Automating Areal Rainfall Calculations for Catchments

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Contents

Summary

Automatic procedures for calculating areal rainfall for catchments using the Institute of Hydrology's triangle method have been produced. These utilise Arc/Info techniques for deriving the catchment boundary and area, a list of raingauges in a buffer zone around the boundary, and Standard Average Annual Rainfall (1941-70) for the catchment. In addition, a mesh is created for use in the triangle method, the spacing being dependent on the size of the catchment and the density of the raingauge network.

The method is tested on five catchments calculating catchment daily average rainfall over a period of eight years and the results are validated by comparing them with results from the conventional manual approach.

Sensitivity to varying buffer zones is also tested.

1. Background

For the calculation of catchment average rainfall, the Institute of Hydrology's (IH) triangle method (Jones, 1983; Acreman, 1986) is widely used. When deriving catchment average rainfall values for a catchment, several prerequisites have to be fulfilled before deploying the existing computer programs described in Boorman *et al.* (1992). Firstly, the catchment boundary has to be identified from a topographical map and the area of the catchment derived. Secondly, the four corners of a tightly fitting quadrilateral around the catchment boundary have to be determined and loaded on to a database, also described in Boorman *et al.* (1992). The quadrilateral - called the 'inner box' - is then used in the rainfall calculations in place of the actual catchment boundary. The quadrilateral area should not differ from the original catchment area by more than ±20%. The search area for suitable raingauges should include the 'inner box' as well as an area around it to capture nearby gauges; for this reason the 'inner box' is enlarged by a factor, normally 1.5, to include all relevant raingauges. An enlargement factor of 1.5 results in the area of the 'outer box' being 2.25 times larger than that of the 'inner box'. The total number of raingauges found in the 'outer box' determines the mesh spacing for the 'inner box'. Thirdly and finally, the program requires the catchment's Standard Average Annual Rainfall for the period 1941-70 (SAAR) which is derived from data supplied by the Met.Office.

All of the above prerequisites can now be derived automatically: with the availability of the IH Digital Terrain Model (DTM) for most of mainland UK, described by Morris & Flavin (1990), it is possible to derive catchment boundaries automatically (Morris & Heerdegen, 1988). In addition it is possible to utilise Arc/Info routines to set up a mesh over a catchment and to identify raingauges in and around the catchment boundary. Mean SAAR for the catchment can be derived from a 1 km SAAR grid which is available as an arc coverage.

A program ('allrgs.aml') has been developed which generates a list of raingauges and meshpoints for a catchment boundary derived from the DTM, which can be fed into another existing program ('arearain') for calculating catchment average rainfalls. Retrievals of daily rainfall data for the UK from the National Water Archive remain unchanged.

2. Description of Arc/Info Program 'allrgs.aml'

The program runs under Arc/Info. Firstly, the point on the river system from which to derive the catchment boundary has to be established. The (x,y) grid coordinates for the outflow of a catchment must match the DTM, which is gridded at 50 m intervals; the grid reference has to be supplied to the nearest 50 m. Information on how to obtain this point is given later.

The program will calculate the resulting catchment area and delineate the catchment boundary.

As the search for suitable raingauges is not confined to the catchment area, an enlarged 'working area' must be defined; this will eventually be plotted on a map (see below). The user is prompted to enter an enlargement factor; it should be at least 1.5 (this enlargement factor should not be confused with the enlargement factor mentioned in Section 1 and which is used in the conventional method when increasing the 'inner box' area to the 'outer box'). In this particular instance, the enlargement factor sets up a 'working area' and all raingauges inside it are copied from the ORACLE database for the creation of a temporary raingauge coverage. It is of course possible to use a bigger enlargement factor should the initial value fail to locate any raingauges or find only very few.

All raingauges inside and around the catchment boundary should be captured and Arc/Info offers a suitable feature for this particular task, namely the creation of buffer zones around polygons. This feature is used for identifying raingauges within the area and, in contrast to the quadrilateral method, surrounds the true catchment boundary with an equidistant buffer zone. At this point in the program the buffer distance is unknown and several buffer distances can be tried, thus giving a series of buffered catchment areas. A graph is enclosed later serving as a guide for choosing suitable buffer distances dependent on catchment area. The program prompts for a minimum and a maximum buffer distance as well as step intervals for the buffer distances to be processed. The program calculates as many buffered areas as required and prints the resulting areas together with the appropriate buffer distances to the screen. It is then possible to interpolate these values to choose a buffer distance which will result in an area close to the preferred value. For example, 2.25 * catchment area has often been used. The user is then prompted to enter the final buffer distance. The program calculates the buffered catchment area and generates an enlarged catchment boundary - the equivalent of the 'outer box' of the conventional method.

After the final buffer around the DTM-derived catchment boundary has been drawn, the reference numbers of all raingauges inside the buffered catchment will be written to a file. This list of raingauges is the equivalent of the list of gauges in the 'outer box' and is used for the calculation of the mesh spacing over the catchment.

The algorithm for calculating the number of mesh points is explained by Jones (1983); this is dependent on the number of gauges found in the 'outer box', or in this case in the buffered catchment. By equating the 'inner box' area with the DTM-derived catchment area and by assuming an evenly spread mesh over the catchment, it is possible to apply the same principle as described by Jones (1983) for obtaining the mesh spacing automatically. A file is written containing the grid references of all meshpoints inside the catchment boundary together with the mesh size.

The DTM-derived catchment boundary is overlain on the 1 km SAAR spatial data obtaining a mean SAAR value for the catchment.

When all prerequisites have been derived automatically, the program offers the option to calculate daily average rainfalls through the 'arearain' program. If the 'arearain' option is chosen, rainfalls can be calculated either for a fixed 8-year period (1985-92) or for a previously defined period.

Finally, the program plots a map of the 'working area' showing the catchment boundary and the final buffer zone together with all daily and recording raingauges as well as all other raingauges (e.g. monthly gauges). For daily and recording raingauges the gauge numbers are printed, other gauges are shown as small squares. The area, mean SAAR value and buffer information are also printed on the plot. The plot can be viewed on the terminal using UNIX commands, e.g. 'ghostview' or the 'File Manager', and printed, if required. The program also plots the river system, provided a coverage has been previously created for the relevant area (Rycraft, 1994, Spatial Data Note 7).

A detailed description of how to obtain the catchment outflow point and to run the program is contained in Appendix A. Suitable buffer distances dependent on catchment size are shown in a graph in Appendix B.

3. Results from Arc/Info Program 'allrgs.aml'

Initially five catchments were chosen for testing the program. The catchments have been used previously for catchment average rainfall calculations and four of the five catchments are in the Representative Basin Catalogue and have available event data (Boorman *et al.*, 1991); thus their catchment boundaries have already been defined and loaded to a database together with the tight fitting quadrilateral; the areas and mean SAAR were also available. To compare results, the catchment boundaries were derived from the DTM, using the grid references as supplied by Bayliss (1995). The Arc/Info routine calculated the area and drew a buffer around the catchment boundary resulting in the buffered area to be close to the catchment area * 2.25. All raingauges inside the buffered catchment area were counted and the average SAAR was obtained from the 1 km SAAR grid. The mesh over the catchment and the mesh spacing were also obtained through the Arc/Info routine. A comparison of results is presented in Table 1 and illustrated in Appendix C (Figures C.1a, C.1b to C.5a, C.5b).

Table 1 Comparison of results for digitised and DTM-derived catchments

catchment	**28008** Dove at Rocester Weir	**39005** Beverley Brook at Wimbledon Common	**45004** Axe at Whitford	**57006** Rhondda at Trehafod	**77002** Esk at Canonbie
area (NRA supplied) km^2	399.0	43.6	288.5	100.5	495.0
area (digitised catchment) km^2	394.49	38.84	278.58	103.18	496.96
area (DTM derived) km^2	401.51	39.71	288.58	102.57	495.85
SAAR (supplied by outside organisation)	1020	633	1052	2200	1507
SAAR (from 1 km grid for DTM derived area)	1019.2	632.9	1051.9	2208.2	1506.4
No. of meshpoints in quadrilateral	529	196	484	144	225
No. of meshpoints in DTM-derived catchment	522	169	435	143	256
Total no. of raingauges in enlarged quadrilateral [enlarged quadrilateral area = quadrilateral area * 2.25]	106	41	95	27	42
No. of gauges with daily rainfall in enlarged quadrilateral	10-13	5-15	18-30	5-8	5-12
Total no. of raingauges in buffered area [buffered area =~(catchment area*2.25)]	102	30	89	25	45
No. of gauges with daily rainfall in buffered area	8-11	4-10	19-30	4-7	7-11

Area

The figures for the catchment areas show that differences exist between the authority-supplied, the digitised and the DTM-derived values. This can be due to several factors: e.g. for catchment 39005 the topographic area does not agree with the drainage area because of the underlying Chalk in the south, or catchments have drainage diversions which do not follow the topography (Bayliss, 1995). For the majority of catchments, however, the DTM-derived catchment boundaries are reliable and accurate.

SAAR
The value of SAAR has a major impact on catchment average rainfall results. For the five catchments tested here the DTM-derived SAAR figures are very close to the authority-supplied values.

Meshpoints
In the conventional method the shape of the tightly fitting quadrilateral and the total number of raingauges in the 'outer box' determine the meshpoints and their spacing. There are often parts of the 'inner box' which lie outside the catchment boundary and likewise there are parts of the catchment which are excluded from the 'inner box'. In Arc/Info it is possible to set up an evenly spaced mesh covering the whole of the DTM-derived catchment. Differences in the mesh and meshspacing for the five test catchments resulting from the two methods are illustrated in Appendix C (Figures C.6a/C.6b to C.10a/C.10b).

Number of raingauges
As for the mesh, the shape of the quadrilateral determines the capturing of raingauges for the catchment when using the conventional method. For four of the five examples more raingauges were found where the quadrilateral was used than for the DTM-derived boundaries. This will affect the meshspacing and can have an impact on catchment average rainfall calculations. When comparing maps showing the catchment together with the captured raingauges (Appendix C, Figures C.1a/C.1b to C.5a/C.5b), the gauges inside the buffered areas seem to be more representative for the catchment than those, for example, near the quadrilateral boundary line. This is particularly noticeable for catchment 45004, where the quadrilateral cuts through the western part of the catchment but at the same time includes a large area outside the boundary to the north of the catchment.

4. Results from Program 'Arearain'

This program calculates the catchment average daily rainfall and for each catchment it was run twice: first using the conventional method of deriving the input, and then again deriving the input through the Arc/Info routine described above. A combination of factors (area, meshpoints, raingauges and SAAR) contributes to the resulting differences in the calculated daily rainfall series.

Area
In the conventional method the quadrilateral area of the 'inner box' is used instead of the catchment area accepting a tolerance level of 20% for the 'inner box' area to the original catchment area (Jones, 1983). The quadrilateral area equals the sum of all subboxes, i.e. the areas associated with each meshpoint inside the 'inner box'. For the DTM-derived catchment

only meshpoints inside the catchment boundary are considered. Therefore, applying the same principle as in the conventional method, the catchment area used in the new 'arearain' program is calculated as the sum of those meshsquares where the centroid is located inside the catchment boundary. Table 2 illustrates the values for area used in the rainfall calculation resulting from both the conventional and the new method.

***Table 2** Comparison of area used in Program 'Arearain'*

catchment	**28008**	**39005**	**45004**	**57006**	**77002**
quadrilateral area (km^2)	410.50	65.03	307.80	120.91	446.06
±% variation of quadrilateral area to authority-supplied area	2.88	49.14	6.69	20.31	-9.89
sum of meshsquares area (km^2)	396.92	39.60	284.01	101.86	496.05
±% variation of sum of meshsquares area to DTM-derived catchment area	-1.14	-0.28	-1.58	-0.69	0.04

The sum of meshsquares area - used in the new method - is certainly closer to the DTM-derived catchment area for all five catchments than the area used in the conventional approach; in fact for two of the catchments the 'inner box' as defined in the database exceeds the suggested tolerance level.

Meshpoints

The meshpoints are closely related to the area mentioned above. For the conventional method each meshpoint in the 'inner box' is considered for the catchment average rainfall calculations, whereas the new method includes only meshpoints inside the DTM-derived catchment boundary.

Raingauges

On the whole fewer gauges were found to be inside the buffered catchment (see Table 1 in Section 3), but those raingauges may be more representative. It should also be noted, that not every raingauge with available daily rainfall is necessarily included for the average rainfall calculations. The location of a particular raingauge could be such that it will never be used when the triangle around a meshpoint is set up.

Another reason for a raingauge to be excluded occurs when it lies outside a maximum distance. This limit is calculated using a formula relating the area of the 'inner box' (in the conventional method) or the sum of all meshpoint squares for a catchment (in the new method) to the number of daily gauges with available rainfall.

SAAR

Another variable which affects the results is the SAAR value. For the five test catchments SAAR was very close to the conventional input. Some initial trials have shown that altering SAAR has a noticeable impact on catchment average daily rainfall results.

The impact of the change in method on the catchment average daily rainfall sequence is shown below for each catchment in Figures 1a - 1e and summarised in Tables 3a - 3e for the years 1985-92. The graph in the lower part of each figure shows the daily average rainfall series for 8 years, the circles are the results from the conventional method (all inputs from ORACLE), the crosses are from the new method (DTM-derived catchment, meshspacing and SAAR; raingauges from the buffered areas). The horizontal lines show the number of gauges with available daily rainfall used in the calculations: solid line for the original method, dotted line for the DTM-derived catchment. The top part of the graph shows the rainfall differences between the two methods on a day by day basis. Negative values indicate a higher average rainfall for the automated procedure than for the original method, whilst positive values signify the opposite.

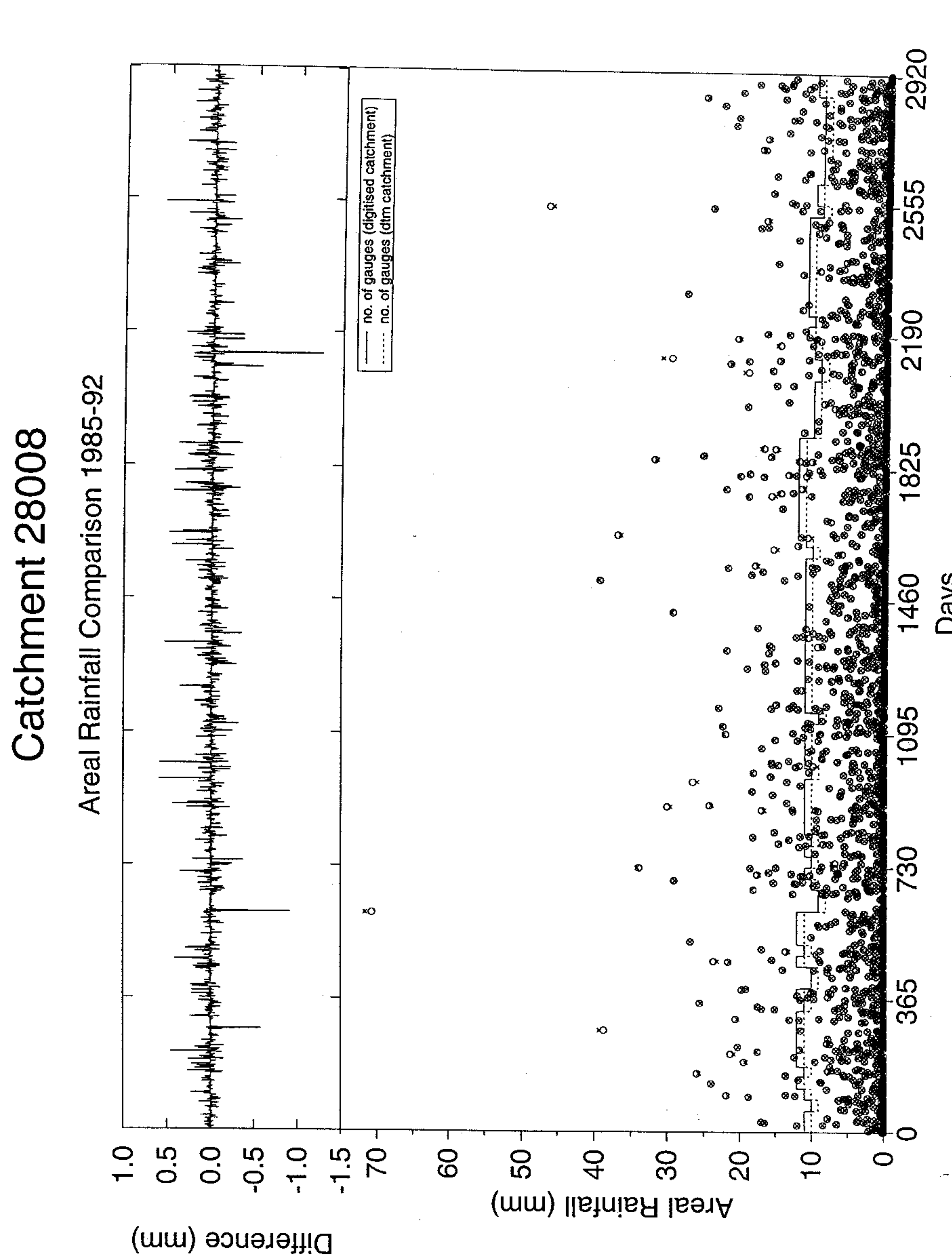

Figure 1a Catchment 28008 - Areal rainfall comparison 1985-92

Catchment 28008

The results of the new method are close to those of the conventional method, this is largely because the shape of the quadrilateral is close to the actual catchment boundary and the raingauge network is quite evenly distributed. Only for one day out of the eight years is the difference greater than 1 mm (Figure 1a).

