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RATIONALIZATION OF THE WESSEX WATER AUTHORITY RAINGAUGE NETWORK

by

P E O'CONNELL, R J GURNEY,
D A JONES, J B MILLER,
C A NICHOLASS (Meteorological Office)
and
M R SENIOR (Wessex Water Authority)

ABSTRACT

The network of gauges measuring daily and monthly rainfall totals within the Wessex Water Authority area has been evaluated in terms of both the standard of the data obtained from individual sites and the extent to which the overall network meets the requirements for rainfall information established in a survey of rainfall data usage. These requirements may be for a certain accuracy, either of rainfall quantities directly or of quantities, such as streamflow, modelled from rainfall data. Both cases have been considered in this study and systematic methods developed to calculate the accuracy of estimates of point or average areal rainfalls using data from any existing or hypothetical raingauge set. A method of rationalizing an existing network of daily gauges produced a number of possible designs for the Wessex area, each based on existing gauges but with additional sites suggested in areas of sparse coverage. One such design containing only two-thirds of the present number of daily gauges is shown to be at least as good as the current network in meeting requirements for rainfall data. Similar but less quantiative techniques suggest alternative networks of recording gauges. The costs of operating existing and rationalized networks within the Wessex Water Authority region are estimated, as are the costs of future rationalization projects.

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PREFACE

On 26 March 1976, a seminar was held at the Meteorological Office's College at Shinfield Park, Reading, on 'Meteorological Office Services (Other than Forecasts) for Water Management'. During the course of this meeting a lively discussion took place on the usefulness of rainfall data to the Water Authorities and to the Meteorological Office. As a result of this discussion, a study was initiated by the Department of the Environment to establish whether or not the present UK raingauge network satisfied the requirements of users. The first phase of this study (Phase I) commenced in August 1976, and was completed in May 1977. The work carried out under Phase I is described in an Institute of Hydrology report entitled "Methods for evaluating the UK raingauge network".

Following the completion of the Phase I report, it was recognised that a case study was required to demonstrate how a water authority network could be redesigned using the techniques developed in Phase I of the study. Following discussions with Mr K F Roberts, Chief Executive of the Wessex Water Authority, Mr S F White of the Department of the Environment invited the Wessex Water Authority (WWA), the Meteorological Office (MO) and the Ministry of Agriculture, Fisheries and Food (MAFF) to collaborate with the Institute of Hydrology in a study aimed at producing a redesigned network for the WWA area. All organizations accepted, and the study commenced in September 1977. A steering group for the study, chaired by Dr J C Rodda of the Water Data Unit,was set up on which the following organizations were represented: Central Water Planning Unit; Institute of Hydrology; Meteorological Office; Ministry of Agriculture, Fisheries and Food; Water Data Unit and Wessex Water Authority.

The Institute of Hydrology has been responsible for coordinating the study, for assessing WWA user requirements and for developing methodology and computer programs. The MO carried out an internal survey of user requirements, set up the archive of rainfall data for the study and were responsible for executing the computational work involved in producing the design networks for the WWA area. Inspections of all daily and monthly raingauge sites in the WWA area were carried out by MO assisted by WWA, who were also actively involved with IH and MO in producing the design networks described in Section 6 of this report. Information on the logistics and costs of network operation were also supplied by WWA. MAFF/ADAS contributed to the study by providing information on their user requirements.

5. NETWORK EVALUATION : OPERATIONAL ASPECTS

6. NETWORK DESIGN

7. NETWORK OPERATION : LOGISTICS AND COSTS

1. INTRODUCTION, SUMMARY AND CONCLUSIONS

1.1 General

The purpose of the present study is to evolve a redesigned and cost-effective network for the Wessex Water Authority area which will enable the costs of meeting users' requirements for rainfall data to be minimised and the data collection programme for the area to be streamlined and made more efficient. Such an objective raises the question of how the design of a raingauge network is to be approached. More fundamentally, it is perhaps pertinent to consider why it is necessary to collect rainfall data at all.

The principal users of rainfall data in the UK are the water authorities, the Meteorological Office which also provides data for other users, and the Ministry of Agriculture Fisheries and Foods (MAFF). Some of the principal uses made of rainfall data by each of these organizations are listed in Table 1.1, where a distinction is drawn between the use of rainfall data in real-time and in retrospect. Both the Meteorological Office and the water authorities require rainfall data in real-time, the former principally for making forecasts of future rainfall and for their verification, and the latter for flood forecasting and flood warning. Much of the hydrological design work undertaken by water authorities requires rainfall data as a primary input. Depending on the problem at hand, data from continuously recording gauges or from gauges providing daily or monthly rainfall totals may be required, frequently in computer compatible form. Networks of telemetering and recording gauges, and daily and monthly-read gauges are thus required to ensure that an 'adequate' description of the spatial and temporal variation of rainfall is achieved. The view of 'adequate' taken by the research hydrologist or meteorologist is that it is desirable to understand as far as possible the distribution of rainfall in time and space. In theory, there is no practical limit to the number of gauges required to achieve this 'adequate' description, as rainfall is characterized by high spatial variability.

A different viewpoint of what is 'adequate' may be held by the applied meteorologist, agriculturalist or water engineer. To them the purpose of a raingauge network is to provide rainfall data for decision-making, in weather forecasting for example, or for the management of crop-production or water resources. The objective of a raingauge network is then to provide rainfall data which will allow 'good' decisions to be made, where the 'goodness' of such decisions is measured in terms of the expected net benefits or losses deriving from them (the term 'expected' is used as such decisions will invariably be made under uncertainty, relying essentially on a statistical description of rainfall). It is here that the cost of acquiring rainfall data enters; clearly there comes a point beyond which the cost of acquiring more rainfall data cannot be justified in terms of the resulting increased benefits to the decision-maker. If sufficient information on costs and benefits are available, then the design of a raingauge network

Table 1.1 (Cont'd)

MAFF	Irrigation requirements	✓	-	-
MAFF	Field drainage design	✓	-	-
MAFF	Forecasts for crop diseases	-	-	✓
MAFF	Crop development and husbandry studies.	✓	-	-

1.2 Network design and operation

The extent to which a raingauge network provides an adequate representation of the distribution of rainfall in time and space is governed by the following major factors

(i) the type of rainfall

(ii) the density and configuration of gauges in the network.

(iii) the (time) resolution of the measuring equipment and procedures

(iv) how close the point measurements from a network are to true rainfall at these points.

The question of how best to distribute a network of gauges within an area will be considered as a network design problem: whether or not a network provides reliable measurements of point rainfall will be viewed as a problem of network operation. To approach the network design problem, some characterization of the statistical structure of rainfall in time and space will be required. If a network of gauges did not already exist in an area, then information about the statistical structure of rainfall would have to be transposed to the area in question from a similar area elsewhere, and a tentative network established to allow more detailed information to be assimilated. This is frequently the case in underdeveloped countries. In developed countries, however, rainfall networks have tended to evolve in a rather arbitrary manner, and while the existence of records of rainfall data for such networks allows the statistical structure of rainfall to be quantified, the extent to which this is achieved will depend on the extent to which the existing network captures the spatial variability of rainfall. For example, networks which have evolved over a period of time tend to be more dense near centres of population, where rainfall will not in general vary very much spatially, and less dense in areas of variable topography where rainfall varies most. Exceptions to this will occur for example when centres of population are sited at higher altitudes. Given a description of the spatial statistical structure of rainfall, the estimation errors for (ungauged) point and areal rainfall estimates can be established, and areas of deficient and superfluous accuracy (relative to user requirements) identified. This can then lead to a smaller network with a configuration more representative of the spatial variability of rainfall. Thus the essence of network design is a satisfactory characterization of the spatial statistical structure of rainfall.

Before attempting to characterize the spatial statistical structure of rainfall, it is necessary to consider whether rainfall generated by varying synoptic situations can be expected to exhibit varying statistical structures. For example, rainfall generated by convective cell activity tends to exhibit much more spatial variability than frontal rainfall. Accordingly, estimates of areal rainfall for the former rainfall type would, for a given network density, be expected methods in the first instance on a national scale.

Work on the Phase I study commenced with an extensive survey of user requirements for rainfall data within the UK, and principal users were identified within the Water Industry, the Civil Engineering Industry, the Agricultural and Meteorological sectors, public utilities, organizations concerned with law, insurance and health. Users were requested (a) to specify whether their requirements were for areal or point estimates,(b) to specify the duration of the interval over which totals were required and (c) to state the required accuracy (expressed either as a % or absolute error (in mm) not to be exceeded on a stated percentage of occasions, usually 95%).

Methods for evaluating the performance of the present UK network were developed and applied under two headings. Where a measured or estimated rainfall quantity formed the direct basis of some decision, this was deemed a direct use of rainfall data; where rainfall data only represented one input to a decision-making process involving a number of variables, perhaps represented by a model, this was classified as an indirect use. The corresponding techniques which were applied were referred to as direct or indirect methods.

