	DEL	GF
8	0.77±0.031	5.72±0.407	1.786±0.107	210.17± 4.49	5.24±1.49	0.86±0.190	0.0221 ± 0.0^2124	6.44±0.773	80.24±1.957	667.9±31.68	0.162±0.0112	2.780±0.347	-0.052±0.007
6	0.74±0.043	4.74±1.247	1.932±0.222	204.81± 9.77	5.36±4.26	1.26±0.499	0.0257 ± 0.0^2242	12.33±2.952	80.82±6.639	677.5±41.31	0.163±0.0040	3.136±0.035	-0.034±0.010
4	0.74±0.042	5.09±0.374	2.070±0.272	197.03±24.83	6.73±7.50	0.96±0.241	0.0241 ± 0.0^2171	8.99±2.560	80.40±2.370	676.4±23.26	0.164±0.0053	3.149±0.007	-0.046±0.010
2	0.78±0.093	5.52±1.029	1.798±0.706	210.29±42.53	10.00±5.80	0.97±0.254	0.0248 ± 0.0^2286	7.93±0.321	80.61±3.627	676.2±36.14	0.168±0.0066	3.150±0.013	-0.050±0.002

all of which increase as the network density decreases (variation in the standard deviations of GLR, DEL is also very large, but not consistently related to network density). This variation in standard deviation of certain of the parameters suggests that they change to accommodate the differences in mean areal precipitation associated with different subsets of the network.

Table 7. Efficiencies (R^2) for fitting and predicting streamflow in Coalburn

No. of gauges in subset	Efficiency: fitting (R^2)	Efficiency: prediction (R^2)
12	92.1	72.11
10	91.9	72.49
10	91.9	72.15
10	92.2	72.45
10	92.1	72.14
10	92.0	72.37
Mean	92.02	72.32
8	91.9	72.69
8	92.2	71.74
8	92.2	72.11
8	92.0	72.50
8	91.9	72.91
Mean	92.04	72.39
5	92.2	71.45
5	92.1	70.15
5	92.0	71.45
5	92.2	70.33
5	92.2	72.53
Mean	92.14	71.18
3	92.2	71.79
3	92.2	72.05
3	92.4	71.95
3	91.9	69.14
3	92.9	71.82
Mean	92.32	71.35
1	92.9	67.37

Coalburn

Table 7 shows the efficiencies of the model for fitting and predicting streamflow in Coalburn. Initially the predicting and fitting efficiencies showed a much greater difference, but examination of the record used for predicting revealed several anomalies in the data for winter 1969. Snow had fallen in November and on two occasions during January and February the weir was frozen for a period of not less than a week each time. The model was unable to take account of these events so these months were excluded from the fitting efficiency calculations.

As with the Cam, reduction in the raingauge network from 12 to 1 weekly gauge gave no reduction in the efficiency of the fitted model. This is not unexpected; the Coalburn catchment is small (1.52 km^2), and its topography relatively smooth, so that spatial variability in precipitation might be expected to be small also. If this were the case, the mean areal estimate of precipitation from 13 gauges would be unlikely to show significant improvement on that from a single weekly gauge.

Table 8. Analysis of variance of R^2 values obtained by varying network densities at Coalburn: R^2 computed for prediction

Source	df	MS	F
Between densities	5	5.0081	7.36***
Single Gauge v. rest	1	18.9428	27.85***
12 Gauges v. 10, 8, 5, and 3	1	0.0854	$0.13^{n.s.}$
Linear trend amongst 10, 8, 5 and 3	1	4.6746	1.0**
Remainder	2	0.7830	$0.72^{n.s.}$
Within densities (residual)	16	0.6802	

Regarding the efficiencies of prediction, an analysis of variance shows that there are significant differences between the mean values of R^2 associated with the six gauge densities (i.e., 13, 10, 8, 5, 3 and 1 storage gauge). This analysis is shown in Table 8. The efficiency associated with one gauge only is significantly lower than that of the other densities, whilst there is some evidence of a trend in R^2 (albeit a slight one) which decreases as gauge density decreases.

Table 7 shows the mean values and standard deviations of the parameter estimates, computed from the 5 spatial arrangements tested in each subset. The standard deviations are variable, but appear to show no consistent trend as gauge density varies, whilst the slight trends exhibited by the means of some parameter estimates (DCT, DCS, for example) are likely to be small relative to their sampling errors.