Table 3a Comparison of results for catchment 28008

	conventional method	**new method**	**difference conv. - new meth.**
catchment average mean daily rainfall (mm) for 1985-92	2.74	2.74	0
standard deviation	4.90	4.90	0.08
range minimum (mm)	0	0	-1.26
range maximum (mm)	70.72	71.63	0.6
catchment average rainfall 1985 (mm)	992	990	2
catchment average rainfall 1986 (mm)	1169	1166	3
catchment average rainfall 1987 (mm)	1016	1016	0
catchment average rainfall 1988 (mm)	1089	1091	-2
catchment average rainfall 1989 (mm)	917	916	1
catchment average rainfall 1990 (mm)	989	989	0
catchment average rainfall 1991 (mm)	789	789	0
catchment average rainfall 1992 (mm)	1045	1043	2
no. of daily gauges used for calculations	9-12	8-11	-

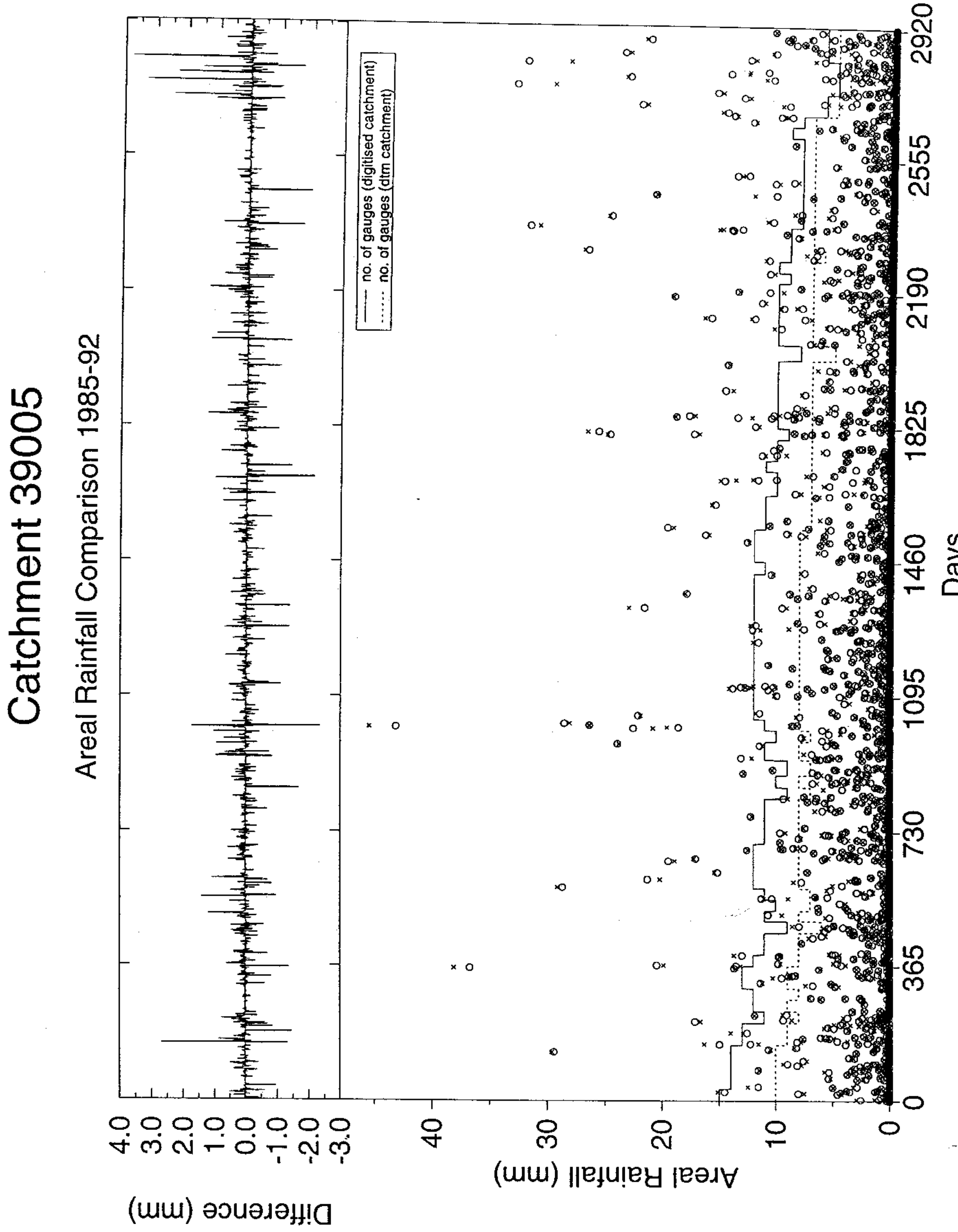

Figure 1b Catchment 39005 - Areal rainfall comparison 1985-92

Catchment 39005

This is the smallest catchment to be tested. The 'inner box' or tightfitting quadrilateral is larger than recommended and therefore the 'outer box' includes considerably more raingauges than the buffered catchment in the new method. For this reason results from the two methods fluctuate over a wider range than for most of the other tested catchments (Figure 1b). When this catchment was run with a larger buffer zone (see Table D.2 in Appendix D), the results for the individual years were closer to those from the conventional method .

Table 3b *Comparison of results for catchment 39005*

	conventional method	**new method**	**difference conv. - new meth.**
catchment average mean daily rainfall (mm) for 1985-92	1.64	1.63	0.01
standard deviation	3.66	3.66	0.25
range minimum (mm)	0	0	-2.34
range maximum (mm)	43.18	45.52	3.76
catchment average rainfall 1985 (mm)	602	599	3
catchment average rainfall 1986 (mm)	660	652	8
catchment average rainfall 1987 (mm)	663	660	3
catchment average rainfall 1988 (mm)	570	569	1
catchment average rainfall 1989 (mm)	546	551	-5
catchment average rainfall 1990 (mm)	513	512	1
catchment average rainfall 1991 (mm)	552	553	-1
catchment average rainfall 1992 (mm)	678	665	13
no. of daily gauges used for calculations	5-15	4-10	-

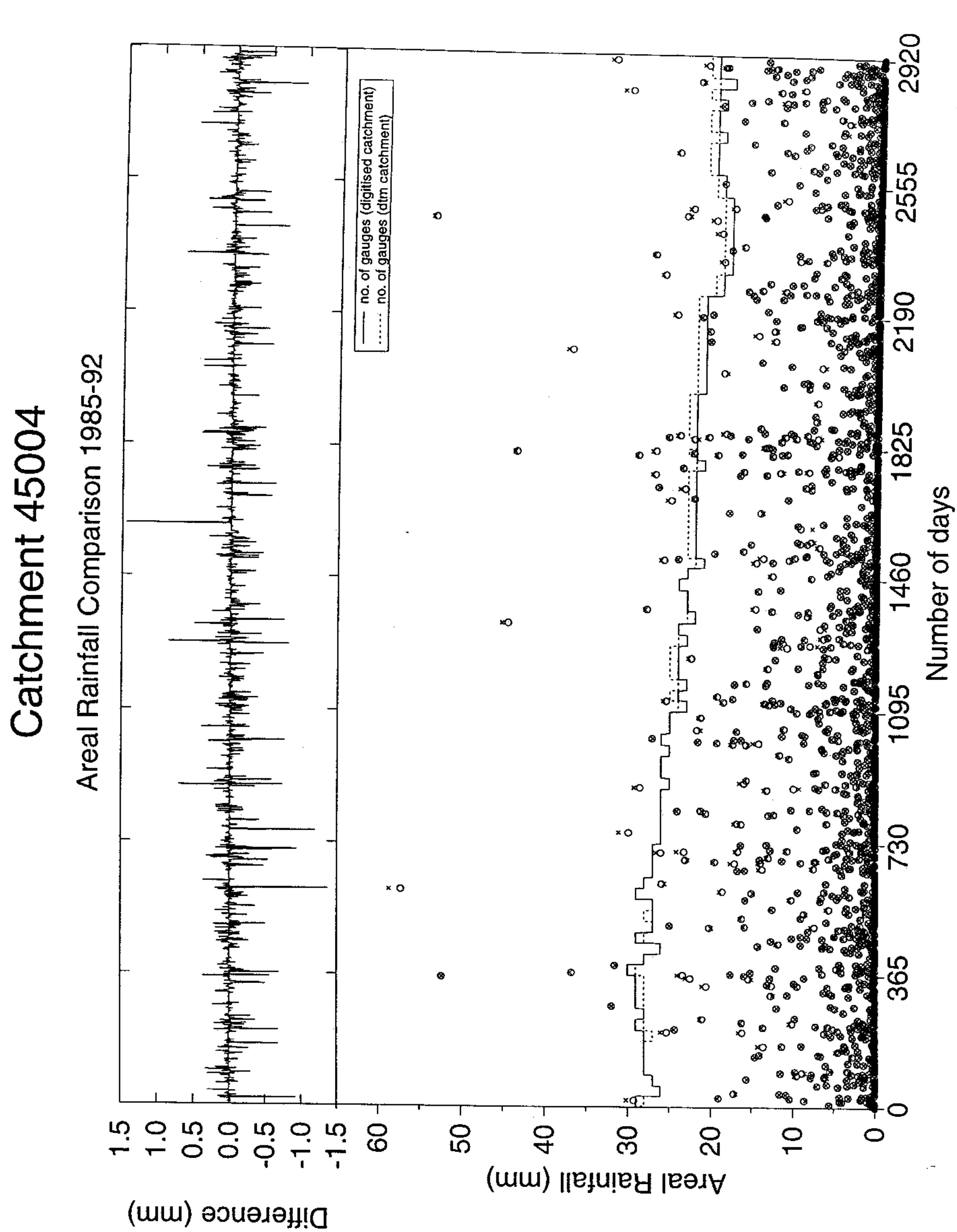

Figure 1c Catchment 45004 - Areal rainfall comparison 1985-92

Catchment 45004

The catchment average rainfall derived from the new method is generally slightly higher than for the conventional method. The quadrilateral excludes part of the wetter (southwestern) catchment but includes a large area to the north of the catchment which is marginally drier. Thus the sets of selected raingauges differ substantially for the two methods and the results are affected accordingly (Figure 1c).

Table 3c Comparison of results for catchment 45004

	conventional method	**new method**	**difference conv. - new meth.**
catchment average mean daily rainfall (mm) for 1985-92	2.60	2.61	-0.01
standard deviation	5.35	5.40	0.11
range minimum (mm)	0	0	-1.37
range maximum (mm)	57.3	58.67	1.45
catchment average rainfall 1985 (mm)	952	956	-4
catchment average rainfall 1986 (mm)	1151	1159	-8
catchment average rainfall 1987 (mm)	894	900	-6
catchment average rainfall 1988 (mm)	920	927	-7
catchment average rainfall 1989 (mm)	1006	1011	-5
catchment average rainfall 1990 (mm)	868	872	-4
catchment average rainfall 1991 (mm)	905	910	-5
catchment average rainfall 1992 (mm)	901	905	-4
no. of daily gauges used for calculations	18-30	19-29	-

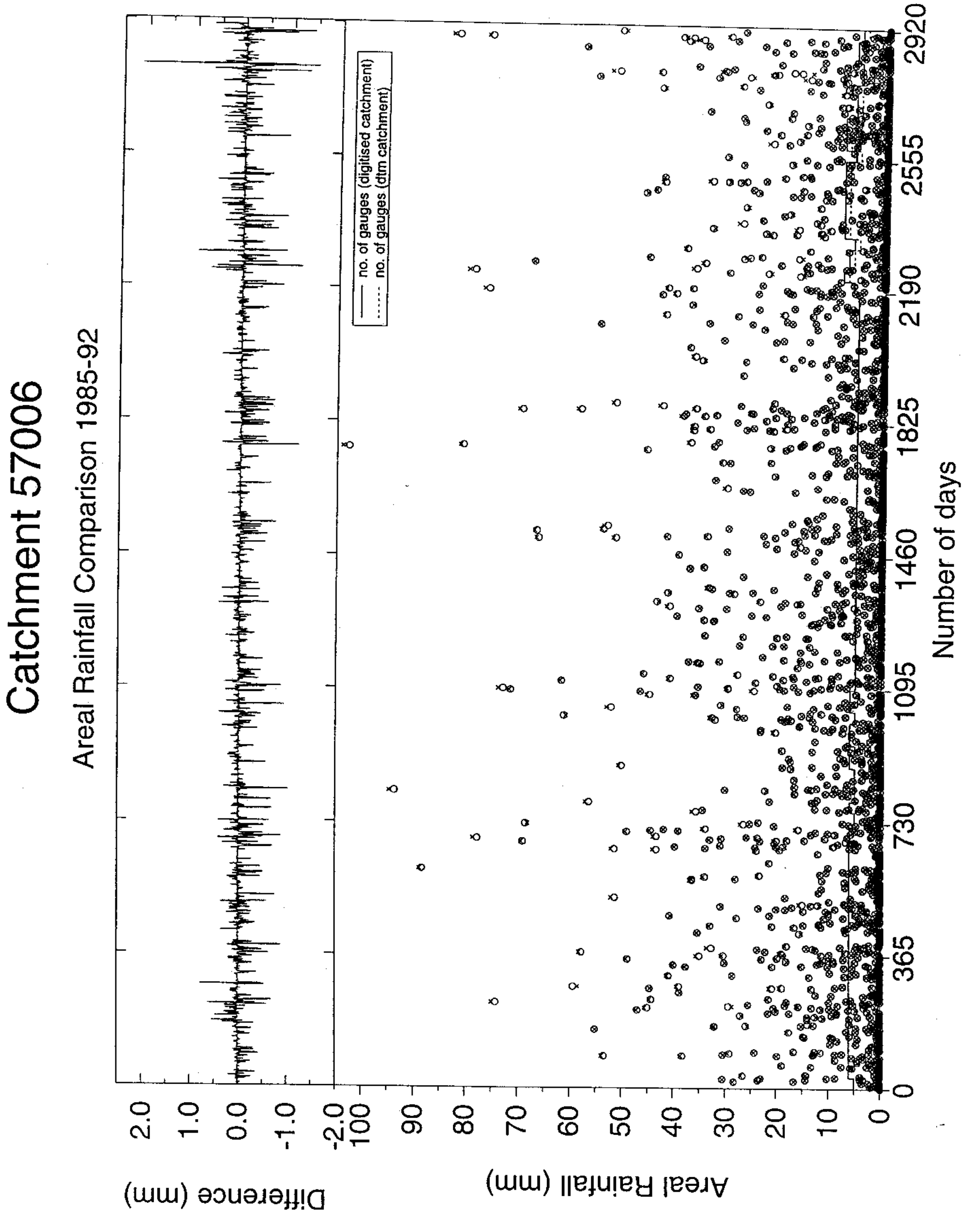

Figure 1d Catchment 57006 - Areal rainfall comparison 1985-92

Catchment 57006

The results for this catchment demonstrate the impact of catchment SAAR on the final figures. Even though identical raingauges are used for most of the catchment rainfall calculations in both methods and the 'inner box' corresponds well with the catchment shape, the results are mostly higher for the new method (Figure 1d). This can be attributed to the higher SAAR value derived through Arc/Info techniques. The program was run a second time using a lower catchment SAAR and the results were much closer to the conventional method (results from this run not shown here).

***Table 3d** Comparison of results for catchment 57006*

	conventional method	new method	difference conv. - new meth.
catchment average mean daily rainfall (mm) for 1985-92	6.40	6.43	-0.03
standard deviation	11.6	11.68	0.17
range minimum (mm)	0	0	-1.51
range maximum (mm)	102.77	103.96	2.13
catchment average rainfall 1985 (mm)	2404	2410	-6
catchment average rainfall 1986 (mm)	2721	2737	-16
catchment average rainfall 1987 (mm)	2088	2096	-8
catchment average rainfall 1988 (mm)	2454	2463	-9
catchment average rainfall 1989 (mm)	2226	2239	-13
catchment average rainfall 1990 (mm)	2268	2278	-10
catchment average rainfall 1991 (mm)	2188	2196	-8
catchment average rainfall 1992 (mm)	2362	2367	-5
no. of daily gauges used for calculations	5-8	4-7	-

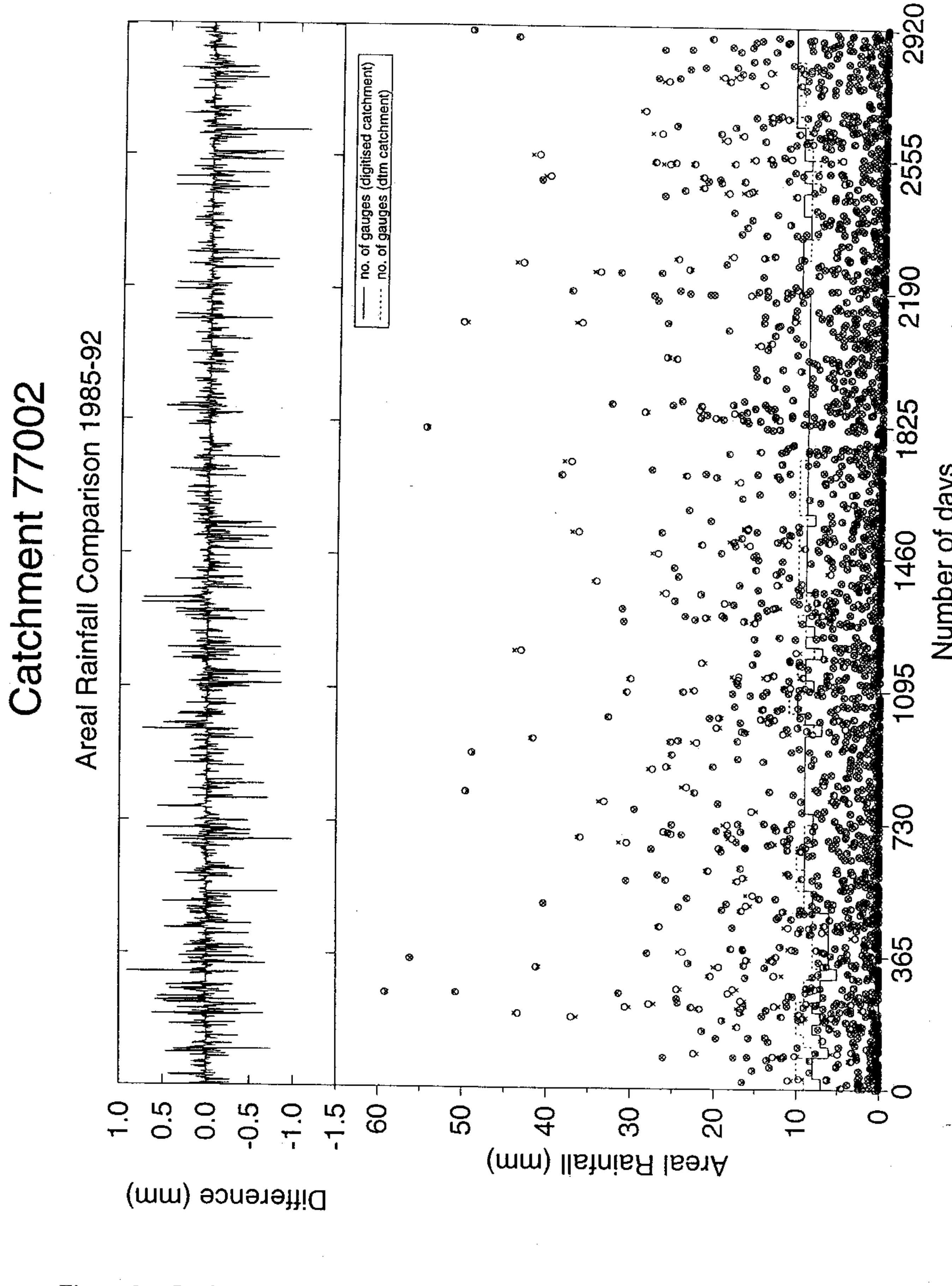

Figure 1e Catchment 77002 - Areal rainfall comparison 1985-92

Catchment 77002

This is the largest catchment in the tested set. The original quadrilateral excludes northern and eastern parts of the catchment. The distribution of raingauges is fairly patchy for a catchment this size. Thus for many meshpoints a triangle cannot be set up and the nearest three gauges are used instead for rainfall calculations. On only one day in eight years is there a difference of more than 1 mm between the conventional and the new method; overall the two methods alternate between calculating the higher catchment average rainfall. See Figure 1e.