The direct method consisted essentially of the following steps:

(i) select areas within the UK containing several hundred daily-read raingauges:

(ii) fit a spatial correlation function describing the decay of correlation with distance within the area;

(iii) use the fitted correlation function to derive optimal weighting procedures for estimating point and areal rainfall over various durations.

Two areas were selected, one in the East of England, containing approximately 700 gauges, and one in the North of England containing approximately 1150 gauges. Three categories of daily data (reflecting days with different amounts of rainfall) were analysed in addition to monthly and annual data. Once correlation functions had been fitted for these areas, estimation errors (expressed as the root mean square error divided by the standard deviation of the rainfall quantity x 100%) were then derived for (i) an optimal point interpolation procedure which assumed that the network was arranged on a triangular grid and which used three gauges to interpolate to a point, (ii) an areal averaging procedure which assumed that the network was arranged on a square lattice and that the area itself was square. Relationships between the estimation error and the spacing of raingauges on a regular grid could then be specified; by entering these relationships with the required percentage root mean square error, the gauge spacings required to meet particular user requirements could then be established. These required spacings were then compared with a map of observed average inter-gauge distances to determine if various user requirements were satisfied. With some exceptions, this was mainly found not to be

The total number of recording gauges (including telemetering gauges) currently operating in the WWA area is 70. Of these, 39 are sited at registered MO daily sites and are principally tilting siphon gauges; however, the data from these gauges are not routinely digitised or archived. Of the remaining 31 gauges, approximately 20 are telemetering gauges while the balance can be interrogated by telephone or radio link.

1.5 *Summary and conclusions*

The present report is the result of a collaborative study between the Institute of Hydrology (IH), the Meteorological Office (MO) and Wessex Water Authority (WWA) to arrive at a rationalized network for the WWA area. Work commenced with a survey of user requirements; IH were responsible for evaluating WWA requirements which were delineated by region where possible, while MO and the Ministry of Agriculture, Fisheries and Foods (MAFF) conducted their surveys to establish their own internal requirements. User requirements were specified as described in Section 1.3 for the Phase I study. The accuracies provided by the present network were evaluated using optimal point and areal estimation procedures to provide guidelines at the design stage, and to enable unreasonable user requirements to be identified. Detailed descriptions of the surveys of user requirements are provided in Section 2.

The methods employed for evaluating the present WWA network and proposed design networks are described in Sections 3 and 4; following PhlR, they may be categorized as direct and indirect methods. In the case of the former, the approach taken has been to identify the spatial correlation structure of rainfall over the WWA area on a localized basis for each (5 km x 5 km) grid square using gauges lying within a surrounding (35 km x 35 km) area. Based on this description of the correlation structure, an optimal point interpolation procedure has been developed whereby any number of irregularly spaced gauges can be used and the interpolation error quantified.

Empirical interpolation at an ungauged point is frequently carried out simply by using the recorded rainfall at a nearby gauge. The accuracy of this technique has been compared with that of the optimal procedure, illustrating the higher accuracy obtained from the latter procedure.

A technique for quantifying the accuracy of areal rainfall estimates has also been developed: any arbitrary shape of area and any irregular configuration of gauges can be treated. This procedure has been applied to a number of regions within WWA where specific areal accuracies are required. An empirical method of areal estimation is also considered.

In Section 4, some possible bases for the use of indirect methods of network evaluation within the WWA area are considered; only daily rainfall-runoff modelling of six selected catchments has, however, been feasible. A similar approach to that used in PhlR has been adopted, with the CLS model being used to describe the daily rainfall-runoff process. The results obtained suggest that reasonable accuracy for streamflow estimation can be obtained from the present network,

(iii) The active participation of the Wessex Water Authority in evolving Design Networks has contributed considerably on the practical aspects of the design; a similar water authority input is to be hoped for in future studies.

(iv) The proposed Design Networks offer much more uniform accuracies for areal rainfall estimates than the present network.

(v) The accuracies given by the optimal point interpolation procedures described in this report are considerably better than the accuracies of procedures currently used in practice.

(vi) Users should not be relied on solely to specify their accuracy requirements; the accuracies provided by an existing network should be used to provide further guidelines, as described in this report.

(vii) For six selected catchments in the WWA area, the accuracy with which daily streamflow could be modelled using a lumped daily rainfall input was found to be satisfactory; however improved results could be expected on some catchments with a better spatial distribution of gauges.

(viii) Sufficient recording raingauge data, archived in computer compatible form, are not currently available in the UK to enable quantitative design procedures for networks of recording gauges to be developed.

(ix) Provision should be made in the future for a further Phase of this study to obtain feedback on the implementation of a Design Network, thus allowing the present design procedure to be modified if necessary.

Somerset Division requirements.

The uses of rainfall data highlighted by each interviewee were tabulated, enabling the critical uses to be identified and the areas where data are required for each purpose to be delineated.

2.2.2 Basic considerations

Many general points arose in the course of the interviews and are explained below, whilst the detailed discussion of particular uses of rainfall data is left to the next section.

The first point which was made by many interviewees is that rainfall is used as general background information in many phases of water engineering, without any further calculations being made with the data. This usage places minimal requirements on the network. Some of the more stringent data requirements could possibly be satisfied by a local enhancement of the network for perhaps a few years only, provided that the data from this short term network can be related to long records of historical data collected from a standing network of gauges. This suggests the possibility of having a basic network which would give sufficient information for many purposes including feasibility studies and storm analysis while forward planning would identify sites for development in sufficient time for an enhanced network to be deployed to provide more accurate design information. However, this principle must be used with caution, as there is no replacement for long records, particularly when the return periods of design events have to be estimated.

The present network of gauges was generally thought to give data of sufficient accuracy for daily and longer duration rainfall. However, many interviewees thought that more recording raingauges giving shorter duration data should be installed. Here the main problem is the assessment of storm rainfall because under storm conditions, common in the Wessex area, intense rainfall may be very localised. A number of extra recording raingauges have been brought into service by WWA in recent months.

2.2.3 Detailed description of data uses

A number of the more important uses of rainfall data were identified and are detailed below. An attempt has been made to assess the accuracy required for each use, though figures quoted must necessarily be subjective. The accuracy required is expressed as that error which should not be exceeded on 95% of occasions which, assuming normally distributed errors, corresponds to two standard errors. Both percentage and absolute errors were quoted. The conversion between these two figures was made by assuming an average of about 170 rain days per year and 1000 mm annual average rainfall in the upland areas which are generally of interest.

(d) River regulation

Many surface reservoirs will in future be used for river regulation; groundwater supplies may also be used in this way. A model of a catchment (upstream and downstream of the reservoir) could be used to forecast natural flows as an aid to deciding on reservoir releases (or groundwater abstractions) required to meet target flows. The model would be run in real-time and use telemetered rainfall and flow data, although historic daily rainfall data would be required during the design stage.

Requirements for designing regulation schemes are similar to yield assessment except that the coverage would have to extend over the whole catchment, not just the headwaters. In addition the chalk catchments of the Avon and Dorset Division and the Bristol Avon catchment may use groundwater for regulation. There is a possibility, in the very long-term, of regulation being introduced anywhere in the region, but only 3 catchments are thought to be possible candidates for such schemes in the foreseeable future: the River Tone, down to Bridgwater (the most likely), the Bristol Avon (down to Bath) and the Hampshire Avon. For operation, telemetering raingauges would be required. Similar equipment is already being installed for flood warning and some sites could be used for regulation purposes also.

(e) Leaching of waste tips

Any waste tips situated over aquifers are likely to cause pollution by means of contaminated rainfall percolating to the groundwater. Old quarries are frequently used for waste disposal and they could be a cause of such pollution in the Mendips (Carboniferous Limestone) and the Cotswolds (Oolites). However tips might be established at sites other than quarries and the whole of an aquifer must be considered at risk. Two types of rainfall data are required for studies of leaching: long-term averages to determine average leaching rates and statistics of intense storms to determine peak rates of leaching.

The data required are average monthly rainfalls and depth-duration frequency statistics, both for points anywhere over aquifers.

(f) Flood warning

Wessex Water Authority's policy is to install telemetry schemes, where necessary, to provide rainfall measurements in real time for flood warning purposes. The Bristol Avon scheme has been installed and is expected to become fully operational during 1978/79. Somerset will probably have an operational system by 1980 and the Avon and Dorset Division by 1983. The MO are installing a low-power radar at Upavon which is scheduled to be operational by December 1978. This will provide additional qualitative information for much of the region - the whole of the Bristol Avon Division and about half of the Somerset and the Avon and Dorset Divisions. Until the telemetry schemes are operational WWA will rely on the present mixture of teletone raingauges, "alarm-out" gauges and reports during storms from selected daily rainfall observers.

accuracy of about 2 mm. If these error limits are adhered to on 95% of occasions the standard error of the estimated catchment fall is then 1 mm. The method used is to distribute the daily falls according to the hourly recording gauge totals. The catchment rainfall is determined by the iso-percentile method, where each gauge total is weighted in proportion to its annual average rainfall.