Table 9. Means and standard deviations of 8 parameter estimates: Coalburn

(See Table 1 for meaning of parameter symbols)

No. of groups	SS	FC	DCT
10	2.386±0.835	0.863±0.0782	153.4±16.06
8	1.870±0.818	0.867±0.0864	146.3±31.51
5	1.812±0.742	0.877±0.0657	125.6± 4.18
3	1.872±0.660	0.894±0.0685	116.3±21.12

DCS	RS	1/DRK
-106.9± 7.34	$0.0242 \pm 0.0^{3}735$	$0.00866 \pm 0.0^{3}302$
-100.5±20.42	$0.0245 \pm 0.0^{3}662$	$0.00958 \pm 0.0^{2}146$
-96.9± 4.05	$0.0261 \pm 0.0^{3}213$	$0.00803 \pm 0.0^{3}102$
-93.5±10.70	$0.0267 \pm 0.0^{3}102$	$0.00800 \pm 0.0^{3}199$

DEL	A
$0.6012 \pm 0.0^{2}506$	2.177±0.0124
$0.6060 \pm 0.0^{2}776$	2.157±0.0303
$0.6066 \pm 0.0^{2}321$	2.210±0.0043
$0.6088 \pm 0.0^{2}154$	2.214±0.0070

The Ray at Grendon Underwood

Table 10 shows the efficiencies of the model for fitting and predicting streamflow in the Ray at Grendon Underwood. As with Coalburn the efficiencies of prediction are undoubtedly less than the efficiencies in the fitting phase.

There was little evidence that the efficiency of fitting was reduced by reducing the number of storage gauges in the network from 14 to 3. Regarding the efficiencies of prediction, there was some slight evidence of a decrease in precision as storage gauge density decreased. Table 11 shows the analysis of variance which suggest these results.

Table 12 shows the means and standard deviation of the estimated parameters, based on the five alternative spatial distributions of the gauges in each subset of the total network. As with Coalburn, it would be unwise to claim any evidence for trend either in means or standard deviations of parameter estimates as the number of storage gauges decreased.

Table 10. Efficiencies (R^2) for fitting and predicting streamflow in the Ray at Grendon Underwood

No. of gauges in subset	Efficiency: fitting (R^2)	Efficiency: prediction (R^2)
14	91.0	80.3
11	91.3	80.9
11	91.0	79.6
11	90.9	80.2
11	90.9	80.2
11	90.9	79.9
Mean	91.0	80.2
8	89.6	79.4
8	91.0	79.7
8	91.3	79.4
8	91.6	82.0
8	90.9	80.6
Mean	90.9	80.2
6	91.6	80.1
6	90.4	79.0
6	90.6	79.7
6	91.2	80.1
6	91.5	79.7
Mean	91.1	79.7
3	90.8	79.6
3	90.6	79.5
3	88.4	78.2
3	91.8	78.4
3	89.0	79.1
Mean	90.1	79.0
2	89.2	75.8

Table 11. Analysis of variance of R^2 values obtained by varying raingauge network densities on the Ray catchment: R^2 computed for prediction

Source	df	MS	F
Between densities	5	4.1381	7.99***
2 gauges v. rest	1	15.2800	29.51***
14 gauges v. 11, 8, 6, and 3 gauges	1	0.3051	$0.59^{n.s.}$
Linear trend amongst 11, 8, 6 and 3	1	4.266	8.24*
Remainder	2	0.4198	$0.81^{n.s.}$
Within densities (residual)	16	0.5178	

Table 12. Means and standard deviations of 7 parameter estimates: Ray at Grendon Underwood

No. of groups	Parameters: SS	FC	DCT	DCS	FS	1/DRK	DEL
11	22.31±0.222	0.878±0.018	208.6 ± 3.04	-38.12±0.568	$0.0233\pm0.0^{3}691$	$0.168\pm0.0^{3}550$	$1.392\pm0.0^{2}183$
8	22.17±0.533	0.882±0.065	212.3 ±15.51	-37.91±2.564	$0.0223\pm0.0^{3}152$	$0.168\pm0.0^{2}173$	$1.389\pm0.0^{2}570$
6	22.17±0.280	0.906±0.030	219.1 ±14.08	-39.24±0.960	$0.0223\pm0.0^{3}749$	$0.168\pm0.0^{2}234$	$1.385\pm0.0^{2}262$
3	22.14±0.616	0.871±0.046	212.4 ± 7.06	-38.55±2.302	$0.0236\pm0.0^{2}155$	$0.166\pm0.0^{2}505$	$1.389\pm0.0^{2}592$

CONCLUSIONS

1. Reduction in the numbers of daily gauges (weekly in the case of Coalburn) has very little effect on the efficiency obtained when fitting the model. Even if but one gauge is used - together with a recording gauge to distribute its catch - any systematic error introduced by the unrepresentativeness of the network is likely to be compensated for during the fitting of the model parameters. This was true of all three catchments.