Table 3e Comparison of results for catchment 77002

	conventional method	**new method**	**difference conv. - new meth.**
catchment average mean daily rainfall (mm) for 1985-92	4.53	4.55	-0.02
standard deviation	7.27	7.30	0.14
range minimum (mm)	0	0	-1.13
range maximum (mm)	59.15	58.9	0.91
catchment average rainfall 1985 (mm)	1780	1777	3
catchment average rainfall 1986 (mm)	1798	1808	-10
catchment average rainfall 1987 (mm)	1539	1542	-3
catchment average rainfall 1988 (mm)	1661	1666	-5
catchment average rainfall 1989 (mm)	1412	1418	-6
catchment average rainfall 1990 (mm)	1794	1797	-3
catchment average rainfall 1991 (mm)	1539	1548	-9
catchment average rainfall 1992 (mm)	1719	1734	-15
no. of daily gauges used for calculations	5-11	7-11	-

5. Sensitivity to Buffer Distance

Arc/Info techniques allow the user to vary the buffer distances fairly easily. Trials were carried out for each of the five catchments to calculate catchment average rainfall by applying several buffer zones and comparing results. Daily rainfalls were calculated first without a buffer zone, i.e. only raingauges inside the catchment boundary were used; then the calculations were repeated enlarging the original catchment area by approximately 1.5, 2.25, 3.5 and 4.5 times respectively.

Results are most obviously affected by the availability of daily rainfall and the location of daily raingauges in relation to the catchment. Enlarging the catchment will affect the meshspacing: as more gauges are included, the resulting mesh becomes finer. When the triangle of raingauges is determined for each meshpoint, raingauges are sorted by their proximity to this point. Therefore more distant gauges are not necessarily included in the calculations. This is shown clearly when enlarging by factors 3.5 and 4.5, where for most of the catchments the number of daily gauges used in the calculations is almost identical or very close and therefore the average rainfall results are very similar.

The results for each catchment are summarised in Appendix D (Tables D.1 to D.5). In general, the catchment average rainfall is not very sensitive to the size of buffer zone, although some enlargement is preferable to increase the number of raingauges used. In other examples, where there are few gauges, this may be more critical.

6. Further Developments

Using the above principle and modifying the appropriate routines, areal rainfall can be calculated for areas other than catchment areas draining to a point on a river. Thus a modified program version has been used for obtaining areal rainfall for 40 km x 40 km MORECS squares. Similarly it will be possible to derive average rainfall for Hydrological Representative Units (HRU) as long as boundary coordinates are being provided.

Use with sub-daily rainfall is also being explored in the context of flood modelling (Spijkers & Naden, 1994) and could easily be added for ungauged catchments.

7. Conclusion

Deriving catchment boundaries from the DTM and locating raingauges in a buffer zone around the catchment dispenses with the usual prerequisites for calculating catchment average rainfalls. The described method is therefore particularly useful when deriving areal rainfall for ungauged or undigitised catchments. On the whole DTM-derived catchments produce fairly reliable boundaries. By using Arc/Info buffering techniques the selection of raingauges is standardised, in contrast to the conventional quadrilateral method. This could result in a more representative set of raingauges. By replacing the mesh based on the handdrawn quadrilateral with Arc/Info derived meshpoints, only points inside the catchment boundary are used for rainfall calculations and automated routines are applied.

Unless the density of the raingauge network and availability of daily rainfall are very poor, a buffer zone resulting in the catchment area * 2.25 produces sound results although the method is not very sensitive to the size of the buffer zone.

7. References

Acreman, M.C., 1986. On estimating a catchment average rainfall total, Institute of Hydrology Applied Hydrology Informal Note 100th Issue.

Bayliss, A.C., 1995. Catchment characteristics for flood estimation: a preliminary set from gridded spatial data, Institute of Hydrology Flood Estimation Handbook Note 13/ACB.

Boorman, D.B., Houghton-Carr, H.A. (Eds), 1992. Acreman, M.C., Bonvoison, N.J., Boorman, D.B., Clayton, M.C., Gannon, B., Houghton-Carr, H.A. & Polarski, M. (contributors) UK representative basin and flood event database manual, Institute of Hydrology Report to MAFF.

Boorman, D.B., Clayton, M.C., Gannon, B. & Houghton-Carr, H.A., 1991. Representative basin catalogue for Great Britain, Institute of Hydrology.

Morris, D.G. & Flavin, R.W., 1990. A digital terrain model for hydrology. Proc. 4th International Symposium on Spatial Data Handling, Zurich, Vol. 1, 250-262.

Morris, D.G. & Heerdegen, R.G., 1988. Automatically derived catchment boundaries and channel networks and their hydrological applications. Geomorphology 1, 131-141.

Jones, S.B., 1983. The estimation of catchment average point rainfall profiles, *Institute of Hydrology Report No. 87.*

Rycraft, N.A., 1994. Access of IH DTM, Digital 1:50000 rivers, catchment boundaries and hydrometric area boundaries via Arc/Info Aml's, Institute of Hydrology Spatial Data Note 7.

Spijkers, T. & Naden, P. 1994. Continuous rainfall-runoff modelling for flood estimation: initial thoughts and data requirements. Report to Ministry of Agriculture, Fisheries and Food.

APPENDIX A

Running Arc/Info Program 'allrgs.aml'

There are two requirements prior to running 'allrgs.aml'. Firstly, if the 1:50,000 digitised river network is to appear on the plot, it has to be created as a coverage by using the appropriate library routine (Rycraft, 1994, Spatial Data Note 7). However, it is not essential for the successful running of the program for the appropriate river coverage to be present, it is only used for presentational purposes. Secondly, the point on the river system from which to derive the catchment boundary has to be established[1].

Both these steps are described in the example below which is for a catchment derived from a point on the river system close to the gauging station of the digitised catchment 28008 (grid reference 411200, 339700).

1. Retrieval of the 1:50,000 digitised river network

(see Spatial Data Note 7 for further details).

The river coverage will be created under Arc/Info and will be called rivcov. Make sure that a coverage with this name does not exist already. If it does and should be kept, copy it first to another coverage before deleting it (arc command: kill).

Logon to a sun workstation and type

1 user@wlsn019> setup arc
2 user@wlsn019> arc

prepare display device (commands: &station 9999 + display 9999)
Arc: &station 9999
Arc: display 9999

check that a coverage with name rivcov does not exist already by listing coverages (arc command: lc)
Arc: lc

```
Available Coverages
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 RGBUCOV        RGCOV         RIVCOV        RIVISCOV
 STCOV
```

If it exists either delete it
Arc: kill rivcov

or copy it to rivcovcopy and then delete it
Arc: copy rivcov rivcovcopy
Arc: kill rivcov

[1]National grid references of DTM grid points nearest gauging stations and located on correct DTM flowpaths are available for 718 catchments on ORACLE table POTFLOOD.DTM_BOUNDARY_INFO (Bayliss, 1995).

retrieve rivers from 1:50,000 digitised river network for a specified area

Arc: &r ~spat/arcamls/extriv
Input the minimum x value...: 396000
Input the minimum y value...: 331000
Input the maximum x value...: 437000
Input the maximum y value...: 380000
Input the required hydrometric area...: 28 (0 if all rivers in the bounding rectangle are to be shown)
Input the required features: 1 (just rivers)
Input the filename of the output file...: outf.rv

.

Input a name for the output rivers coverage...: rivcov

.

Do you need to keep the ASCII data file? 1=yes, 2=no: 2

.

When the aml is finished, list all available coverages.

Arc: lc

Available Coverages

RGBUCOV	RGCOV	RIVCOV	RIVISCOV
STCOV	(RIVCOVCOPY)		

The new coverage rivcov has no built topology which will be required later in the plotting program. Use the arc command build <coverage> lines to construct the topology.
Arc: build rivcov lines

Exit from arc (arc command: q).
Arc: q

2. Finding the coordinates from which to derive the catchment boundary

From the 1:50,000 maps establish the approximate grid reference of the 'gauging point'. A library routine exists, which will interpret the DTM and find and print various datatypes for a specified area at 50 m grid intervals. The user has to be linked to the ~nrfa libraries for this to work. In the example a point should be found on the DTM which is as close as possible to the (x,y) coordinate (411200, 339700).

Logon to a workstation and type

1 user@wlsn019> gridlook

```
====> zone 0                       (zone 0 for mainland UK)
====> origin 411100 339600         (100 m has been subtracted from the above point)
====> size 400 400                 (sets a size of 400 m to east and north from the origin)
====> datatypes surface.character  or datatypes swa.surface.character[2]  (displays the surface types)
====> print                        (print to screen)
>.........
>.........
>........R
>........R
>.......R.
>....RRR..
>....R...R
>...R....R
>....R..R.
```

Data types: surface.character

.

(MINX,MINY,MAXX,MAXY)=(411100,339600,411500,0340000) ZONE= 0

The above display shows the surface datatype in character format for every cell at 50 m intervals for the 400 m square starting from the origin (411100, 339600) in the lower left corner, the letter 'R' meaning river. In the above example several rivers are present in the 400 m square. To pick the correct flowpath, the same square should be displayed again, but this time showing datatype for cumulative catchment area. Each cell with the letter 'R' will have a corresponding value with the cumulative catchment area, which is the number of 50 m grid squares draining to this point. This can be achieved by specifying the datatype to be displayed as area.numeric.

```
====> datatypes area.numeric  or datatypes swa.area.numeric[2]
====> print
>      21      2      4      1      1      3      7      2      5
>      22      3      6      1      1      2      4      8      3
>      23      4      7      2      1      2      3      5 159140
>      24      5      1      8      3      2      3      4 160582
>      25      1      6      2      9      4      3 160592      1
>      26      1      2      7     19 160604 160599      1      1
>       1     28      1      3 160629      2      1      1     10
>       1     31      1 160682      1      1      1      1     13
>      13     14     50      1 160687      1      1     16      1
```

Data types: area.numeric

.

(MINX,MINY,MAXX,MAXY)=(411100,339600,411500,0340000) ZONE= 0

From the two displays the path of the main river can now be identified by matching the 'R' cells with the higher numeric value cells. The other 'R' cells corresponding to the lower numeric values show the paths of tributaries. In this example the location of the underlined 50 m cell at grid coordinate (411350, 339750) is chosen for deriving the catchment boundary; the next downstream cell includes another tributary and increases the catchment area. At this point the DTM information should be compared with the original 1:50,000 maps to determine the exact location of the 'gauging point' in relation to the river network.

```
====> quit          (leave gridlook)
```

[2] some areas of the DTM are currently held under user 'swa'; should the default datatypes retrieval return no data, then the second option with 'swa' inserted should be tried.

3. Running 'allrgs.aml'

In the example below only relevant screen output is shown and explained; the Arc/Info routines and the Fortran programs display a lot of information which for the purpose of this exercise is ignored.

Initially the aml generates the catchment boundary from the (x,y) coordinate point which was found in the previous step. A rectangle is created from the minimum and maximum (x,y) points of the catchment and the rectangle is enlarged to create a 'working area' by a factor supplied by the user (normally at least 1.5). Raingauges inside this enlarged rectangle are copied from ORACLE to be used by the program; in fact the 'working area' is extended by another 5 km in all directions during the raingauge search to capture as many raingauges as possible. The 'working area' of the catchment can be increased by supplying a bigger enlargement factor at the start of the program thus increasing the search area.

To run the program:
Logon to a sun workstation and type

1 user@wlsn019> setup arc
2 user@wlsn019> arc

Arc: &r ~lcm/data/arcinfo/rggen/allrgs (running allrgs.aml)
a catchment will be derived from a point on the river system
the point must be a multiple of 50 and in metres
enter the x-coordinate of the point: 411350
enter the y-coordinate of the point: 339750
the catchment will be enlarged for the map and the raingauge search
normally the enlargement factor = at least 1.5
enter enlargement factor: 1.5

.

.

```
********************************************
 start of program nextract
number of points from DTM  1039
area from dtm     401.510 sqkm
           quad     402425   339675
                    427325   339675
                    427325   370475
                    402425   370475
enlarged quad       396200   331925
                    433550   331925
                    433550   378175
                    396200   378175
buffer maximum in m   6963 (this is only meant to be a guide, in practice this figure is too high,
                          see Appendix B)
coordinate net should be at  10km interval
plot as P
 .
 .
end of nextract program
********************************************
```

.

.

.

The user is prompted to enter a range of bufferzones and step intervals for calculating a number of buffered catchment areas. Appendix B gives some guidelines on the choice of buffer distances in relation to the catchment area. From these results the user can determine which buffer size is to be used for the final buffer distance. All raingauges found inside the final buffer are output to a file which can then be used in further programs.

Input the minimum buffer distance in m: 4000
Input the maximum buffer distance in m: 4750
Input buffer step intervals in m: 250

.

.

****
start of program bufprint
401.51 sqkm for catchment
903.40 sqkm for enlarged catchment *2.25
827.64 sqkm with buffer of 4000.00m around catchment
856.32 sqkm with buffer of 4250.00m around catchment
885.35 sqkm with buffer of 4500.00m around catchment
914.74 sqkm with buffer of 4750.00m around catchment
end of program bufprint
****

The above list shows various catchment sizes: the first line refers to the actual catchment size, the next line shows the size of the area * 2.25. The following 4 lines show the various buffered catchment areas with the appropriate buffer zones which were previously entered as minimum and maximum buffer distances and then modified by the step interval. The user should interpolate these to find a suitable size and area. In the above example the buffered area should approximate the catchment area * 2.25, (i.e. 903.4 sqkm).

The final buffer distance has to be entered next.

Input buffer distance: 4660

.

.

At the end of the program the user has the option to derive daily average rainfalls. If average rainfalls are to be calculated, they can be either for (a) previously defined period(s) or for a standard eight year period (1985-1992).

For user-defined periods a file 'dates.input' must exist specifying the dates:
1st line: number of periods (free format)
2nd line: start date of first period (day, month, year - free format - e.g. 01 01 1990)
3rd line: end date of first period (format as 2nd line)
following lines depend on the number of periods defined in the 1st line
4th line: start date of second period
etc..

****
do you want daily catchment average rainfall for this catchment?
enter: 1 for yes - 2 for no
enter 1 or 2: 1
The start and end dates of the rainfall calculations are:
1: in the file dates.input
2: dates between 1/1/85 and 31/12/92
enter: 1 for input from file - 2 for default 8 years

enter 1 or 2: 2
start of program areadtm
.
.
daily catchment average rainfall in file dcrain
end of program areadtm
****

The layout of file 'dcrain' is as follows:
column 1: year
column 2: number of day in year
column 3: catchment daily average rainfall in mm
column 4: number of gauges with daily data
column 5: running output number
column 6: number of gauges used in calculations
.
.
Exit from arc (arc command: q)
Arc: q

By the end of the run several files and arc coverages will have been created. File 'alrgbuf.data' is a list of all raingauges inside the buffered catchment and can be used as input to the catchment average rainfall program 'arearain'. File 'rgbuf.data' is a list of all daily and recording raingauges inside the buffered catchment, the easting and northing grid points are also listed (note the frequency of the rainfall readings - whether daily, monthly etc. - has been derived from ORACLE table 'FLOOD.RAIN_GAUGE_DETAIL' originating from the Met.Office; the frequency details have not always been totally reliable). File 'meshis.dat' contains all meshpoints together with the grid coordinates inside the catchment boundary. The size of the meshcells is contained in file 'mesh.info' (the 2nd item in the 2nd line is size in $(m*100)^2$).

The postscript file containing the plot is called 'rgsmap.ps' and can be viewed and/or printed. The plot shows the enlarged quadrilateral in turquoise; it is important to check that the buffered catchment area is contained inside this rectangle. This can also be checked in Arc/Info by using the arc command 'describe <coverage name>', which displays the minimum and maximum (x,y) coordinates to the screen. If the enlarged quadrilateral coverage (coverage name 'eqdcov') is smaller than the resulting buffered catchment (coverage name 'cabucov') it could mean that not all raingauges have been captured for the buffered area. The extent of the raingauge coverage (coverage name 'rgcov') can also be checked to make sure that it is larger than the buffered catchment coverage. Should the buffered catchment area be larger than the other coverage(s), the aml 'allrgs' should be run again specifying a bigger enlargement factor for the 'working area' at the start of the program.