For the derivation of the unit hydrograph, a short period of recording raingauge data and flow data may be sufficient; two wet winters suffice in most cases, provided they contain a sufficient number of flood events. Clearly, the more flood events available, the more reliable the estimated unit hydrograph becomes. While for some investigations it may be possible to deploy a recording raingauge temporarily to collect sufficient data, there are a number of other factors which require that a standing network of recording raingauges be maintained in any case:

(1) Having derived the unit hydrograph, depth-duration-frequency relationships are also required to estimate the flood of the desired return period.

(2) Land drainage work is often started after a large flood and the design engineers, and others, normally test the proposed design against this flood. The test requires short duration rainfall data, and flow data.

(3) The Institute of Hydrology is often requested by water authorities to analyse past flood events. The analysis requires the relevant rainfall and flow data.

Thus, while a component of design work may be satisfied by deploying recording gauges on a temporary basis, such gauges could not meet any of the above three requirements.

In summary the flood design methods used require a recording gauge network, supplemented on occasions by temporary gauges, and sufficient daily gauges to enable the daily catchment rainfall to be estimated to with ± 2 mm on days when more than 5 mm of rain falls. The catchment areas involved are less than 100 km^2 and often small enough for the rainfall to be considered as "point rainfall". This information is required throughout the region, except for the Chalk areas in the Avon and Dorset Division.

(h) Urban drainage design

The design methods used are those of Road Note 35 (Dept. of the Environment, 1976), that is the Lloyd-Davis or Rational Method for small areas and the TRRL method for larger developments. Both methods use rainfall statistics applicable to the particular geographical location based on the Flood Studies Report (NERC, 1975).

Road Note 35 gives a set of profiles for use with the TRRL method or, alternatively, profiles from particular storms may be used. Recording raingauge data are required, with durations as short as a few minutes

Within each category a convenient sub-division is provided by the time interval over which rainfall totals are required; these range from periods of less than an hour up to monthly or annual totals. Although the present survey was directed to the use of data from the WWA area, the replies showed that while most MO users do not have specific requirements in the WWA area, they have general requirements which it would be appropriate to introduce into a raingauge network rationalization exercise in any water authority area.

2.3.2 Rainfall forecasting and forecast verification

Three branches within the MO, MO 2 (Central Forecast Office), MO 6 (Defence Services) and MO 7 (Public Services) currently have a responsibility for making rainfall forecasts, and each branch uses data from MO synoptic stations in the WWA area. These stations report rainfall as part of their hourly observation, the rainfall being measured primarily by distant-reading tipping bucket gauges. While these reports do not form part of the WWA archived data set, the readings may be used by the Authority in near real-time and each station has a registered daily check gauge, records from which are archived.

The Central Forecast Office has an overall responsibility for forecasts of heavy or prolonged moderate rain, but MO 6, through Upavon and its outstations, and MO 7, mainly through the Southampton Weather Centre, have a similar responsibility in the WWA area. They are required to provide warnings of severe weather to many organisations, including the water, Police, Ministry of Defence, local government and building authorities. Although not appropriate at the small civil airports within the WWA area (Bournemouth (Hurn) and Bristol (Lulsgate)), MO 7 have to provide warnings of heavy rain to the major airports, where severe weather can affect landings, take-offs and ground movements.

For these purposes, hourly rainfall rates are required in near real-time, both from within the WWA area and also from areas outside, especially in the up-wind direction. There is a general dissatisfaction within the MO with the sparse network of hourly recording gauges - there are no such gauges with data easily accessible to the MO over most of the WWA area, except in the extreme east and north. More data of this nature, from additional gauges, perhaps automatically interrogated, in the centre, south and west of the WWA area would assist in providing better forecasts. These extra gauges would still be required in the event of the future implementation of a weather radar system and they could be used to provide the forecaster with near real-time calibrations of the radar system.

Those branches which make rainfall forecasts as described above also use data from MO gauges, recording hourly or 12-hourly, to verify their forecasts. In addition, two other branches use measured rainfall data to verify their forecasts. MO 11 are responsible for developing numerical forecast models which include forecasts of rainfall and MO 13 make operational long-range forecasts.

Weekly Weather Report Stations. On the 15th day of each month, monthly rainfall totals (for the previous month) from a much denser network of so called 'SMD stations' are used to update the estimates.

Non-routine rainfall enquiries are received from many sources including the building/civil engineering industry, legal and insurance businesses and the water industry. They are answered with both routinely available and specially acquired data. Many enquiries involve daily or monthly totals at specified points and it is necessary to provide data from the actual site (although interpolation to intermediate points is permissible in some cases); an observational accuracy of ± 5% for monthly and ± 10% for daily rainfall at a point is desirable. In particular, the legal profession will accept interpolated rainfall estimates only if there is attendance in court by the person who made the interpolation. Insurance companies will only accept data from a gauge if it is within 5 km of the point of interest, otherwise it is necessary to provide a gauge and observer at the event for which the insurance cover is being provided. Figure 2.3 shows the areas within Wessex, which were not within 5 km of a registered daily gauge in 1977.

For the above purposes, it would be helpful to maintain at least the present network of daily and monthly gauges, and the enquiry section suggests that an additional registered gauge in the Avon Docks area would be very helpful to them. For enquiries involving periods of less than a day the situation is more difficult as the network of recording gauges is much more sparse than the network of daily gauges. An additional problem is that the charts from the majority of gauges are kept by the water authorities and private observers and are available only on request. Figure 2.4 shows the distribution of recording gauges in the WWA area, and differentiates between those for which some data are collated by MO, and those which are classed as 'unregistered' and whose data are kept by the water authority, local authority or private observer.

The Climatological Services Branch (MO 3) answer any enquiries about climate, or weather on particular dates which include information about rainfall. (Enquiries involving rainfall only are passed to MO 8c). The enquiries are similar to those reaching MO 8c, coming from legal and insurance sources, leisure and building industries etc. To answer them, the daily and monthly raingauge network is used; a desirable accuracy for point rainfall is ± 20% for daily totals. (As before, interpolation is not usually acceptable for legal enquiries). Many enquiries involve rainfall intensity. For these enquiries it is desirable to be able to estimate the intensity of rain to ± 20%, which is beyond the scope of the present recording raingauge network.

Forecast Offices answer enquiries that mainly involve present weather conditions, so that use is made of data from hourly, 6-hourly and 12-hourly reporting stations. It is felt that a more evenly distributed network of such stations, and a standardisation of reporting times would significantly improve the service which the Forecast Offices can give.

involves monthly totals, so that for this purpose daily gauges read less frequently would be acceptable. Figure 2.5 shows the stations in Wessex which were still open in 1977 and which have continuous records of over 30 years in length.

The MO Radar Research Laboratory at Malvern are developing a radar network in Western England (with radars being installed soon at Camborne (Cornwall) and Upavon (in Wessex), and at a later date at Clee Hill (Shropshire) and Hameldon Hill (Lancashire)), which will be used to provide rainfall measurements over much of England and Wales in real-time. In connection with each radar, data from recording gauges will be used to develop a climatology of calibration factors (the relationship between gauge and radar-measured rainfalls). MO sites and those at Cannington/North Moor and Weymouth/Winfrith within the WWA area will be used. For some special studies, data from the daily gauge network will be used as well, although 24 hour data will smooth out many of the variations in the calibration factor. However, it is expected that these data will provide a guide to the range over which quantitative radar measurements are acceptable. Some hourly measurements made at local Meteorological Offices (as described before) will be used for real time assessment of the reliability of the radars. The daily gauge network requirement for these purposes is 1 gauge per (10 km x 10 km) square but with 1 per (5 km x 5 km) square in regions of variable topography (and in other parts if possible).

2.4 The use of rainfall data from the Wessex Water Authority area by the Ministry of Agriculture, Fisheries and Food

2.4.1 Introduction

The Ministry of Agriculture, Fisheries and Food (MAFF), has an interest in the gauging of rainfall at a number of levels, mainly through its Agricultural Development Advisory Service (ADAS). Although much of the use of rainfall data is for background information, a considerable number of trials or experiments take place each year requiring quantitative rainfall data either from the national network or from specially installed gauges.

MAFF/ADAS has some responsibility for flood warning and flood design and this is discussed in Section 2.4.2. The Ministry's more general requirements for rainfall data are described in Section 2.4.3 and this is followed by detailed descriptions of the use of rainfall by some of the scientific services.

2.4.2 Flood warning, land drainage and flood protection

MAFF has a general responsibility for flood warning, land drainage and flood protection. Responsibility for the implementation of permanent works and warning systems rests with water authorities, internal drainage boards and local authorities, and government grants are available towards the cost of such schemes. Flood warning schemes require special networks of telemetering gauges, while, for flood estimation, long-term records of daily catchment areal rainfalls are required, together with data from at least one recording gauge. Further information on these requirements is given in Section 2.2.3.

(iv) efficiency of soil acting herbicides;

(v) the degree of poaching risk;

(vi) modified cultivation advice, eg direct drilling;

(vii) soil conditions for sub-surface operations like sub-soiling and moling.

(c) Machinery working

Rainfall data are required for investigations into the available machinery work-days at peak times related to specific soil types.