To some extent, therefore, an index of precipitation, such as might be obtained from one or more recording gauges and a very limited number of daily recording gauges, is all that is required to fit the model reasonably well; interpretation of the parameters in physical terms will be made more difficult, however, because the values obtained for them may reflect raingauge network deficiencies. (c.f. the results for the Cam at Dernford Mill).

2. There is evidence from all three catchments that the efficiency of prediction is reduced to some extent by reducing the numbers of daily (weekly) gauges; the loss of efficiency was small for the two smaller catchments - the Ray and Coalburn - and rather greater for the Cam.

REFERENCES

Dickinson, W.T. and Douglas, J.R. 1972. A conceptual runoff model for the Cam cathcment. Institute of Hydrology Report No. 17.

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APPENDIX I

CAM CATCHMENT Thiessen polygon areas in hectares. Total area 19,423 ha.

Gauges	10	8				
Samples		1	2	3	4	5
Gauge Nos.	1,2,4,5, 6,7,9,10, 11,12.	2,4,6, 7,9,10, 11,12.	1,2,4, 6,7,9, 11,12.	1,4,5, 6,9,10, 11,12.	2,4,5, 7,9,10, 11,12.	1,2,4, 5,6,9, 11,12.
1	2179	-	2141	3412	-	3421
2	1355	1381	1507	-	1437	1665
4	936	1377	1242	1878	1864	919
5	2973	-	-	3681	3171	3529
6	1726	2825	4544	2117	-	2066
7	2325	4595	3961	-	2825	-
9	1218	2300	1169	1287	2337	1299
10	1584	1575	1612	1740	1639	-
11	1924	2014	-	1940	2825	1911
12	3203	3356	3247	3368	3325	4613

Gauges	6				
Samples	1	2	3	4	5
Gauge Nos.	1,2,4, 5,7,9.	1,5,6,9, 10,11.	1,4,5,10, 11,12.	2,5,6,10, 11,12.	5,6,9,10, 11,12.
1	2382	4385	4518	-	-
2	4116	-	-	2336	-
4	3217	-	2310	-	-
5	3739	3582	4081	3838	3852
6	-	2573	-	4087	3436
7	2677	-	-	-	-
9	3292	2424	-	-	3406
10	-	3895	1751	1620	1951
11	-	2565	2903	1962	2517
12	-	-	3859	5580	4261

Gauges	4				
Samples	1	2	3	4	5
Gauge Nos.	1,10 11,12.	2,6, 11,12.	1,6, 7,10.	2,6, 7,10.	1,5, 6,10.
1	5800	-	5080	-	6352
2	-	2706	-	5612	-
4	-	-	-	-	-
5	-	-	-	-	3639
6	-	7833	5555	4919	4797
7	-	-	4103	5272	-
9	-	-	-	-	-
10	2048	-	4685	3620	4645
11	7307	2103	-	-	-
12	4268	6781	-	-	-

COALBURN CATCHMENT Thiessen polygon areas (hectares). Total area 152.1 hectares.

Gauges	13	10				
Samples		1	2	3	4	5
Gauge Nos.	1,2,3,4, 5,6,7,8, 9,10,11, 12,13.	1,2,3,4, 5,6,8, 9,10, 11,12.	1,3,4,5, 6,7,8,9, 10,12.	1,3,4,5, 8,9,10, 11,12, 13.	1,3,4,5, 6,8,9, 10,12, 13.	1,2,3,4, 5,7,8, 10,12, 13.
1	5.5	6.9	6.9	8.4	8.6	6.0
2	4.2	4.2	-	-	-	4.2
3	5.6	5.4	8.0	6.4	6.1	6.9
4	1.8	1.8	2.6	2.7	3.1	2.2
5	14.1	15.3	23.1	25.2	14.3	33.4
6	16.7	21.2	18.1	-	21.4	-
7	5.4	-	5.0	10.5	-	10.0
8	15.8	21.7	20.6	21.7	16.3	29.6
9	20.6	-	24.2	-	21.8	-
10	29.2	51.3	42.9	35.4	29.4	42.8
11	16.7	22.3	-	23.6	15.5	-
12	0.4	2.0	0.7	0.7	-	0.7
13	16.1	-	-	17.5	15.6	16.3

Gauges	8				
Samples	1	2	3	4	5
Gauge Nos.	1,2,5,7, 8,9,10, 11.	1,2,3,4, 8,11,12, 13.	1,2,3,4, 5,7,9, 11.	1,4,5,6, 8,10,11, 13.	3,4,5,7, 8,10,11, 12.
1	6.8	19.8	7.1	9.4	-
2	8.5	4.9	3.7	-	-
3	-	5.2	11.7	-	7.2
4	-	2.0	2.2	6.2	5.1
5	26.7	-	51.6	15.8	27.6
6	-	-	-	19.1	-
7	11.0	-	11.2	-	14.0
8	16.6	22.2	-	22.6	20.7
9	22.1	-	39.1	-	-
10	43.7	-	-	38.6	57.9
11	16.7	61.6	25.5	24.7	18.1
12	-	3.3	-	-	1.5
13	-	33.1	-	15.7	-