The river network (coverage name 'rivcov') is only plotted for illustrative purposes. Determining the input coordinates for aml ~spat/arcamls/extriv in advance can sometimes be difficult. The easiest way to get the coordinates is to run aml 'allrgs' having previously determined the point on the river system from which to derive the catchment boundary but omitting the initial creation of the relevant river coverage. Then, before quitting Arc/Info, issuing the arc command 'describe eqdcov' will return the minimum and maximum coordinates of the enlarged quadrilateral coverage. These coordinates, possibly slightly enlarged, can then be used to create the river coverage as explained in Section 1 of this Appendix. Running the Arc/Info aml 'allrgs' again will then produce a plot showing the appropriate river coverage.

N.B. When the various coverages, which appear as directories in the Unix system, are no longer needed, they can be deleted in Arc/Info by issuing the arc command 'kill <coverage>'.

APPENDIX B

Guide to Buffer Distances

When running program 'allrgs.aml' under Arc/Info, it is not always easy to choose a sensible initial buffer distance which will result in enlarging the catchment area by 2.25. As a rough guide, values from Figure B.1 can be used for deciding on a minimum buffer distance. It is then up to the user to choose the maximum buffer distance and the buffer step interval. The program prints the buffer distances together with the resulting areas to the screen. The final buffer distance can be interpolated from these values and entered to continue running the program.

If required, this step can be further automated at a later stage.

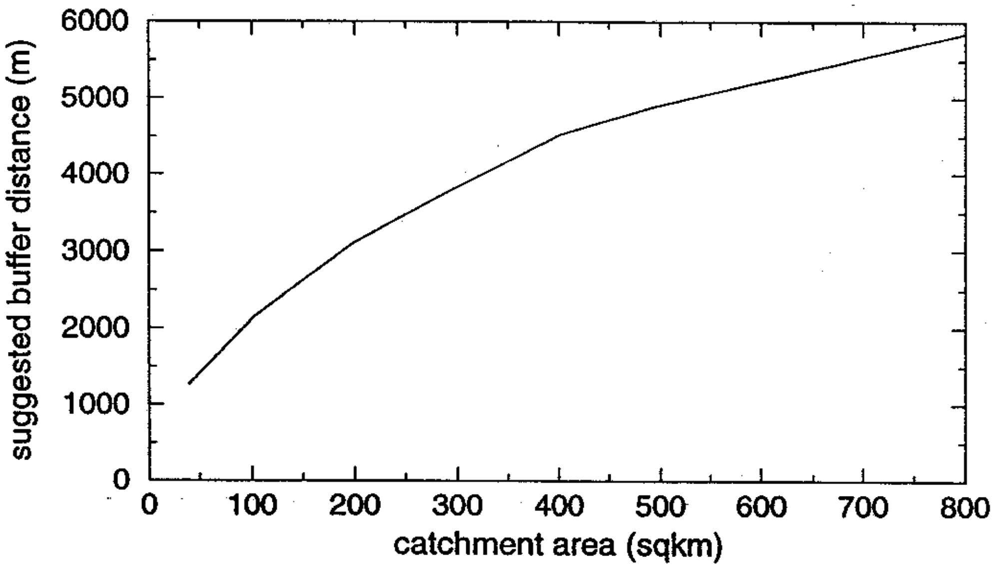


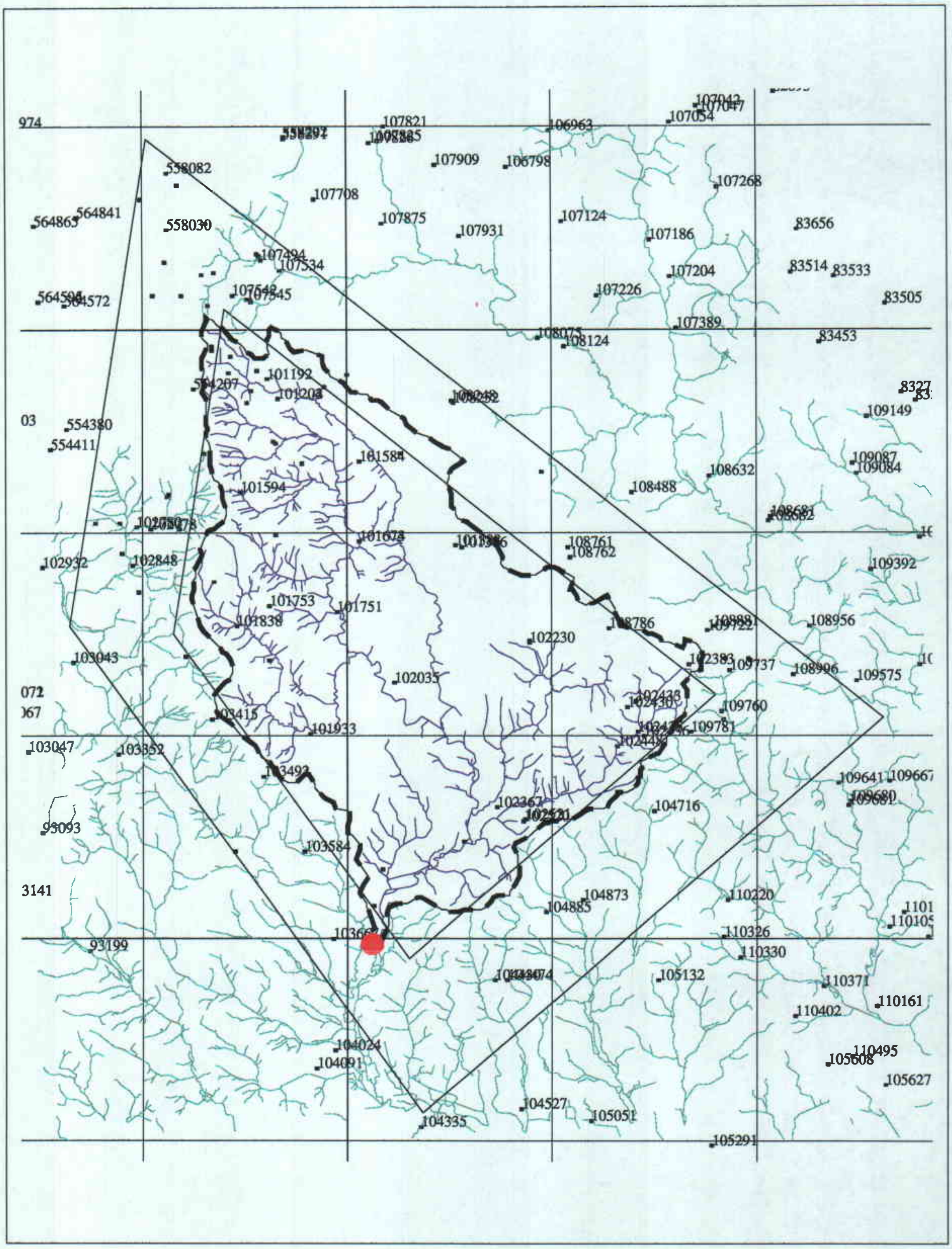
Figure B.1 Suggested buffer distances for enlarging catchment area by 2.25

APPENDIX C

List of Figures

Daily and Recording Raingauges

Catchment 28008



One grid square equals 10km x 10km

Figure C.1a

Daily and Recording Raingauges

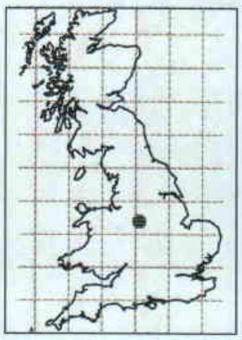
Catchment derived from DTM at (411350,339750)

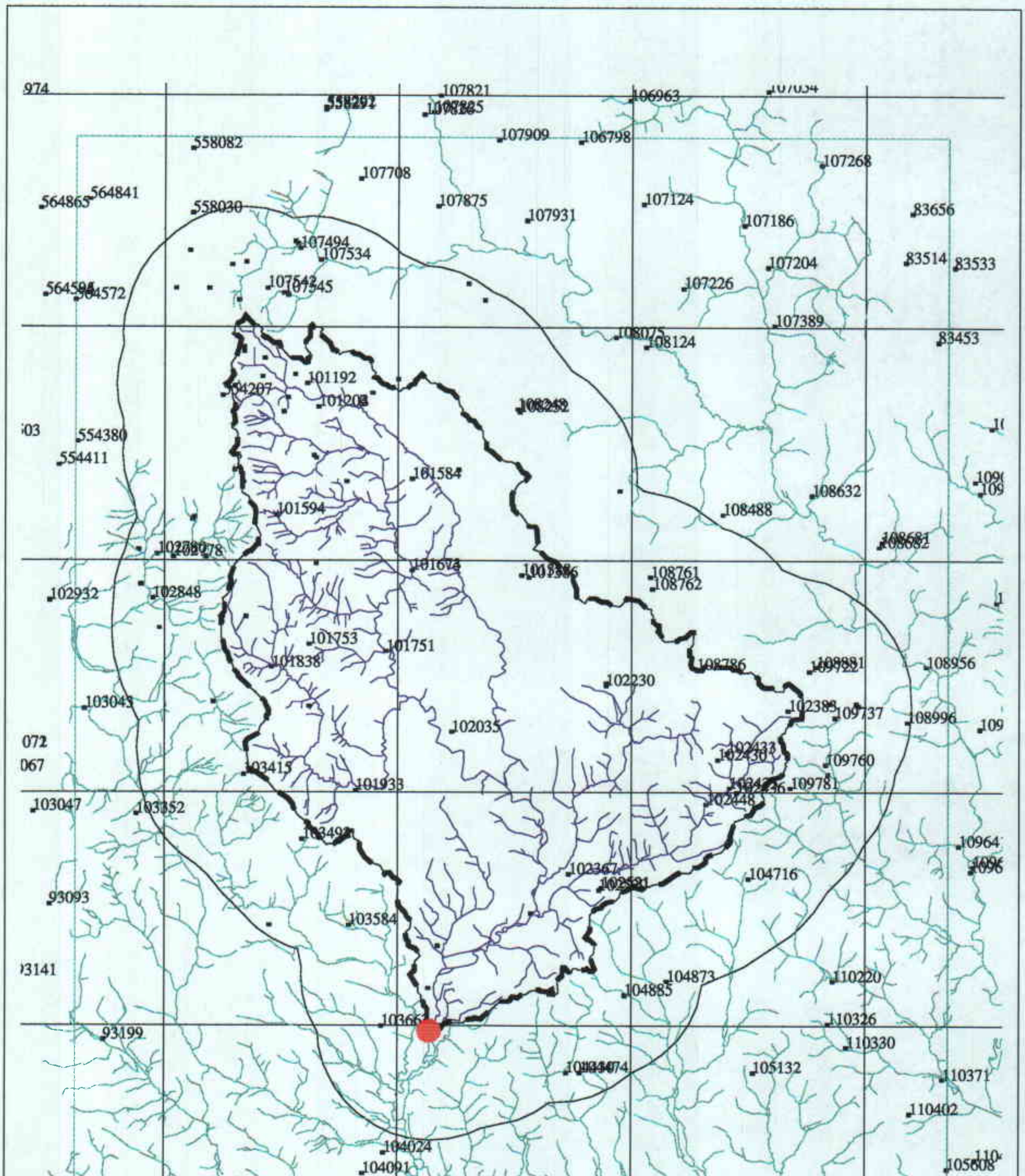
401.51 sqkm catchment area

1019.20 SAAR 1941-70

904.12 sqkm buffer area

4660 m buffer distance



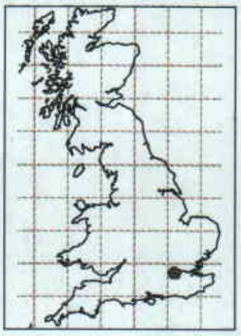


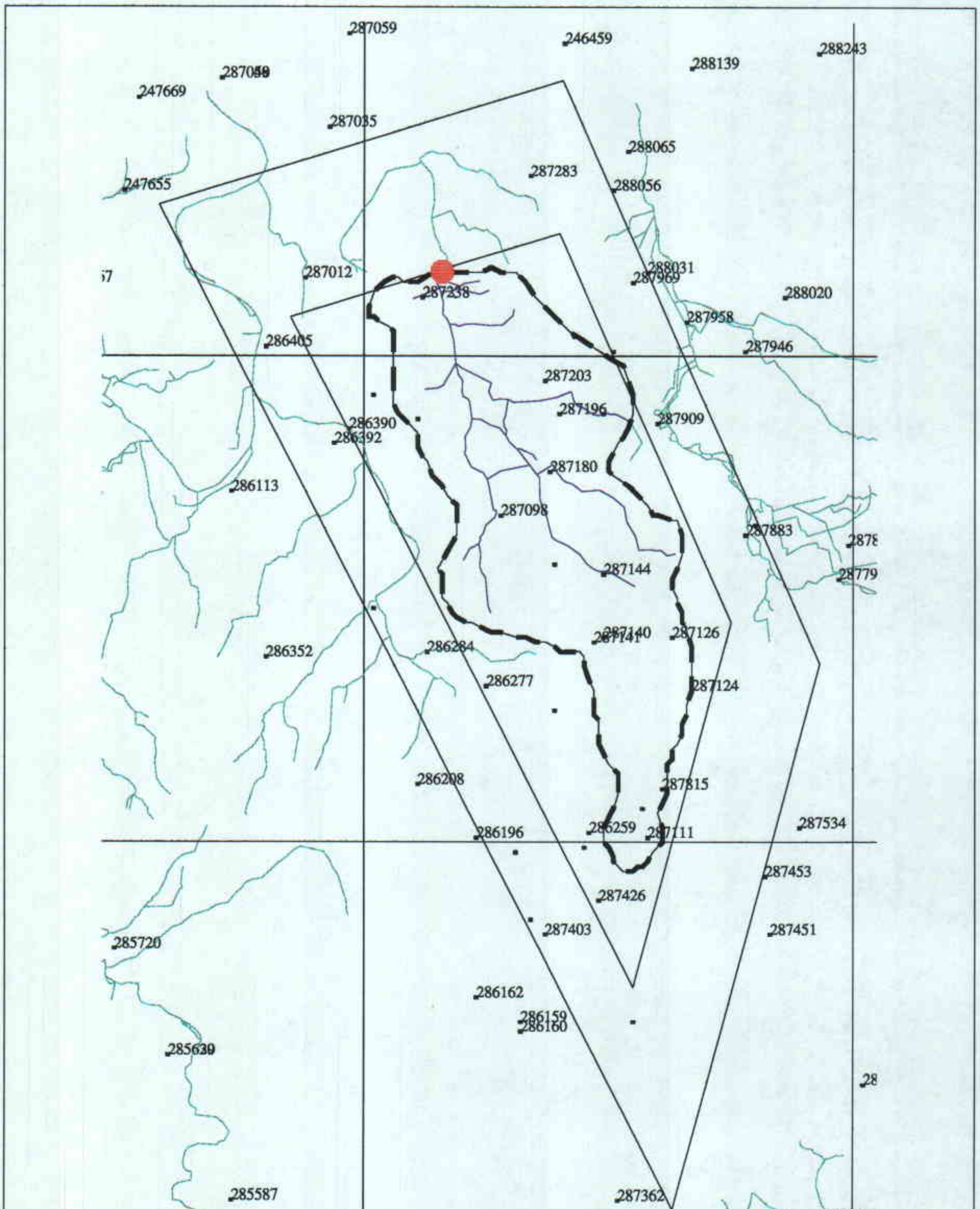
One grid square equals 10km x 10km

Figure C.1b

Daily and Recording Raingauges

Catchment 39005





One grid square equals 10km x 10km

Figure C.2a

Daily and Recording Raingauges

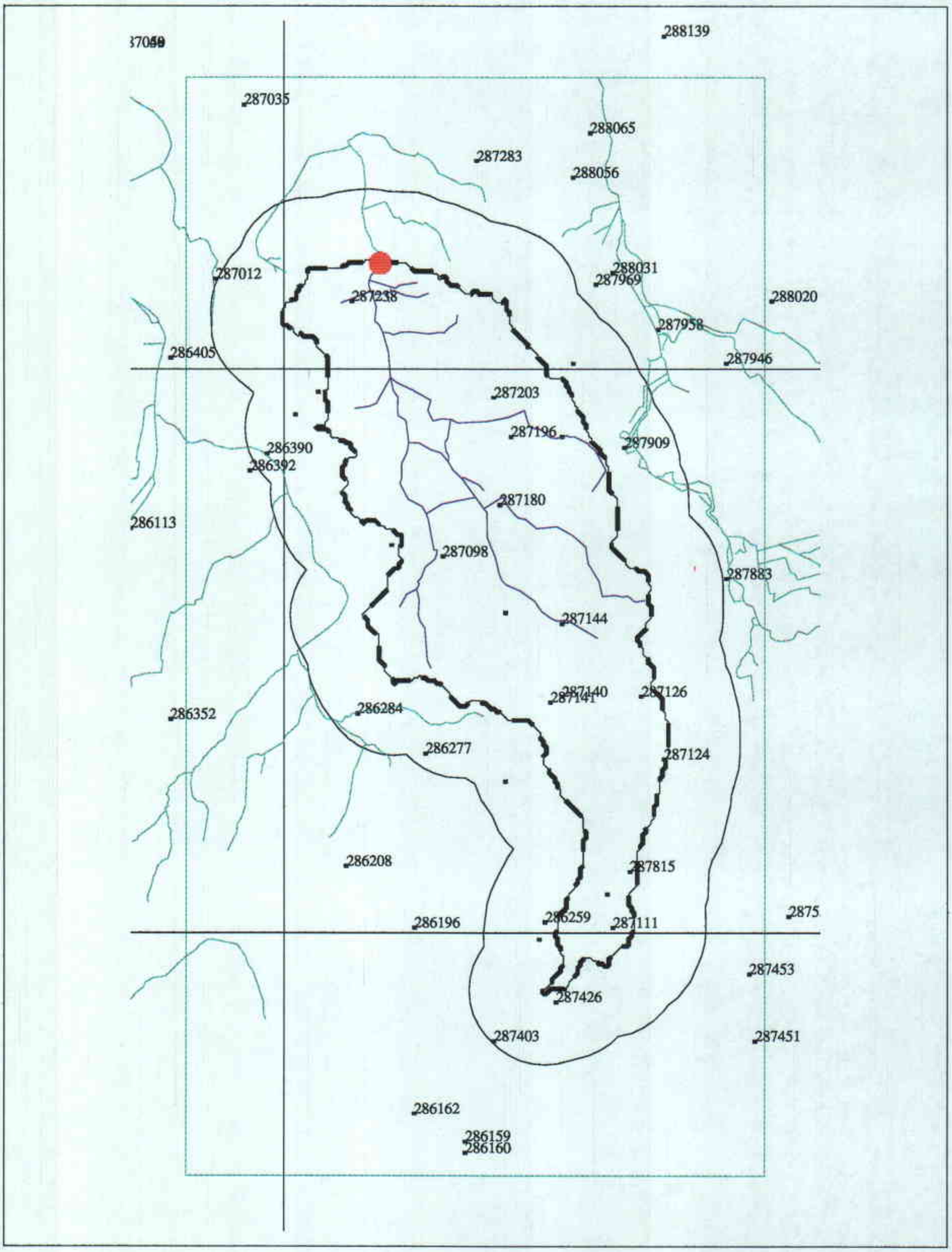
Catchment derived from DTM at (521700,171850)