(d) Seasonal modification to systems of crop production

Weather is dynamic and continuously varying between and within seasons, so that it becomes very important to be able to provide advice on seasonal modifications to systems of crop production. These modifications are usually concerned with such aspects as soil management, agro-chemical use, forecast of disease risk and its control, etc. Specific advice is often sought in connection with:

(i) "blueprint" production systems;

(ii) modifications in respect of cultivation systems such as direct drilling; and

(iii) adjustments within grassland management systems related to specific soil types.

2.4.5 Biological requirements

The biological disciplines also have a requirement for detailed rainfall data. This need may best be met by siting recording raingauges and and other measurements more closely than at present, at say all Experimental Husbandry Farms and Experimental Horticultural Stations. Most Agricultural Research Institutes deploy sophisticated meteorological equipment and obtaining access to this and the wider use of such agro-meteorological records should be considered. Generally, the present raingauge network meets ADAS biologists' needs; more detailed micro-climatic (rainfall) data can only be assembled by siting instruments within the crop concerned or the locality under observation.

2.5 Overall summary of requirements

Wessex Water Authority's requirements for rainfall data are summarized in Table 2.1. Daily areal averages figure prominently among these requirements; details of the accuracies required are stated in terms of an absolute error (in mm) not to be exceeded on 95% of occasions, and have been estimated as far as possible through detailed consideration of the use made of the data. The WWA requirements for daily areal averages do not extend over the whole area; specific areas relating to between gauges should not exceed 10 km, with a 5 km spacing being preferable. Daily read gauges are preferred to monthly gauges. The estimation accuracies from any rationalized network should ideally not be less than those from the existing network.

The requirements of MAFF/ADAS are satisfactorily covered by the MO accuracy requirements given in Tables 2.2 and 2.3 under the heading of Agriculture. Again, these requirements separate into those for daily and monthly data and those requiring short duration data, sometimes reported in near real-time.

APPLICATIONS		Data Required		Point observational resolution required	Interpolation accuracy required on 95% of occasions over at least 90% of region	Special Requirements
		Space	Time			
Enquiries						
General	Point	Point	(Day (Month	± 10% ± 5%	3 mm* Days $\geqslant$ 1 mm 13 mm* Month	(1 Gauge/10 km essential (1 Gauge/5 km desirable
	Area	5 km^2-$10^5 km^2$	(Day (Month	Not applicable	3 mm* for areas > 10 km^2 13 mm* for areas > 20 km^2	
Legal/Insurance		Point	Day	± $10\%^{x}$	Not Applicable	Gauge within 5 km of point
Agriculture						
Field Drainage Design		Point	1 - 5 days	± $10\%^{x}$	Not applicable	Long period records essential
Advice on Irrigation		Point or Small Area	2 days	± $10\%^{x}$	3 mm* (2 days)	Growers should have their own gauge
Research Investigations						
Rainfall research and development		Point and area	1 day to 1 year	± $10\%^{x}$ Day ± $5\%^{x}$ Month	Not applicable	10 km gauge spacing essential
Synoptic and mesoscale studies		Area 10 km^2 - $10^5 km^2$	1 day	Not applicable	3 mm for areas > 10 km^2	5 km gauge spacing for special studies
Climatic change		Point	1 month	± 5%	Not applicable	Requires groups of long period stations with 50 km between groups
Radar-rainfall research		Point	1 day	± 5%	3 mm* days $\geqslant$ 1 mm	10 km gauge spacing essential with 5 km spacing in hilly regions

Table 2.2 Summary of the Meteorological Office's requirements for rainfall data (from the daily and monthly network)

^{x}Estimated *Estimated from performance of existing networks (See Section 6)

Applications	Data required Space	 Time	Point observational resolution required	Type of network used	Special requirements
Research Investigations cont'd					
'MORECS'	40 km x 40 km 20 km x 20 km	1 day*	± 1 mm Rain ⩽ 10 mm ± 20% Rain > 10 mm	Synoptic	
Communications	Lines	10 secs to 2 mins	± 20% at 100 mm/hr^{x}	Special networks	requires lines of fast response gauges with 1 km spacing
Radar - rainfall research	Point and area	1 hour 1 day*	± 0.2 mm^{x} Hour ± 5% Day	Hourly synoptic plus special recording gauges	

* in real-time   + in near-real-time   x estimated

Table 2.3 (cont'd) Summary of the Meteorological Office's requirements for rainfall data (short period and real-time uses)

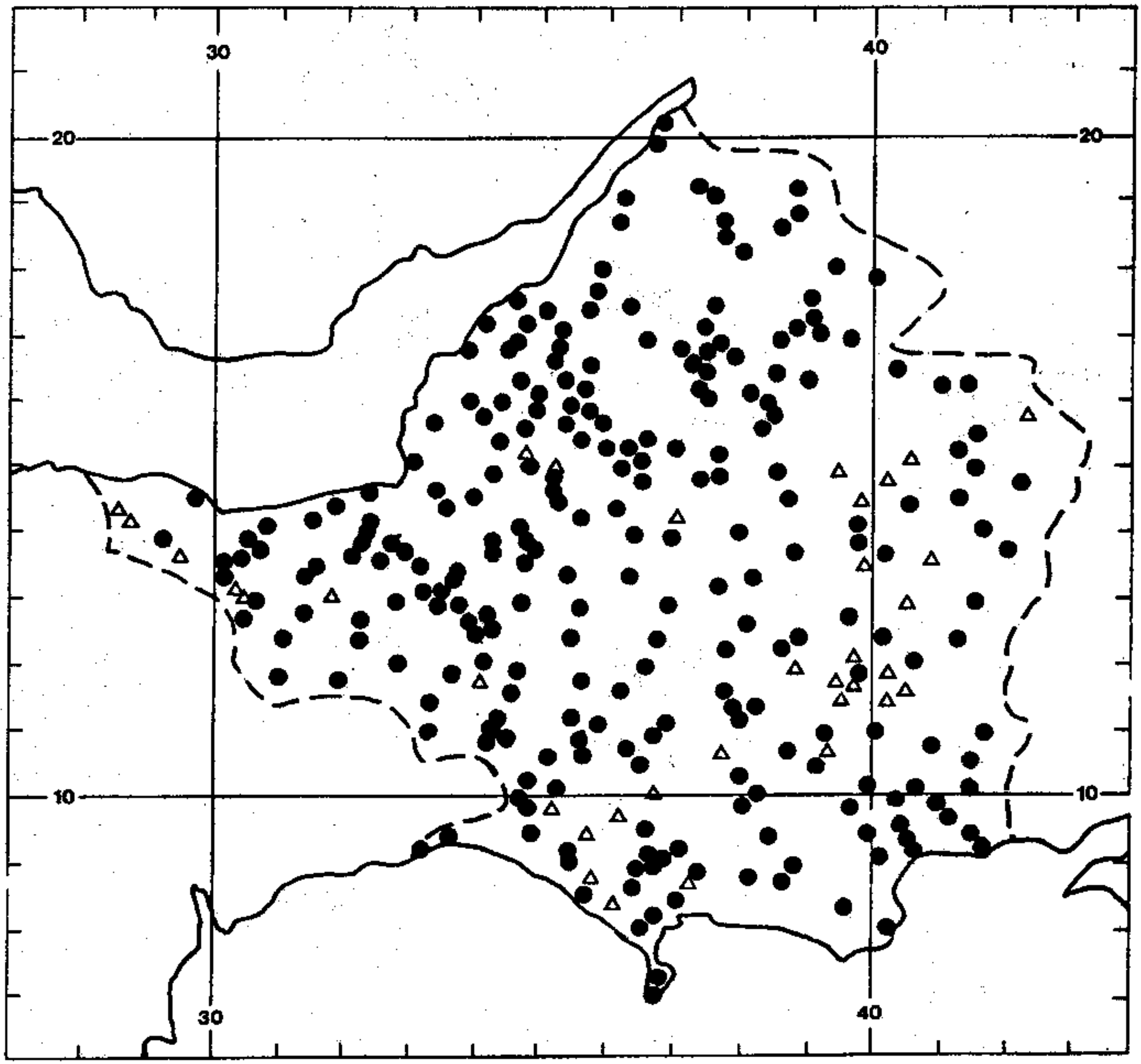


Figure 2.2 Daily and monthly rainfall stations with records available on the national rainfall archive in October 1977.