COALBURN CATCHMENT (continued)

Gauges			5		
Samples	1	2	3	4	5
Gauge Nos.	2,3,5, 6,7.	1,3,4, 8,9.	6,7,8, 9,11.	1,2,4, 6,13.	4,5,6, 10,13.
1	-	54.7	-	7.9	-
2	8.0	-	-	30.4	-
3	31.7	17.7	-	-	-
4	-	2.7	-	23.1	26.1
5	76.3	-	-	-	41.9
6	28.5	-	48.7	53.6	24.0
7	7.6	-	10.8	-	-
8	-	21.6	18.2	-	-
9	-	55.4	39.5	-	-
10	-	-	-	-	44.7
11	-	-	34.9	-	-
12	-	-	-	-	-
13	-	-	-	37.1	15.4

Gauges			3		
Samples	1	2	3	4	5
Gauge Nos.	2,5,12.	1,3,5.	4,10,13.	3,4,6.	3,10,13.
1	-	16.2	-	-	-
2	27.5	-	-	-	-
3	-	29.4	-	60.1	76.2
4	-	-	69.5	5.4	-
5	117.2	106.5	-	-	-
6	-	-	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-
9	-	-	-	-	-
10	-	-	61.4	-	55.3
11	-	-	-	-	-
12	7.4	-	-	-	-
13	-	-	21.2	-	20.6

GRENDON CATCHMENT

Gauges	14	10				
Samples		1	2	3	4	5
Gauge Nos.	1,2,3,5, 6,7,9,11, 12,14,17, 20,21,23.	1,2,3,5, 6,7,9,11, 17,20,21.	1,2,3,6, 7,11,12, 14,21, 23.	1,3,5,6, 7,9,12, 14,17, 20,23.	1,2,6,9, 11,12,14, 17,20,21, 23.	1,2,3,5, 6,9,12, 14,17, 21,23.
1	38	38	42	57	40	63
2	80	69	70	-	74	72
3	1	7	7	47	-	7
5	20	29	-	35	-	29
6	147	141	209	156	189	166
7	86	86	116	78	-	-
9	266	539	-	283	50	-
11	2	93	12	-	50	-
12	254	-	349	282	281	274
14	319	-	490	304	318	372
17	328	553	330	351	317	333
20	154	208	-	156	156	-
21	48	93	44	-	17	45
23	113	-	187	107	105	186

Gauges	8				
Samples	1	2	3	4	5
Gauge Nos.	2,3,5,9, 11,12,20, 23.	6,7,9,11, 12,14,17, 23.	2,3,5,7, 11,14, 20,23.	1,2,3,5, 6,17,20, 21.	1,2,5,9, 17,20,21, 23.
1	-	-	-	88	185
2	143	-	98	80	82
3	16	-	11	5	-
5	22	-	66	129	47
6	-	238	-	411	-
7	-	98	304	-	-
9	697	281	-	-	686
11	6	10	100	-	-
12	440	281	-	-	-
14	-	372	883	-	-
17	-	359	-	836	541
20	187	-	150	218	164
21	-	-	-	89	45
23	345	217	245	-	106

GRENDON CATCHMENT (CONT)

Gauges	6				
Samples	1	2	3	4	5
Gauge Nos.	2,6,7, 9,14,17	1,2,11, 12,14,23	1,2,11, 12,14,20	1,5,9, 14,17,20	2,3,6, 14,17,23
1	-	281	282	268	-
2	90	82	82	-	75
3	-	-	-	-	11
5	-	-	-	44	365
6	160	-	-	-	-
7	82	-	-	-	-
9	401	-	-	431	-
11	-	10	10	-	-
12	-	417	429	461	-
14	501	718	807	464	797
17	622	-	-	188	408
20	-	-	246	-	-
21	-	-	-	-	-
23	-	348	-	-	200

Gauges	2	3				
Samples		1	2	3	4	5
Gauge Nos.	1,2	1,2 21	6,7,9	12,21,23	14,17,23	5,6,12
1	1782	742	-	-	-	-
2	74	-	-	-	-	-
3	-	-	-	-	-	-
5	-	-	-	-	-	31
6	-	-	240	-	-	563
7	-	-	94	-	-	-
9	-	-	1522	-	-	-
11	-	-	-	-	-	-
12	-	-	-	1190	-	1272
14	-	-	-	-	1232	-
17	-	-	-	-	418	-
20	-	-	-	-	-	-
21	-	1040	-	248	-	-
23	-	-	-	418	206	-