39.71 sqkm catchment area

632.93 SAAR 1941–70

89.27 sqkm buffer area

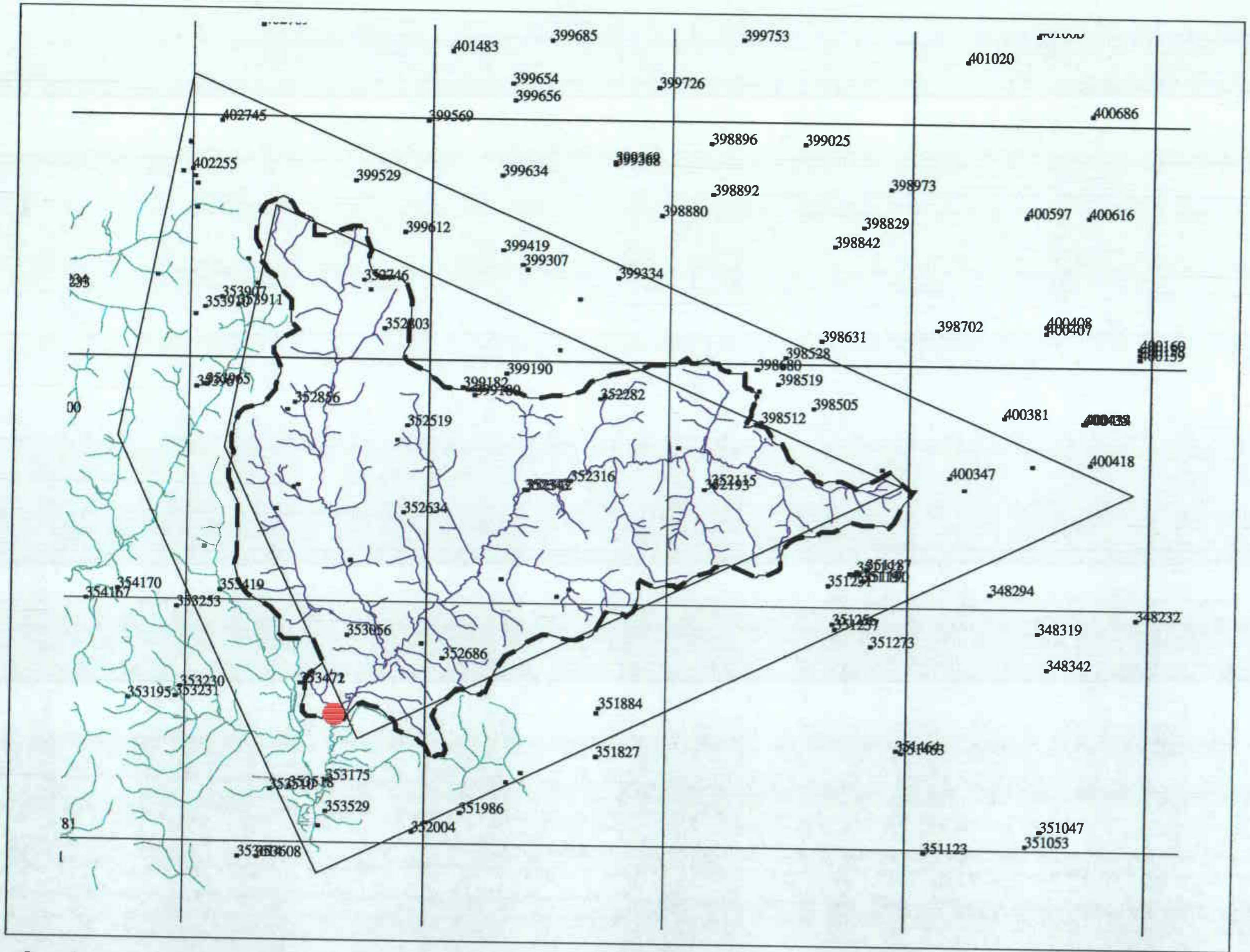
1265 m buffer distance



One grid square equals 10km x 10km

Figure C.2b

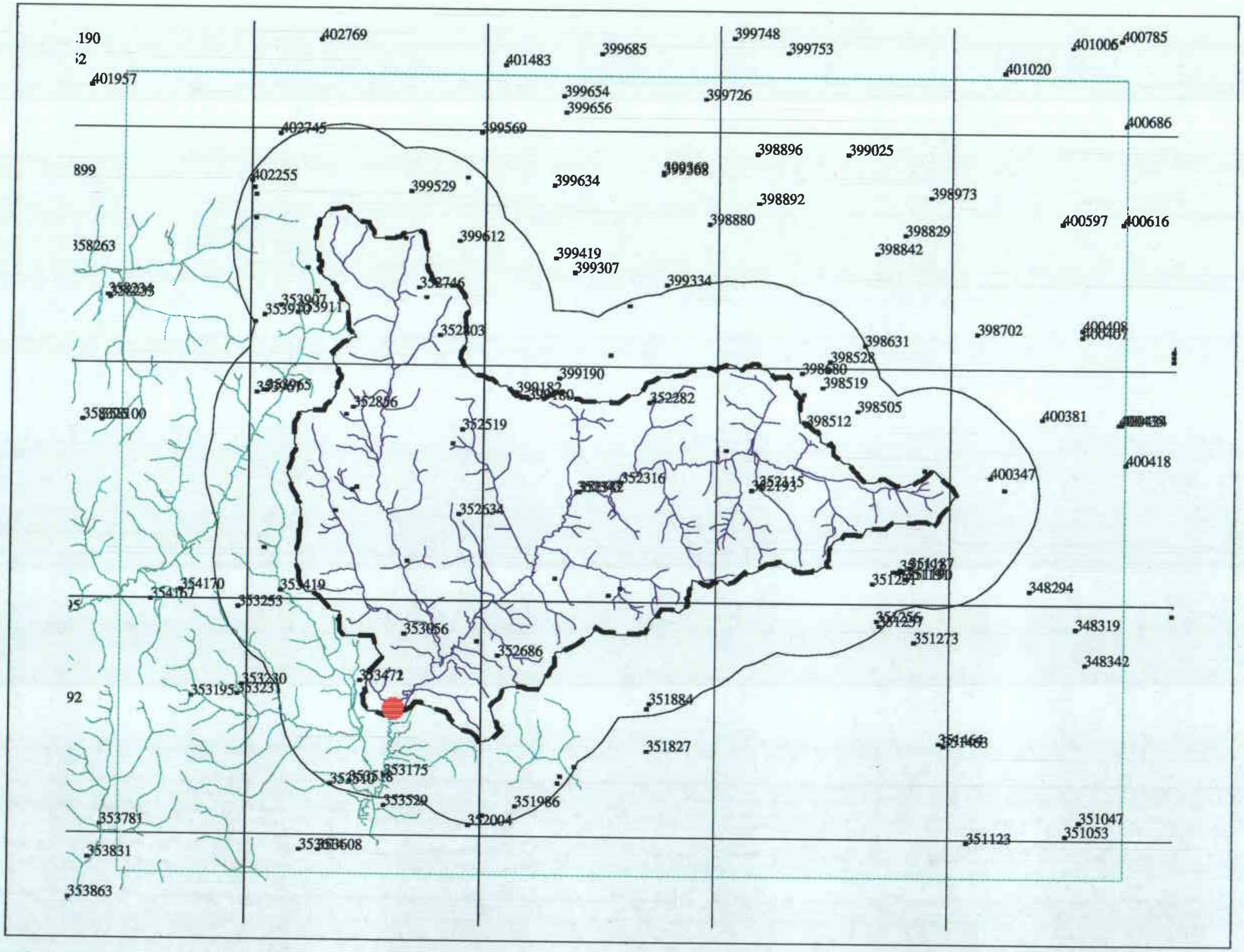
Daily and Recording Raingauges – Catchment 45004



One grid square equals 10km x 10km

Figure C.3a

Daily and Recording Raingauges – Catchment derived from DTM at (326250, 95400)



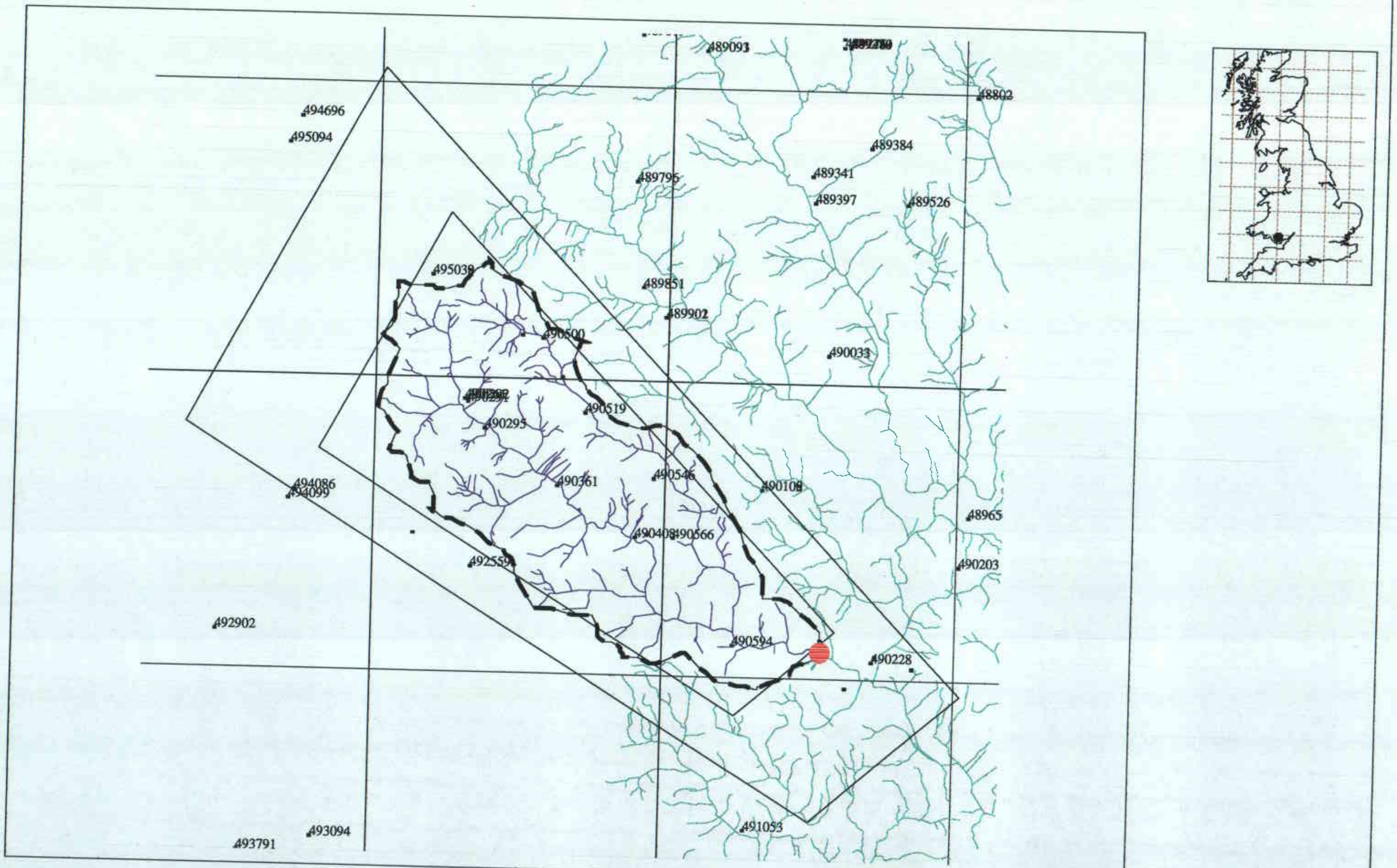
One grid square equals 10km x 10km

288.58 sqkm catchment area
1051.93 SAAR 1941–70

649.49 sqkm buffer area
3520 m buffer distance

Figure C.3b

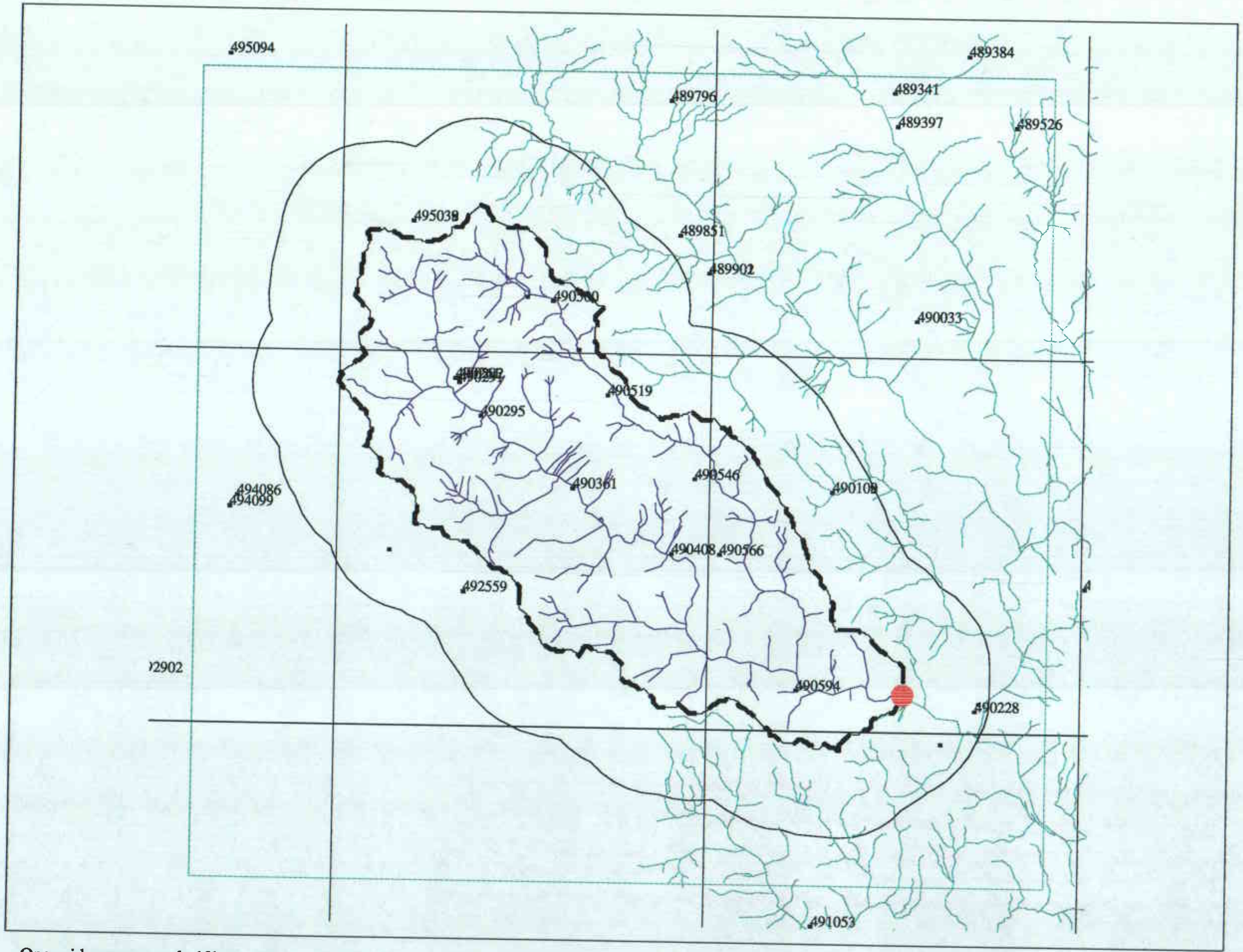
Daily and Recording Raingauges – Catchment 57006

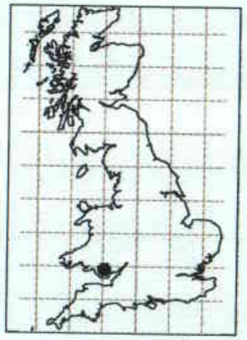


One grid square equals 10km x 10km

Figure C.4a

Daily and Recording Raingauges – Catchment derived from DTM at (305250,191000)