● Daily Stations

△ Monthly Stations

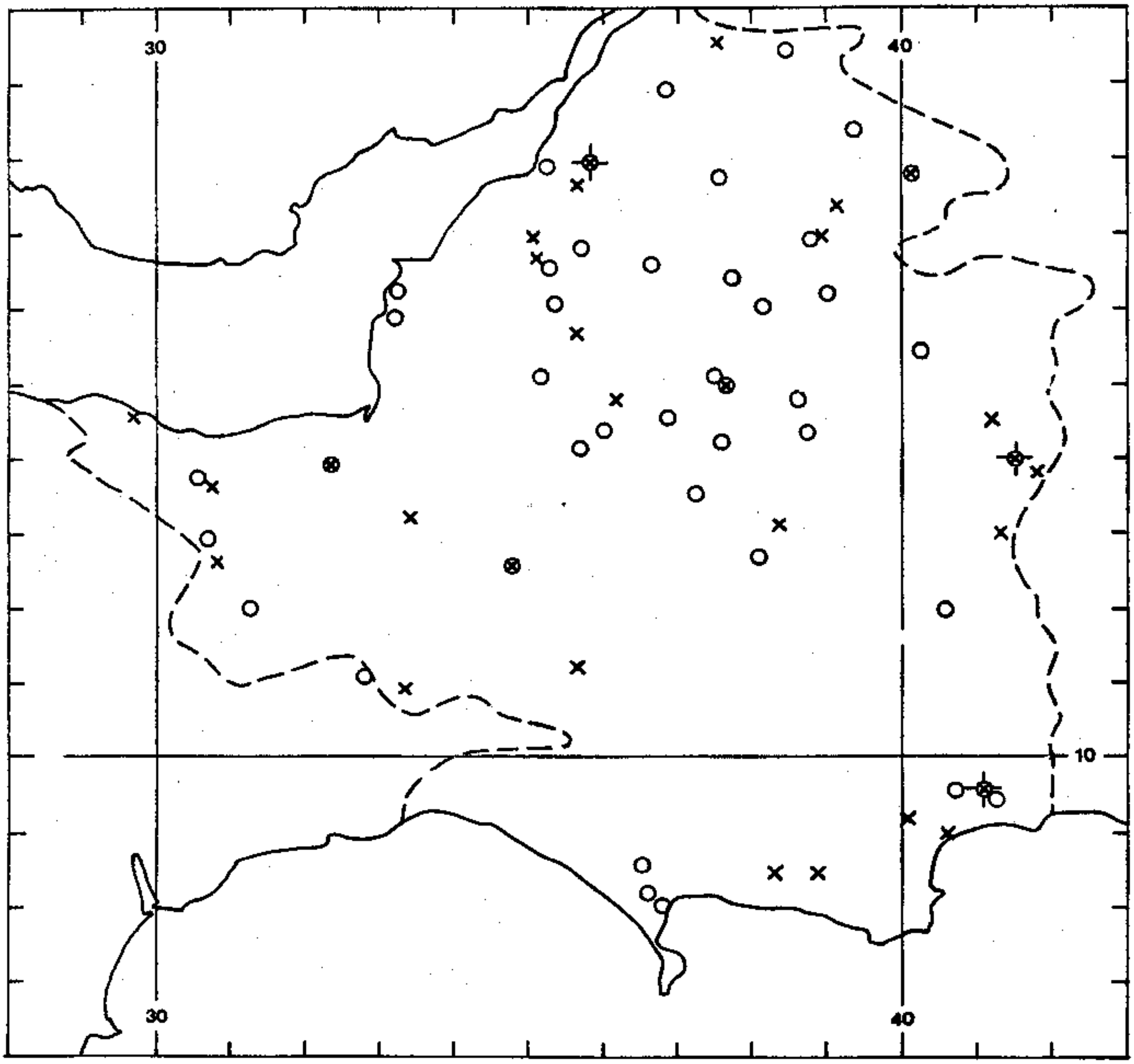


Figure 2.4 Recording raingauges in Wessex Water Authority area

× Data held by MO

○ Data held by WWA

⊗ Stations that have been or will be digitised using PEPR system

⌖ MTER (magnetic tape event-recording) stations

3. NETWORK EVALUATION: APPLICATION OF DIRECT METHODS

3.1 Introduction

As in the Phase I Report (PhlR) the term "direct methods of network evaluation" is taken to cover those procedures concerned with the accuracy of estimation of rainfall quantities. "Indirect methods of network evaluation", which were also considered in the above report, evaluate the accuracy with which derived quantities, such as streamflow, can be estimated by given procedures from available rainfall data. Only direct methods are considered in this section.

Methods for calculating the accuracy of estimation of point and areal rainfall quantities were given in PhlR, for any specified arrangement of raingauges, using the covariance structure of measured rainfalls. In Section 7 of the same report a procedure based on these techniques, and on estimates of user requirements, was suggested for obtaining an assessment of a given network for the interpolation of point rainfall within a large area. Section 3.4 of this report describes the application of this procedure to monthly and daily totals in the Wessex Water Authority area. The methods described here are used in Section 6 to evolve a number of designs for the WWA network, one of which will ultimately be implemented.

The highly skewed statistical distributions of short-period rainfall totals (periods of less than a month) make it somewhat inappropriate to apply the same type of techniques as for longer period totals. Section 3.5 describes some investigations of daily and shorter period data using a simple technique: this enables the differences in the behaviour of interpolation techniques when applied to high and low rainfall quantities to be displayed.

The accuracy of estimation of areal average rainfall for days and longer periods is considered in Section 3.6, where a procedure to calculate this accuracy for any arrangement of raingauges and any shape of area is described: previous work described in PhlR had been limited to gauges sited on a square grid with the area also restricted to be square. Also considered are some simple procedures for estimating the average rainfall over an area during short periods when a record from a recording raingauge is used to distribute over a day the rainfalls recorded by several daily read gauges.

3.2 Data

3.2.1 Daily and monthly data

Direct methods of network evaluation are applied to several different categories of rainfall data in this report: a brief description of the data is given in Table 3.1. When considering the national network of raingauges, consisting of daily and monthly read gauges, three

a. Cardington : a network of 21 raingauges operated by the Meteorological Office in Bedfordshire for the period 1957-1962, the gauges and their clocks being calibrated to give accurate 2 minute totals at each gauge. As the network was designed to study storm movements, only data for 150 selected storms were available. The minimum storm duration was 30 minutes, but for most storms rainfall for at least twice this duration was recorded. This network covered a region approximately 14 km in diameter.

b. Winchcombe : a network of 34 raingauges operated by the Meteorological Office in Gloucestershire for the period 1962-1967. The gauges were similar to those at Cardington and were spread in a 6 km diameter region; 2 minute totals for 133 storms were available.

c. Ceiriog : a network of 11 gauges operated as part of the Dee Weather Radar Project for several years, and giving a continuous record of 15 minute totals. Data for the years 1973 and 1974 were used in the present study and the network represented a region of diameter 20 km.

d. Hirnant : a network of 6 gauges also operated as part of the Dee Weather Radar Project, and providing similar data to the Ceiriog. Data for 1973 and 1974 were again used here, for a region of approximately 12 km diameter.

For the four catchments the data were converted into 30 minute totals : this represents a time resolution typically required by users.

3.3 Calculation of accuracies of estimated quantities

3.3.1 Errors of estimation

It is clear that any raingauge network cannot measure the rainfall at every point in its region. Instead, the measurements obtained at raingauge sites are used to infer values for the rainfall at other particular points, or for the average rainfall depth over a given area. These inferred values estimate the true quantities but, because in practical situations the true values are not known, the errors of the estimated values are also unknown. However, given certain reasonable assumptions, the likely size of these errors can be quantified.

Suppose that a particular way of estimating the desired rainfall quantity has been chosen. That is, given observed measurements from a network of K gauges, denoted by $X_1, \ldots X_K$, a subset of these ($X_1, \ldots X_P$, say) is used to estimate the required quantity by a given formula, $\hat{Y} = \hat{Y}(X_1, \ldots X_P)$. Let Y denote the true value of the quantity. Then the error of the estimate is $e = \hat{Y} - Y$. If, now, several different occasions on which the estimation is performed are considered, the corresponding estimates, true values and errors are denoted by $\hat{Y}_t$, Y_t and e_t respectively ($t=1, 2, \ldots$), where $e_t = \hat{Y}_t - Y_t$. For simplicity it will be assumed that the occasions

3.3.2 Empirical estimates of mean square error

Consider a situation in which a number of gauges in a locality have been operating for some years and it is proposed to cease recording at one of the sites. In future the rainfall totals at this site are to be estimated in a prescribed manner from the recordings at the other gauges. Thus given readings $X_1, \ldots X_p$ at the other gauges the estimate of rainfall at the discontinued site would be given by a function $\hat{Y}$ of these readings, as above. An obvious way of estimating the mean square error of the estimator in this situation is to use the available historical data directly. That is, for a set of historical data of sufficient length, the interpolation estimator $\hat{Y}_t$ is calculated as if the gauge were not recording and compared with the known value Y_t actually recorded at the site. A number of pairs of estimates $\hat{Y}_t$, and true values, Y_t, are then known and the estimate of mean square error

$$\text{est. mse} = \frac{1}{N} \sum_{t=1}^{N} (\hat{Y}_t - Y_t)^2 \qquad (3.2)$$

can be calculated. The estimated rmse is simply obtained by taking the square root of this quantity and can then be used to assess the likely size of the future errors when the gauge is removed. Clearly a basic assumption is that the historical data provide a sample representative of the future values. Estimates of mean square error and of root mean square error obtained by calculations such as that in equation (3.2) will be called empirical estimates.