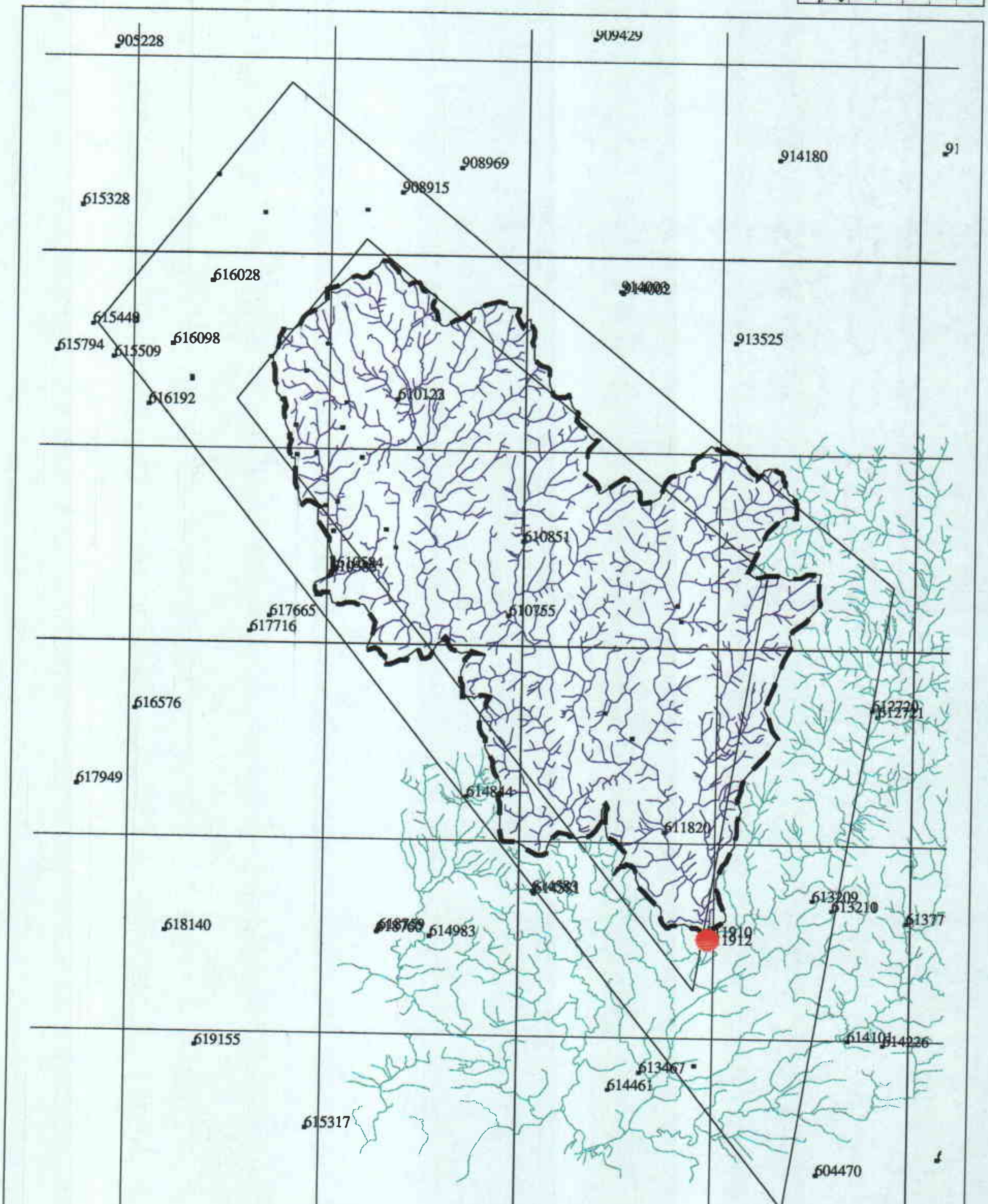
102.57 sqkm catchment area
2208.15 SAAR 1941–70
231.05 sqkm buffer area
2320 m buffer distance

One grid square equals 10km x 10km

Figure C.4b

Daily and Recording Raingauges

Catchment 77002



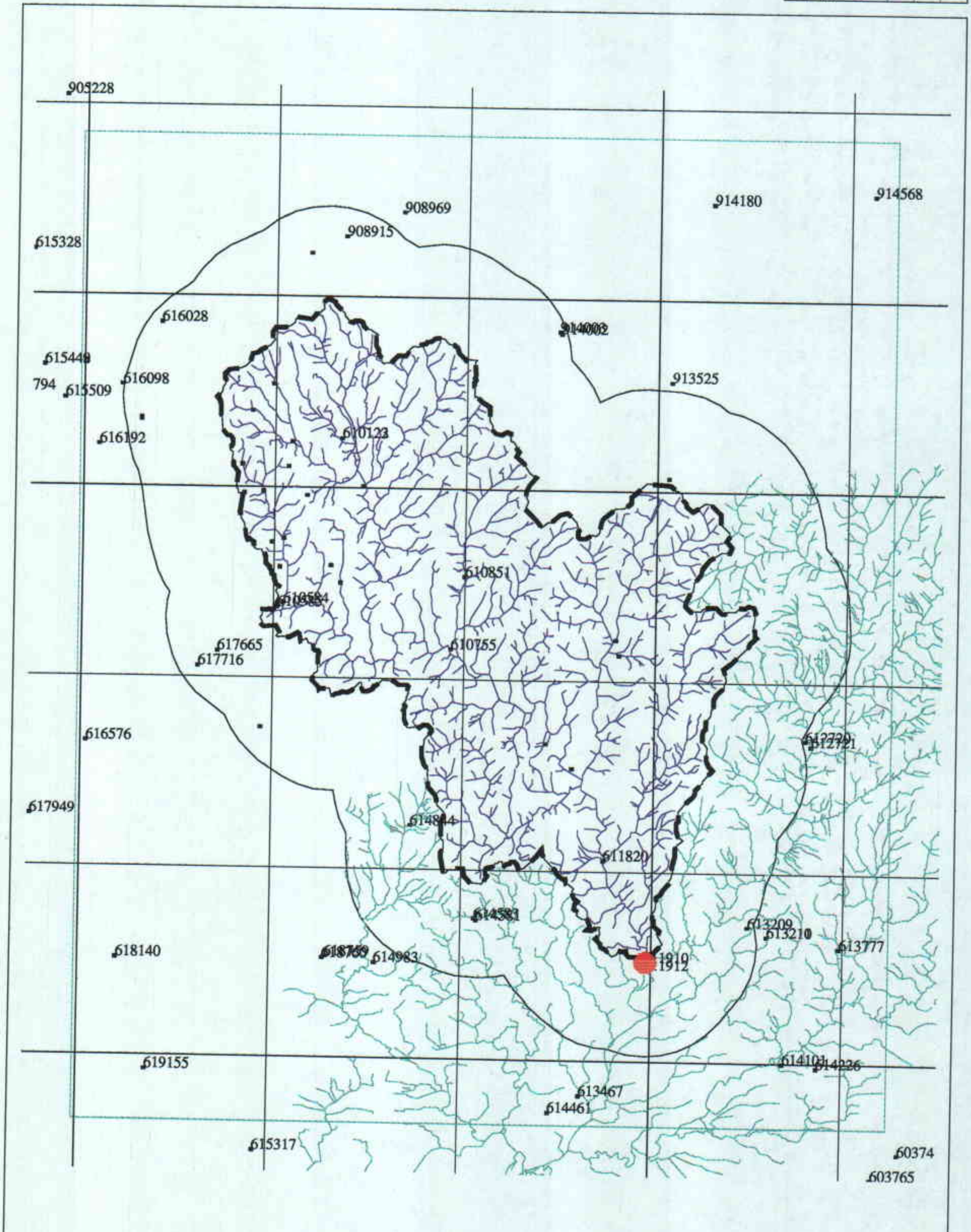
One grid square equals 10km x 10km

Figure C.5a

Daily and Recording Raingauges
Catchment derived from DTM at (339700,575250)

495.85 sqkm catchment area
1506.41 SAAR 1941-70

1115.36 sqkm buffer area
4930 m buffer distance

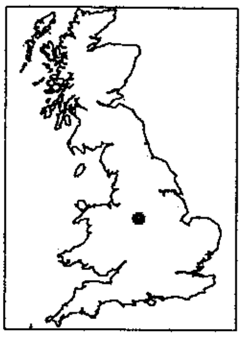


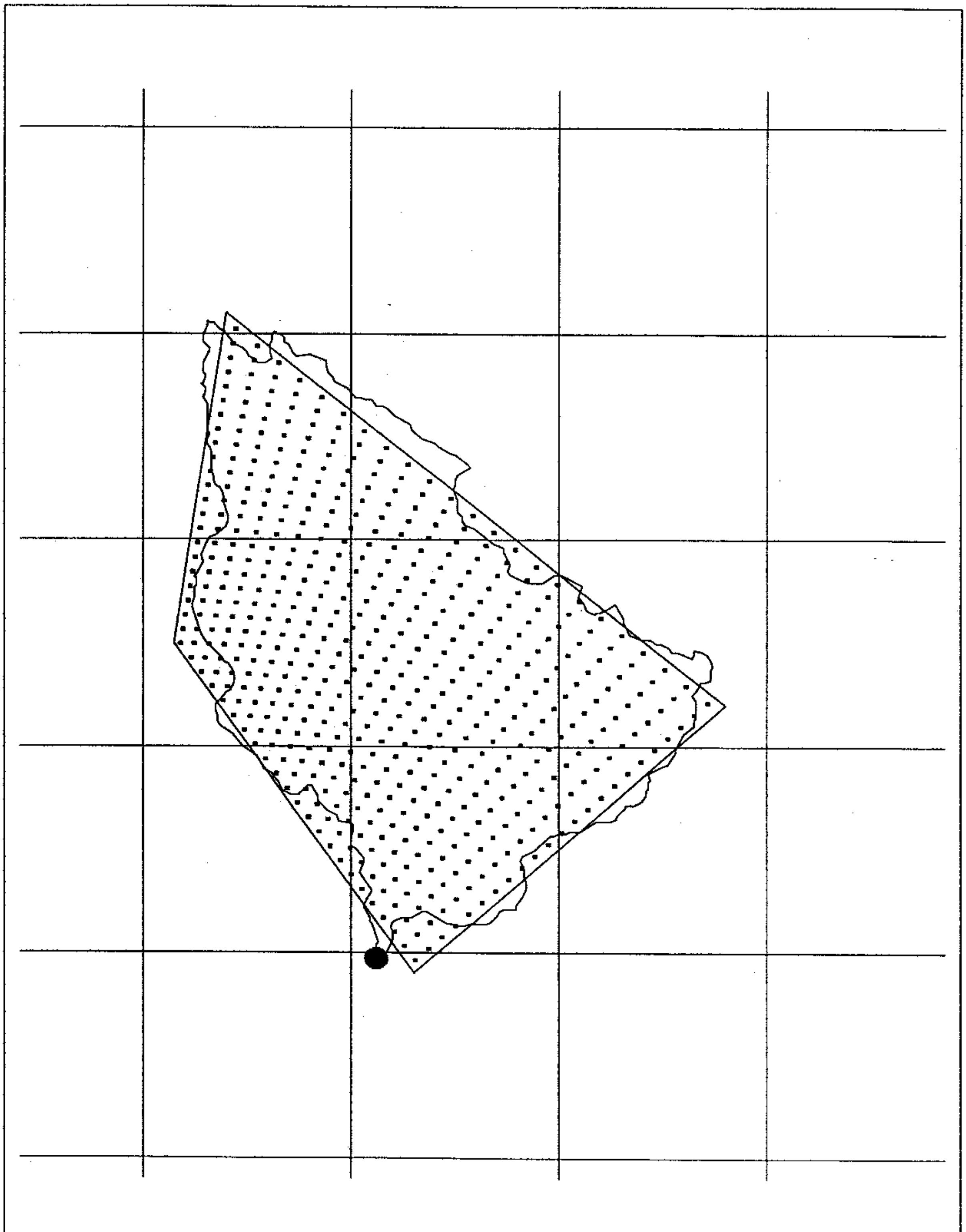
One grid square equals 10km x 10km

Figure C.5b

Meshpoints for
Catchment 28008

529 Meshpoints



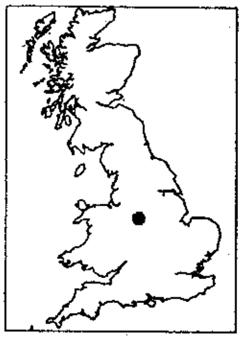


One grid square equals 10km x 10km

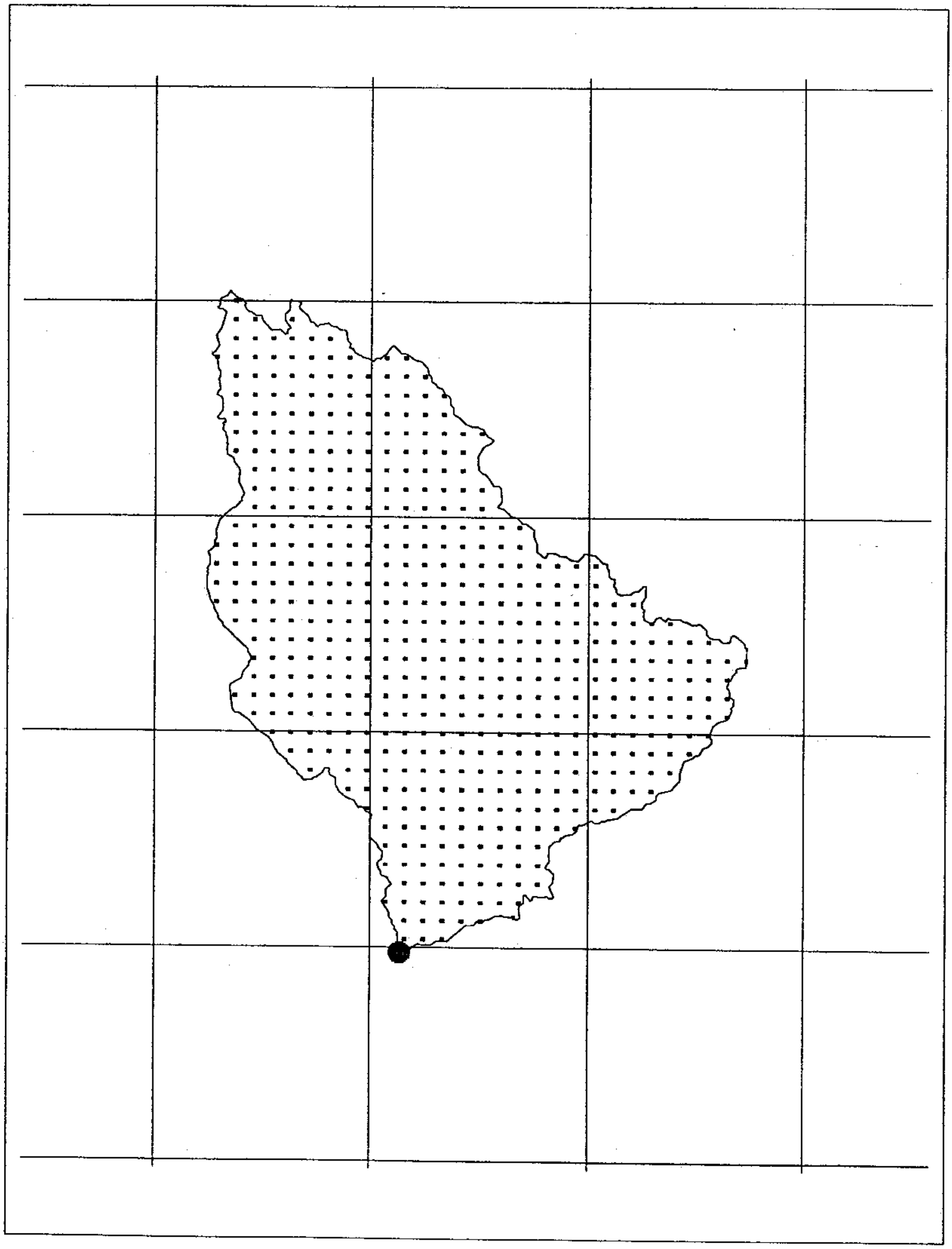
Figure C.6a

Meshpoints for

Catchment derived from DTM at (411350,339750)