While the above calculations are simple to perform, the method cannot be applied to assess the effect of establishing new gauge sites, of interpolating to ungauged sites nor to find the size of the errors of estimates of areal average rainfall because in no case is the necessary information available. However an extension of the method is possible and is used later. Suppose that the statistical behaviour of rainfall at various points within a region is very similar, then, if there is a configuration of gauges elsewhere in the region matching both the proposed set of gauges and the interpolation point, the above estimate of mse in equation (3.2) may be calculated from the second set of gauges and transferred to the required site. Clearly for most networks such matches would be extremely rare unless the estimator uses information from only a single gauge: if this is the case then all that is required is to find a pair of existing gauges the required distance apart and (if orientation is relevant) at the required orientation. If there is more than one such pair then the estimates of mse could be averaged. Alternatively, all pairs of gauges might be considered and the relation of the mean square error to the distance between the gauge and the interpolation point could then be examined. This latter approach is taken in Section 3.5 where consideration is given to the estimation procedure for which the rainfall at a point is estimated as exactly the recording at a nearby gauge. No extension to the problem of areal averages is possible although Section 3.7 uses the estimate of areal average rainfall obtained from a number of gauges in place of the true value;

described in Appendix C. Thus the best (linear) estimator can be found without trial and error.

The mean square errors of estimates of areal average rainfall can also be calculated by this theoretically based method. The average rainfall over an area is essentially just the average of the rainfalls at all the points in the area and the covariance between the rainfall at any such point and the rainfall recorded at any gauge is, again, given by the spatial covariance structure which can be estimated as suggested above. Mathematical details of the derivation of the mean square error of estimates of areal averages are given in Appendix D.

When the theoretically based method of determining accuracies is used in this report, the mean square errors calculated are those of estimates of the true rainfalls at the appropriate sites rather than estimates of the quantities that would have been recorded had gauges been available at the sites. The difference here is that estimated rainfalls would show larger departures from records at the site than from the true rainfall due to the extra variability arising from measurement errors - two identical gauges placed side-by-side would generally not record identical rainfalls. The effect of measurement errors is that the covariance between measured rainfalls at two points arbitrarily close together is less than the variance of the rainfall measured at a single point - the limiting covariance is essentially the variance of the "true" rainfall. However, very short distance covariances are not available and so there is some risk that the effects of measurement errors and those of any short range climatic disturbances might be confused.

3.3.4 Interpretation of mean square errors

Section 3.3.1 introduced the mean square error (alternatively, root mean square error) as a quantity to measure the accuracy of estimates of rainfall: here this quantity is related to another, possibly more easily interpreted, property of the statistical distribution of the errors.

If the distribution of the estimation errors were normal, then it would be true that only 5% of the absolute values of the errors would be larger than twice the root mean square error (more exactly a factor of 1.960). (This does not take into account the effect of inaccuracy in the estimate of rmse). Thus the statement that the root mean square error of an estimator is, say 1 mm, could be reinterpreted as meaning that 95% of estimates calculated on independent occasions would be within 2 mm of the true value. Other percentages could be obtained by applying other scaling factors.

The distributions of rainfall totals over shorter durations are markedly non-Normal but the distribution in question here is the distribution of errors from interpolation. Even if the parent rainfall distribution is non-normal, can it still be said that 95% of estimates are within 2 rmse's of the correct value? Application of Tchebycheff's inequality shows that, for any distribution of errors,

3.4 Mapping of optimal point interpolation error

3.4.1 Outline of technique

Section 5 of PhlR considered several different forms of linear interpolators for point rainfall: the estimator used throughout this report (except in Sections 3.5 and 3.7) is the optimal estimator with coefficients summing to one. Thus consider a set of rainfall totals $X_1, \ldots\ldots X_p$ recorded at P gauges; then the estimator $\hat{Y}$ of the rainfall Y at any point is

$$\hat{Y} = b_1 X_1 + b_2 X_2 + \ldots\ldots b_p X_p, \tag{3.3}$$

where $\{b_i\}$ satisfy

$$b_1 + b_2 + \ldots\ldots + b_p = 1 \tag{3.4}$$

and are chosen to minimise the mean square error of $\hat{Y}$ as described in PhlR (see also Appendix C of this report). The restriction given by equation (3.4) implies that if the observed values $X_1, \ldots\ldots X_p$ are all equal then the estimator $\hat{Y}$ takes this same value. As discussed in Section 3.3, the accuracy of the estimator $\hat{Y}$ is measured by its mean square error as an estimator of the true (but unknown) rainfall Y,

$$\text{mse } (\hat{Y}) = E\{(\hat{Y} - Y)^2\}.$$

An expression for this quantity is given by equation (C.6) (Appendix C) in terms of the covariances of rainfalls at the various sites. If it is considered that the position of the point at which interpolated rainfall is required varies, while the gauge sites remain fixed, this expression allocates a value to each point in the horizontal plane, namely the mean square error of interpolation (using the optimal estimator) at that point. This function of spatial position can then be presented as a contoured map enabling a visual assessment to be made of those points having relatively poor interpolation error. Essentially this is the method suggested in PhlR.

The accuracy of an estimator of point rainfall clearly depends on the number and relative positions of the gauges to be used; in this context the following points are worthy of note:

(a) Because it has been assumed that each estimator is the optimal estimator of the form (3.3), the mean square error of interpolation to a given site must decrease as additional gauges are added to the set included in the interpolation formula.

(b) It is reasonable to suppose that including gauges at a large distance will have very little effect on the mean square error, provided that intermediate gauges have already been included.

(c) The procedure is repeated for all (5 x 5) squares. The surrounding squares of size (35 x 35) used for adjacent (5 x 5) squares overlap each other to a considerable extent providing smoothing, firstly of the correlation parameters and secondly of the interpolation accuracy.

(d) Using the 1 km grid values of point interpolation error, produce a contour map for the whole region.

This technique is illustrated in Figure 3.2. It was found that a size as small as 5 km was necessary for the basic grid (step (a)) in order to reduce the size of the residual discontinuities at the boundaries of these areas, allowing a smooth contour map to be drawn.

A preliminary investigation of the correlation structure of daily and monthly rainfall totals showed that it was only reasonable to fit a correlation function, decaying exponentially with distance, up to a distance of 35-40 km and this was the basis of the choice of square size in step (b) (i). There was some suggestion that at distances greater than 40 km the correlation function begins to rise. The form of the correlation function fitted was

$$\rho(u,v) = a + (1-a-\varepsilon)\ \exp\{-b[(u + c_1 v)^2 + (c_2 v)^2]^{\frac{1}{2}}\} \quad (u,v) \neq (0,0) \qquad (3.5)$$

where u and v described the x- and y- differences between gauge coordinates. Near the origin this function approaches the value $1-\varepsilon$ rather than unity: thus some allowance is included for the effect of 'measurement error' and microscale disturbances as discussed in Ph1R. The results from the fitting procedure suggest that the rainfall totals from two gauges at effectively the same site would have a root mean square difference of about 3 mm for monthly totals, which is not unreasonable. Details of the fitting procedure in which the five parameters $(a, b, c_1, c_2, \varepsilon)$ are estimated are given in Appendix B: the estimation technique is essentially the same as that used in Ph1R.

The size of the square in step (b) (iv) needs to be chosen with some care: it should not contain too many gauges (not more than 50, say), for then the size of the matrix to be inverted becomes large, but, on the other hand, there should be enough stations so that the effect of adding further stations outside the chosen region would be negligible. Clearly it would be possible to devise a technique of automatically selecting, for example, the 30 closest gauges but the procedure used was considered simplest to implement for the present study. In practice, it may be necessary to use gauges for interpolation which lie outside the region used for fitting the correlation function. There is no practical difficulty in doing so but clearly this would have to assume that the fitted correlation function held outside the fitting region. Details of the techniques used for estimation of correlations and for fitting correlation functions are given in Appendices A and B. The overall procedure is still in need of further

Figure 7.8 of PhlR is similar to Figure 3.3 here, there being two major differences. Firstly the map in PhlR gave contours of interpolation error as a fraction of the standard deviation of rainfall; here contours are drawn at intervals of rmse in millimetres. The other major difference is that here gauges outside the region contoured are used in the interpolation, whereas, in the diagram in PhlR, only those gauges shown on the map were used.

3.5 Accuracy of empirical point interpolation procedures

3.5.1 Discussion

Unsophisticated interpolation techniques are often used when interpolating rainfall, particularly when the interpolation is being performed manually. Perhaps the most common method of interpolation in the UK is to take the rainfall recorded at the nearest operating raingauge as the estimate of the rainfall at any required point. This is equivalent to the use of Thiessen polygons, more usually associated with the estimation of areal average rainfalls, where in effect the rainfall recorded at a gauge is associated with all those points which are nearer to that gauge than to any other: in practice the estimate of areal average rainfall weights the readings at the gauges according to the areas associated with them.

In order to assess this method of point interpolation, the empirical method of calculating the mean square error of an estimator (Section 3.3.2) was used. Here the procedure need not be restricted to gauges which are actually nearest neighbours and, indeed, all pairs of gauges within each region concerned were considered. As suggested in Section 3.3.2, from a pair of gauges a certain distance, d, apart whose recorded rainfalls are $\{X_t : t = 1, \ldots, N\}$ and $\{Y_t : t = 1, \ldots, N\}$, an estimate of the rmse of the interpolation procedure (which estimates the rainfall Y_t at a point by the recording X_t at a gauge a distance d away) is obtained

$$\text{est. rmse} = \{\frac{1}{N} \sum_{t=1}^{N} (Y_t - \hat{Y}_t)^2\}^{\frac{1}{2}} = \{\frac{1}{N} \sum_{t=1}^{N} (Y_t - X_t)^2\}^{\frac{1}{2}}. \qquad (3.6)$$

Since a number of pairs of gauges are available, at different distances apart, it may be hoped to identify an underlying smooth curve of root mean square error against distance by plotting the estimated rmse's against the corresponding distances. The optimal interpolation procedure can also be applied at the same sites, allowing a comparison between the two approaches; this is carried out in Section 3.5.2 for daily and monthly data. Only the empirical approach has been applied to data from recording gauges (that is for rainfall totals over periods of 2 minutes to several hours) because for this type of data, the statistical distributions are extremely skew and contain a high frequency of zero values and it was therefore felt that the application of correlation based techniques might be inappropriate. Section 3.5.3 describes the results for recording raingauge data and Section 3.5.4 applies a similar empirical technique to the problem of combining a daily total with data from a recording gauge at a different site.

in Section 3.3.2 was also applied to the half-hourly data from the networks of recording gauges described in Section 3.2.2. Figures 3.9a - 3.12a show plots of rmse against distance for the Cardington, Winchcombe, Ceiriog and Hirnant data sets, respectively. The plots for the Cardington and Winchcombe data are similar, as are those for the Ceiriog and Hirnant data but the values of rmse for the former pair of networks (typically in the range 0.3-0.75 mm) are over twice the size of those for the latter pair of networks (typically of the order of 0.15 - 0.3 mm). The greater magnitude of the rmse for the Cardington and Winchcombe data may be attributed to the fact that the data were selected to cover storms whereas the Hirnant and Ceiriog data were sampled continuously.

As discussed in PhlR the accuracy of an estimate of rainfall may depend substantially on the amount of rainfall recorded at the gauges used in the interpolation. For example if zero rainfall is observed at each of the gauges, the estimate of rainfall would also be zero and since a zero rainfall at the interpolation point would be very likely, the typical size of the error (as measured by rmse) would be small. The error is likely to be larger if larger rainfalls are observed. To examine this effect for the empirical estimation technique the following questions were asked:

> What is the typical size of estimation error when the observed half-hourly rainfall at the nearest gauge is
>
> (1) zero?
>
> (2) non-zero and up to 1 mm?
>
> (3) greater than 1 mm?

In order to consider these questions, the estimation of root mean square error in equation (3.6) was modified so that, for any pair of gauges with recorded values X_t and Y_t, the estimate is now

$$\text{est. rmse} = \{\frac{1}{N_c} \sum_c (Y_t - X_t)^2\}^{\frac{1}{2}}$$

where the summation is over those times t for which X_t satisfies the particular condition (1), (2) or (3) above which is being considered, and N_c is the number of such times in the summation. The result is an estimate of the root mean square error of the estimate conditional on an observed value being in a particular range.

Figures 3.9-3.12 show the results obtained for the Cardington, Winchcombe, Ceiriog and Hirnant data sets. It can be seen that for all networks there is a marked decrease in accuracy with increasing rainfall, as suggested above. Thus, for the empirical interpolation method, confidence bounds of different width could be placed upon the estimated value, depending on the observed value. The greater scatter of the estimated rmse's for observed rainfalls of greater than 1 mm is partly accounted for by the small number of occasions on which such events happen. The difference in magnitude between the rmse's for the Cardington and Winchcombe networks and the rmse's for the Ceiriog and Hirnant networks, noted above, is less marked when high rainfalls more general situations are easily obtained as described in PhlR, but their evaluation presents certain difficulties. When the estimate is based on data from P gauges, the expression involves P 2-dimensional integrals and one 4-dimensional integral, generally of mathematically intractable form. The mean square error of an estimate of an areal average is often small but its expression involves the difference between two large quantitites: this means that each of these large quantities has to be determined to high relative accuracy to obtain even a moderate relative accuracy in any numerical evaluation of the mse.

When special assumptions are made about the form of the covariance function $\gamma(u;v)$, which gives the covariance between rainfalls at sites with coordinates u and v, the integrals mentioned above can be reduced to somewhat simpler forms: the assumption used throughout this report, as in PhlR, is that of spatial stationarity, ie

$$\gamma(u_1,u_2;\ v_1,v_2) \;=\; \gamma^*(u_1 - v_1,\ u_2 - v_2)\ .$$

Details of the evaluation of the required integrals are given in Appendix D. As for point interpolation (Section 3.3), the root mean square error calculated is that of the optimal linear estimator with coefficients summing to unity, as in equation (3.3).

The mean square error of an estimate of areal average rainfall depends both on the size and shape of the region concerned and on the number and positions of the raingauges used in the estimate. Here three catchments are considered and it is assumed that estimates of the average rainfall over each catchment are required, using data only from raingauges within each catchment. The areas under consideration are fairly irregular in shape. The catchments used were those of the Brit, the Tone and the Bristol Avon, with areas of 120, 420 and 2200 km^2 respectively; their locations are shown in Figure 3.14. For the computation of the mean square error the boundaries of the catchments were represented by relatively coarse sets of straight line segments. These representations are shown in Figures 3.15-17 together with the arrangements of raingauges in the catchments. As can be seen, gauges which are actually inside the true catchment boundaries are, in some cases, outside the digitised representation of the catchment. Nonetheless all gauges shown in the diagrams are assumed to be employed in the estimates of areal average rainfall.

For each of the above catchments, the mean square error of the optimal linear estimator of average areal rainfall was calculated for monthly rainfall totals and for each of the categories of daily totals using the gauges recording and registered with the Meteorological Office in February 1978. For convenience, the same gauges were assumed to be used for daily and monthly estimation. For the Bristol Avon catchment the parameters of the correlation function were estimated from historical records for gauges within the catchment whereas, for the smaller catchments, gauges in a region surrounding the catchments were used in order to obtain a reasonable number of sample correlations to use recorded half-hourly totals at each gauge in turn. For each such gauge estimates of the mean areal rainfall over the Ceiriog and over the Hirnant catchments were obtained by forming (i) the simple arithmetic mean of the actual half-hourly totals at gauges within each catchment and (ii) the simple arithmetic mean of the redistributed half-hourly totals. Assuming, first of all, that the mean of the actual recordings is the true average rainfall over the area, then the mean square error of the estimate of average rainfall obtained using the redistributed rainfall totals can be calculated as in equation (3.2). Estimates of root mean square errors obtained in this way are shown in Figure 3.18 where the rmse's are plotted against the distance of the gauge used to redistribute the "daily totals" from the centre of the catchment. Here the centre was taken to be the centroid of the gauge positions within the catchment. Because the values used in place of the true average rainfall over the catchment were the same whatever gauge was used to redistribute the daily rainfalls the effect of using a value other than the true catchment average should be about the same for each estimate of rmse. The true rmse's are likely to be larger than the estimates produced in this way.

The root mean square errors for the estimates of areal average rainfall over the Ceiriog are generally smaller, particularly for large distances, than those for the Hirnant. This may be explained by the fact that the catchment of the Ceiriog has greater area than that of the Hirnant although it may be caused by the use of values other than the true catchment averages. The rmse's show a moderate increase with distance, and they are similar in size to those obtained for both the empirical point estimation and for the estimate of point rainfall derived by redistributing daily totals as discussed in Sections 3.5.3 and 3.5.4. For the monthly and daily totals it was found (Section 3.6) that estimates of areal average rainfall were more accurate than those for point rainfall: it may be that the catchments considered here are too small for the effect to be noticeable.

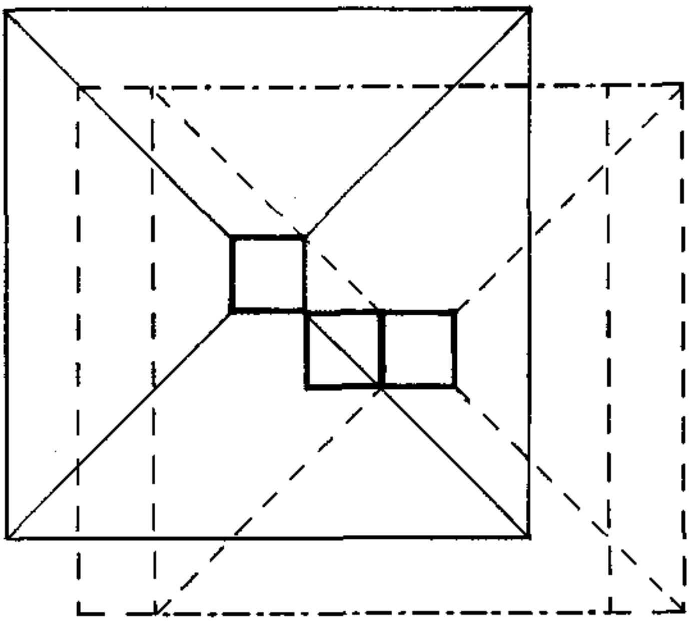


Figure 3.2 Square regions used for interpolating to points within each adjacent 5 km square.