522 Meshpoints

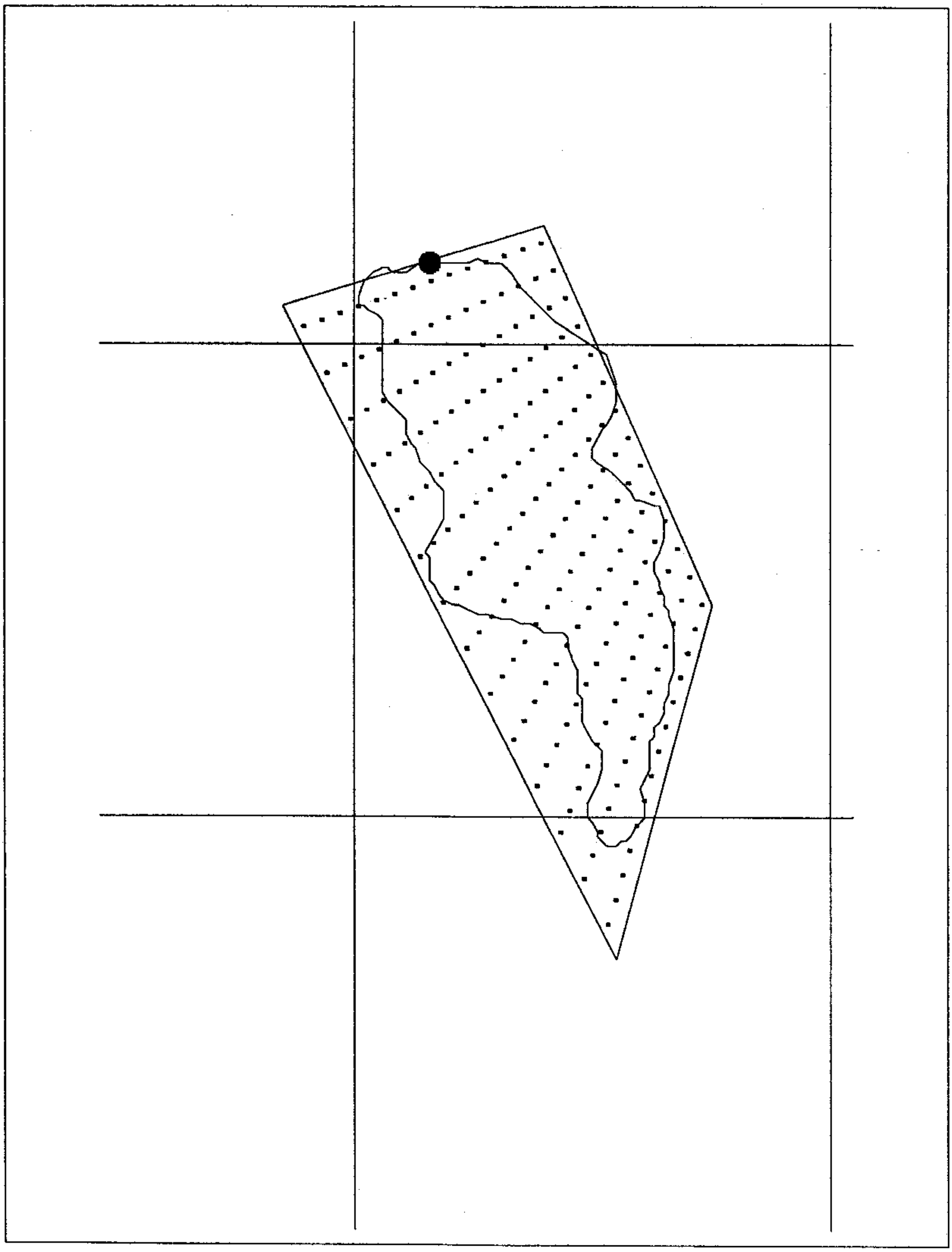


One grid square equals 10km x 10km

Figure C.6b

Meshpoints for
Catchment 39005

196 Meshpoints



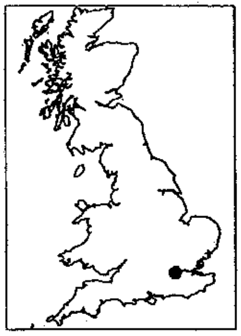
One grid square equals 10km x 10km

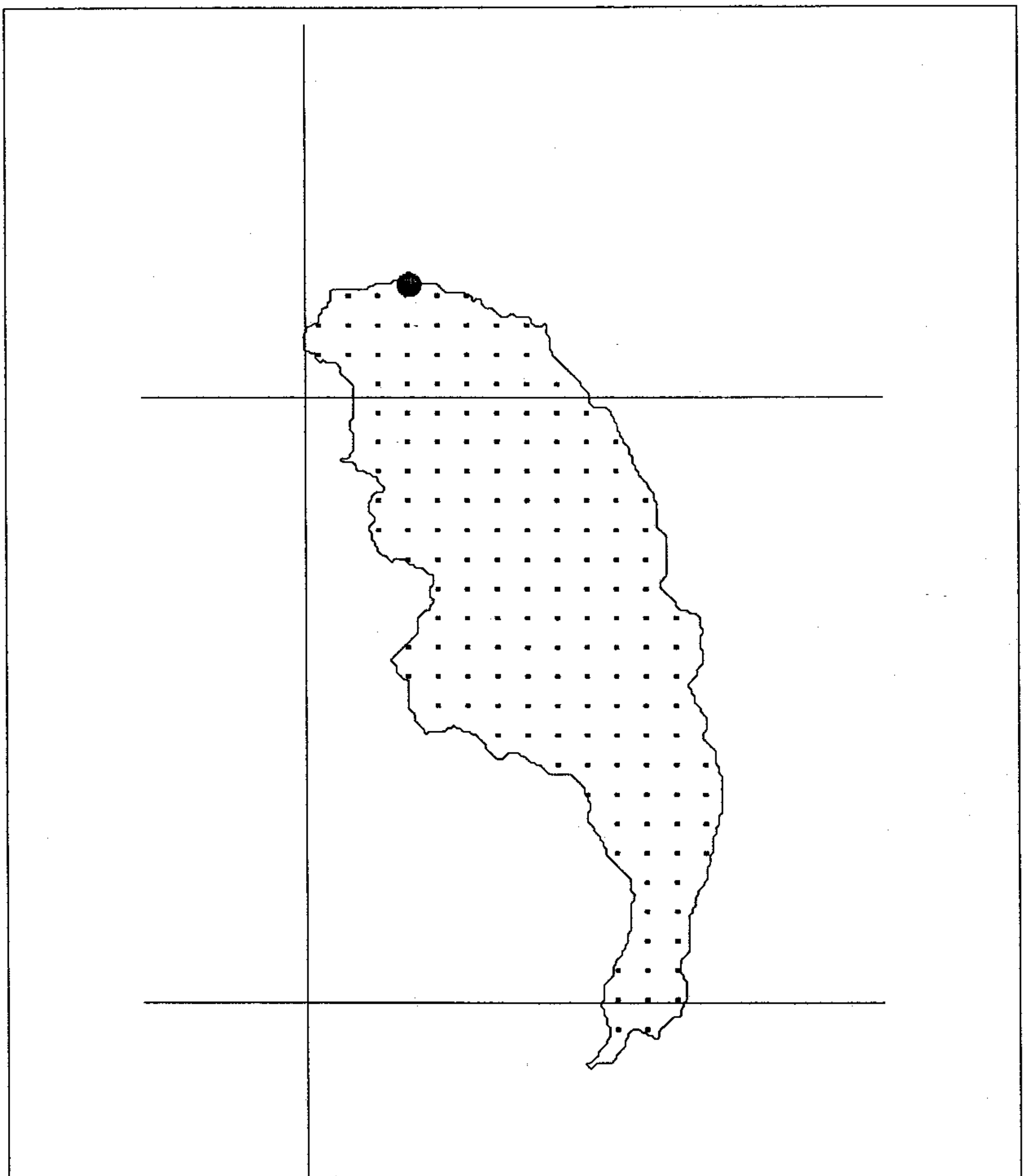
Figure C.7a

Meshpoints for

Catchment derived from DTM at (521700,171850)

169 Meshpoints

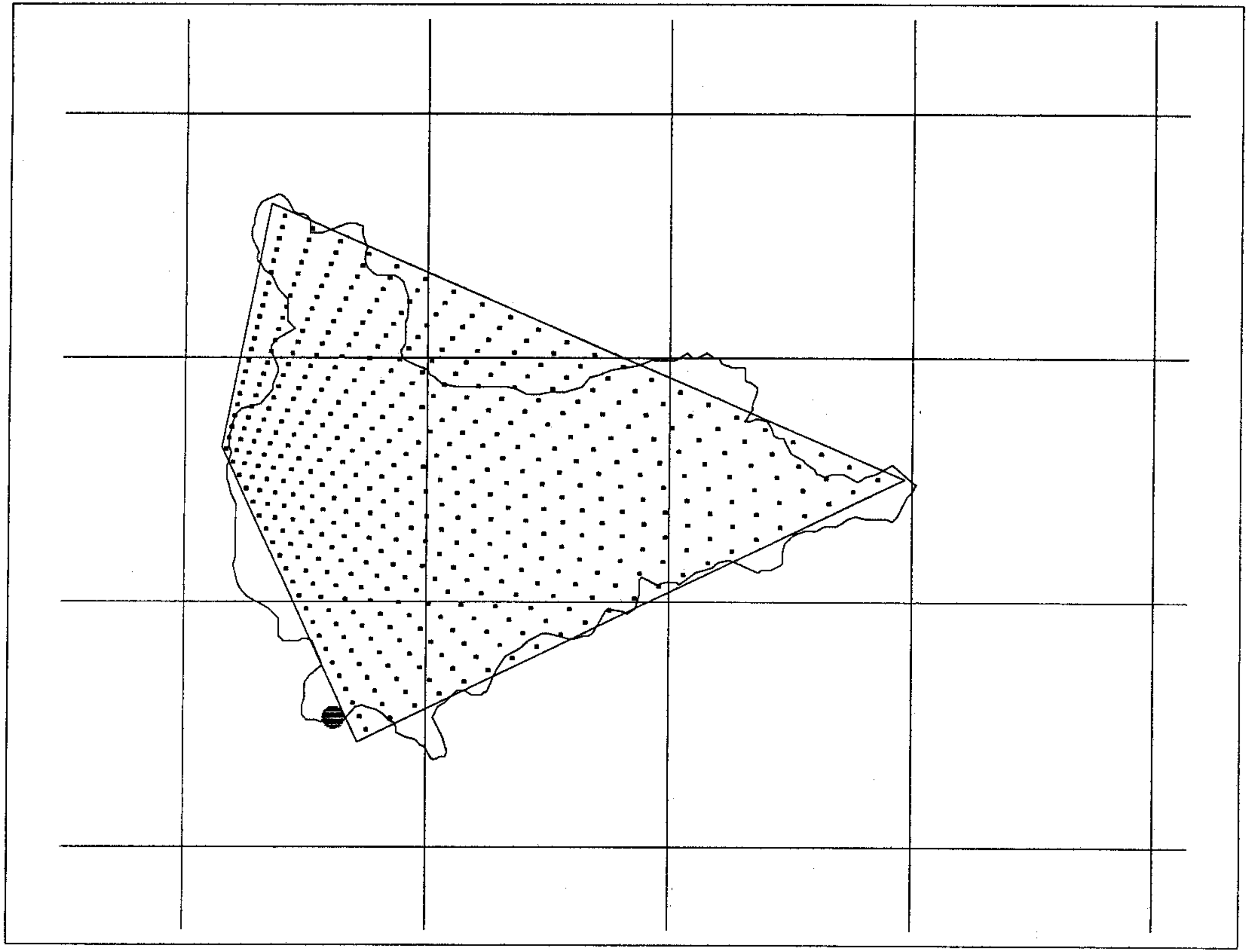


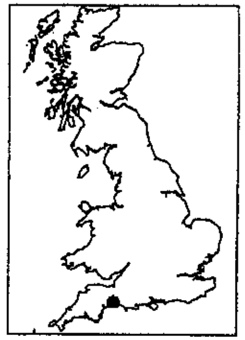


One grid square equals 10km x 10km

Figure C.7b

Meshpoints for Catchment 45004



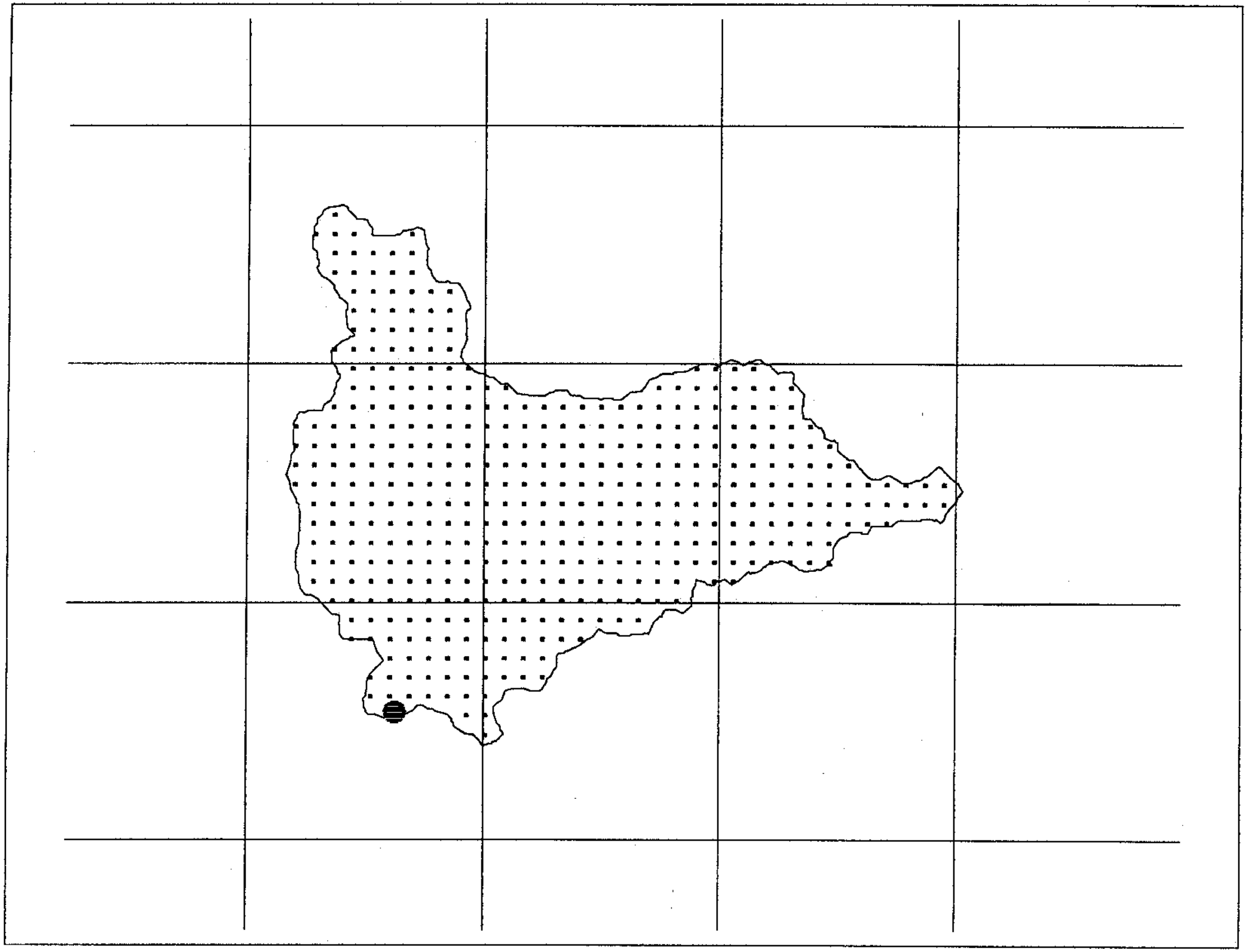


484 Meshpoints

One grid square equals 10km x 10km

Figure C.8a

Meshpoints for Catchment derived from DTM at (326250, 95400)

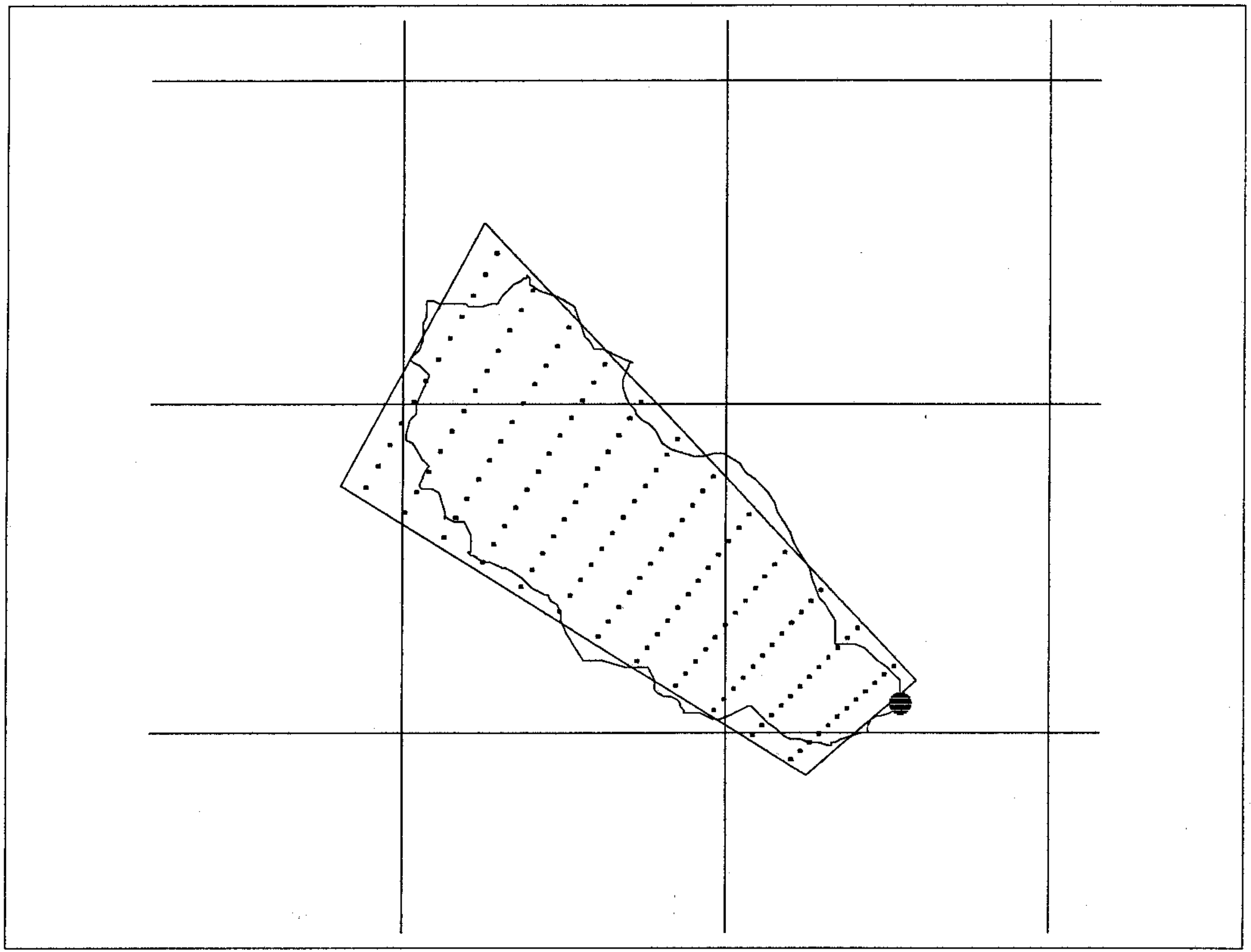


435 Meshpoints

One grid square equals 10km x 10km

Figure C.8b

Meshpoints for Catchment 57006

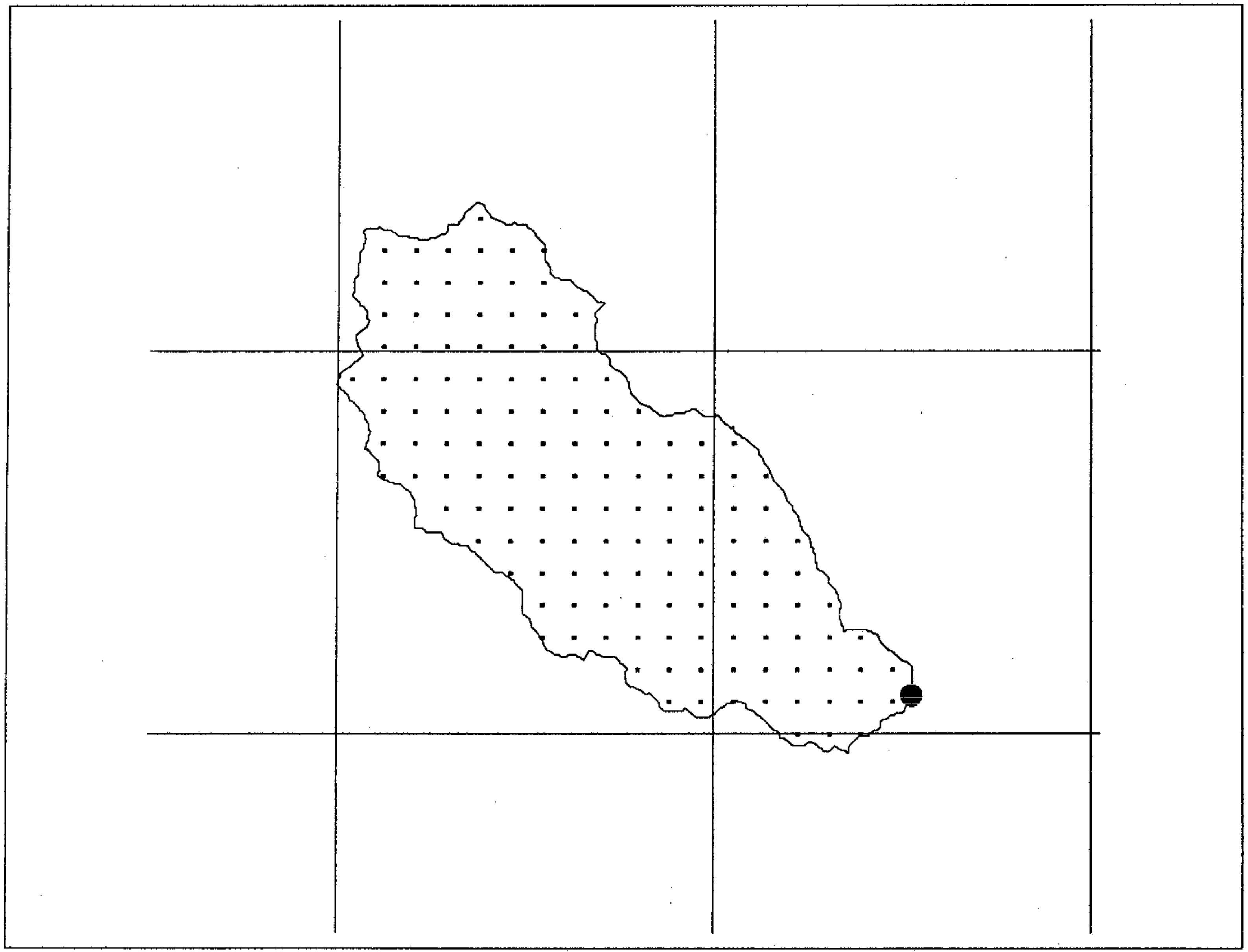


144 Meshpoints

One grid square equals 10km x 10km

Figure C.9a

Meshpoints for Catchment derived from DTM at (305250,191000)



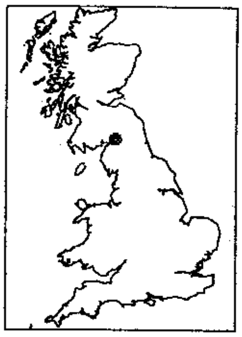
143 Meshpoints

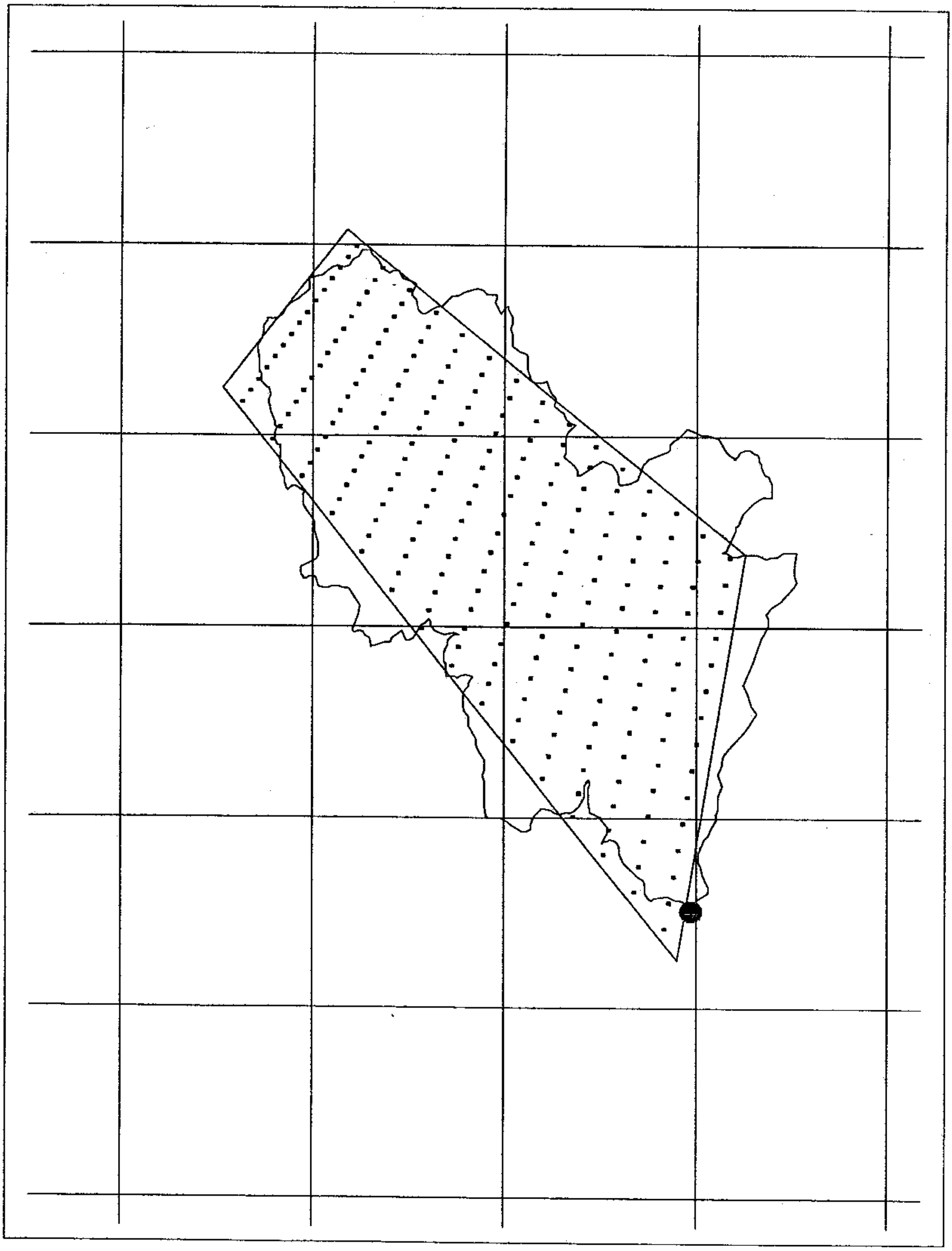
One grid square equals 10km x 10km

Figure C.9b

Meshpoints for
Catchment 77002

225 Meshpoints





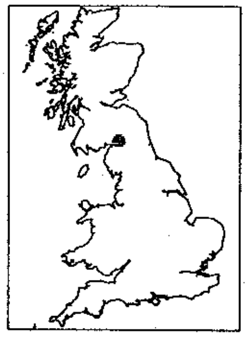
One grid square equals 10km x 10km

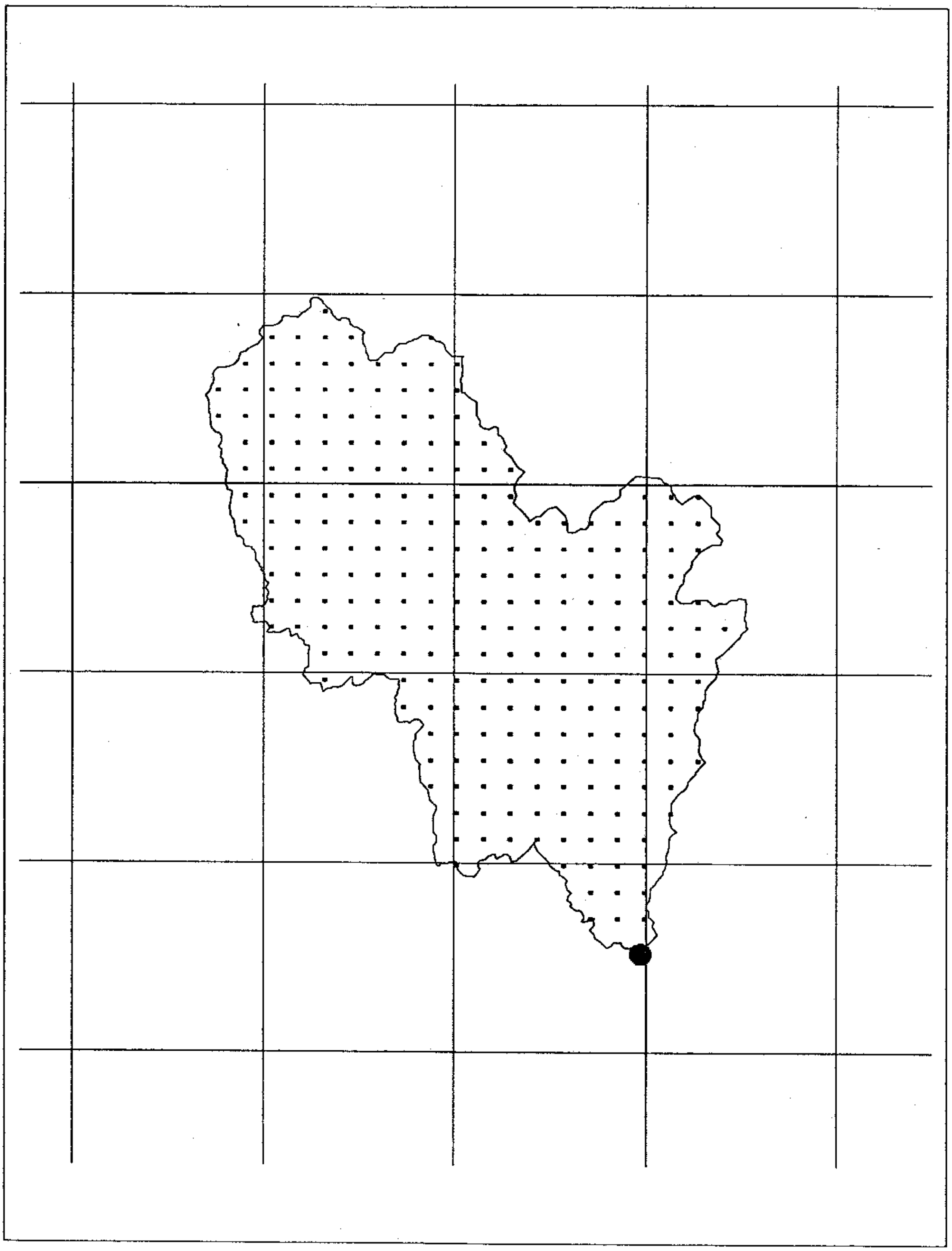
Figure C.10a

Meshpoints for

Catchment derived from DTM at (339700,575250)

256 Meshpoints





One grid square equals 10km x 10km

Figure C.10b

Appendix D

Results from Testing Sensitivity to Buffer Distance

The following tables summarise catchment average rainfall results for varying buffer distances for each catchment. The first column shows results using raingauges inside the catchment only, in the other four columns the area is enlarged by 1.5, 2.25, 3.5 and 4.5 times respectively for the raingauge search. For the conventional method a maximum distance is allowed from a mesh point to any of the gauges in its triangle provided there are at least three working gauges; therefore for a catchment with very good raingauge coverage the more distant rainfall will be ignored for the calculations (compare the last two rows in the following tables showing number of daily gauges with available rainfall against number of gauges actually used). The conventional method recommends that the 'outer box' be 2.25 times the tightfitting quadrilateral area; the results here confirm this to be a sensible factor for the new method when choosing the buffer distance, although they also demonstrate that there is little sensitivity to the enlargement factor.

Table D.1 Results for catchment 28008

	catchment area	catchment area * 1.5	catchment area * 2.25	catchment area * 3.5	catchment area * 4.5
catchment average mean rainfall (mm) for 1985-92	2.72	2.74	2.74	2.74	2.74
standard deviation	4.96	4.96	4.90	4.90	4.90
range maximum (mm)	70.75	71.97	71.63	71.18	71.28
catchment average rainfall 1985 (mm)	983	991	990	990	990
1986	1163	1171	1166	1166	1167
1987	1006	1011	1016	1016	1016
1988	1092	1091	1091	1093	1093
1989	904	915	916	916	917
1990	986	992	989	989	989
1991	779	784	789	789	788
1992	1039	1047	1043	1043	1043
total number of raingauges in buffered area	46	68	102	146	198
number of raingauges with daily rainfall	2-5	3-7	8-11	14-20	20-27
number of daily gauges used in calculations	2-5	3-7	8-11	11-16	13-16

Table D.2 Results for catchment 39005

	catchment area	**catchment area * 1.5**	**catchment area * 2.25**	**catchment area * 3.5**	**catchment area * 4.5**
catchment average mean rainfall (mm) for 1985-92	1.63	1.63	1.63	1.64	1.64
standard deviation	3.69	3.67	3.66	3.68	3.69
range maximum (mm)	45.95	45.71	45.52	44.52	44.60
catchment average rainfall 1985 (mm)	599	599	599	601	602
1986	653	651	652	656	656
1987	661	660	660	662	662
1988	569	569	569	570	570
1989	554	552	551	550	550
1990	513	511	512	511	511
1991	555	553	553	554	554
1992	671	665	665	676	677
total number of raingauges in buffered area	17	25	30	44	61
number of raingauges with daily rainfall	2-7	3-8	4-10	5-15	8-18
number of daily gauges used in calculations	2-7	3-8	4-10	5-15	7-17

Table D.3 Results for catchment 45004

	catchment area	catchment area * 1.5	catchment area * 2.25	catchment area * 3.5	catchment area * 4.5
catchment average mean rainfall (mm) for 1985-92	2.58	2.61	2.61	2.61	2.61
standard deviation	5.34	5.41	5.40	5.40	5.40
range maximum (mm)	59.46	60.06	58.67	58.45	58.47
catchment average rainfall 1985 (mm)	951	957	956	955	956
1986	1152	1159	1159	1158	1159
1987	892	896	900	901	901
1988	915	926	927	927	928
1989	999	1009	1011	1010	1010
1990	857	870	872	871	871
1991	894	907	910	910	910
1992	892	904	905	904	904
total number of raingauges in buffered area	30	42	89	138	176
number of raingauges with daily rainfall	10-12	13-17	19-30	28-41	36-50
number of daily gauges used in calculations	10-12	13-17	19-29	23-33	25-33

Table D.4 Results for catchment 57006

	catchment area	catchment area * 1.5	catchment area * 2.25	catchment area * 3.5	catchment area * 4.5
catchment average mean rainfall (mm) for 1985-92	6.50	6.51	6.43	6.44	6.42
standard deviation	11.97	11.91	11.68	11.71	11.65
range maximum (mm)	102.54	102.10	103.96	104.50	102.77
catchment average rainfall 1985 (mm)	2407	2421	2410	2408	2407
1986	2744	2750	2737	2735	2733
1987	2097	2109	2096	2097	2098
1988	2503	2514	2463	2462	2451
1989	2275	2272	2239	2242	2238
1990	2345	2349	2278	2281	2280
1991	2234	2218	2196	2198	2194
1992	2415	2386	2367	2381	2368
total number of raingauges in buffered area	15	18	25	34	41
number of raingauges with daily rainfall	1-3	2-4	4-7	6-10	7-12
number of daily gauges used in calculations	1-3	2-4	4-7	6-10	7-12

Table D.5 Results for catchment 77002

	catchment area	catchment area * 1.5	catchment area * 2.25	catchment area * 3.5	catchment area * 4.5
catchment average mean rainfall (mm) for 1985-92	4.55	4.55	4.55	4.56	4.56
standard deviation	7.33	7.31	7.30	7.31	7.31
range maximum (mm)	58.68	58.70	58.90	58.77	58.94
catchment average rainfall 1985 (mm)	1781	1780	1777	1778	1779
1986	1806	1802	1808	1806	1806
1987	1539	1543	1542	1548	1550
1988	1663	1666	1666	1678	1678
1989	1422	1416	1418	1421	1421
1990	1802	1799	1797	1793	1793
1991	1550	1550	1548	1558	1558
1992	1738	1734	1734	1743	1743
total number of raingauges in buffered area	27	33	45	78	98
number of raingauges with daily rainfall	4-7	5-9	7-11	12-19	14-21
number of daily gauges used in calculations	4-7	5-9	7-11	11-15	11-15