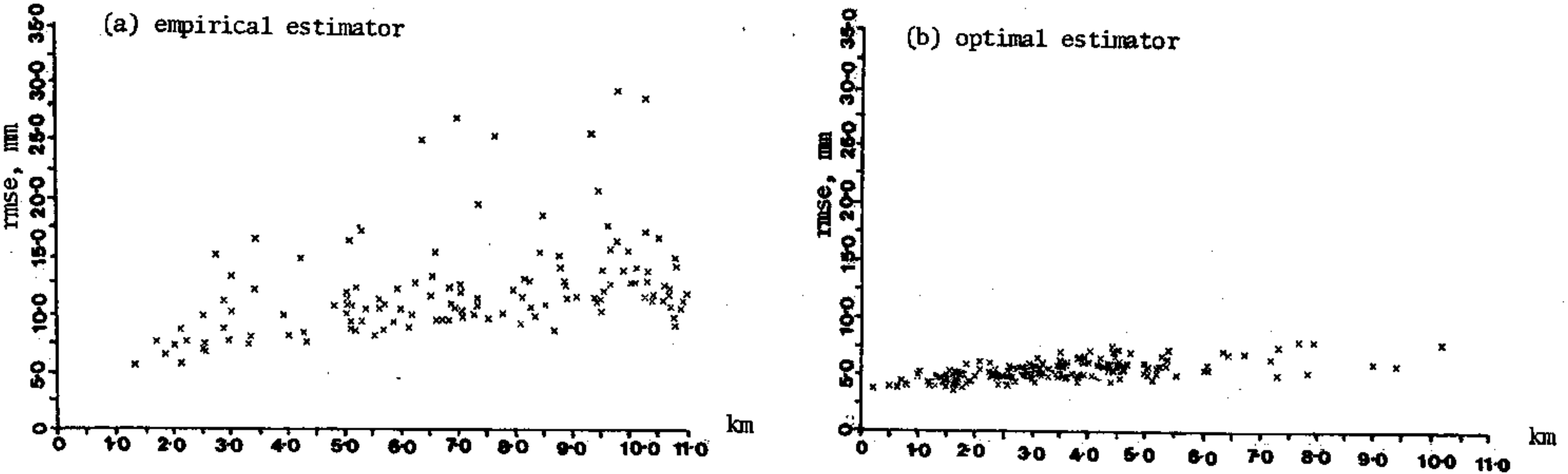


Figure 3.5 Sample root mean square errors : monthly totals

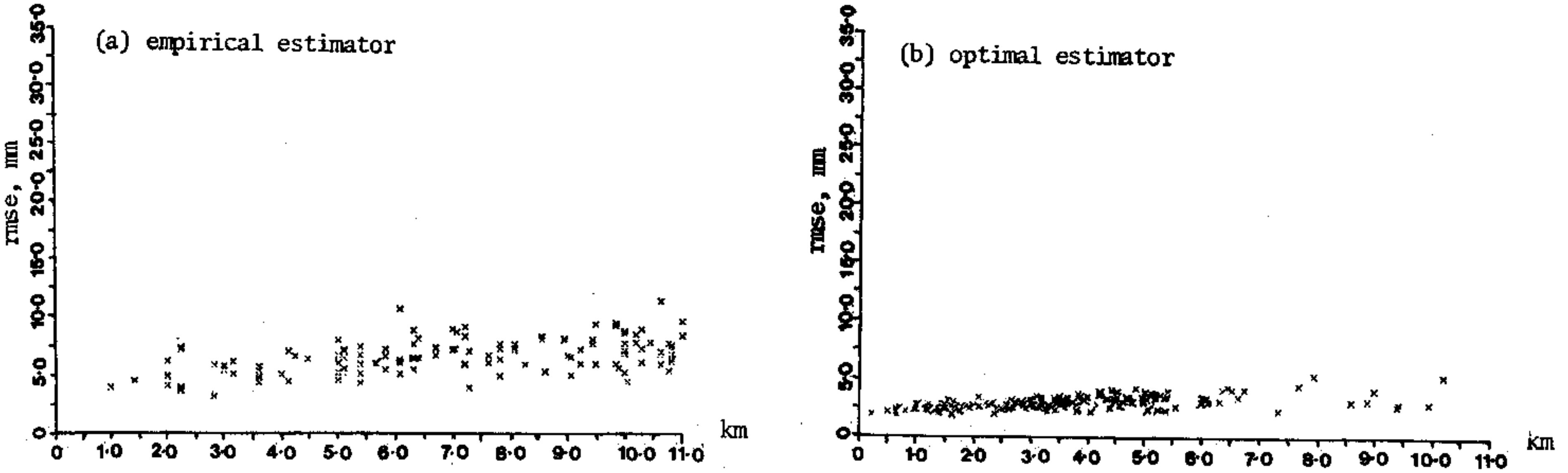


Figure 3.6 Sample root mean square errors: daily totals

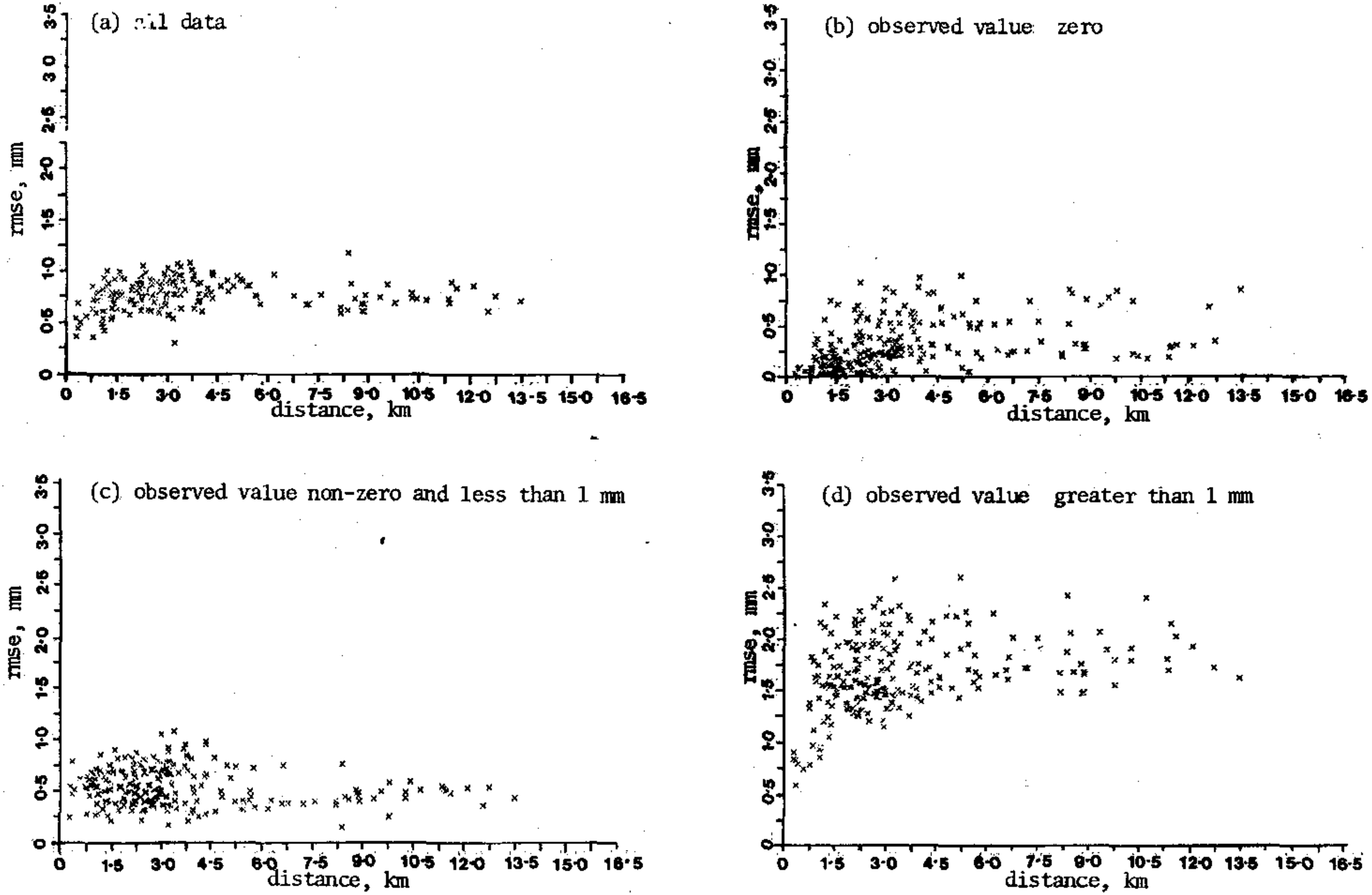


Figure 3.9 Sample root mean square errors for the empirical estimator : half-hourly totals, Cardington

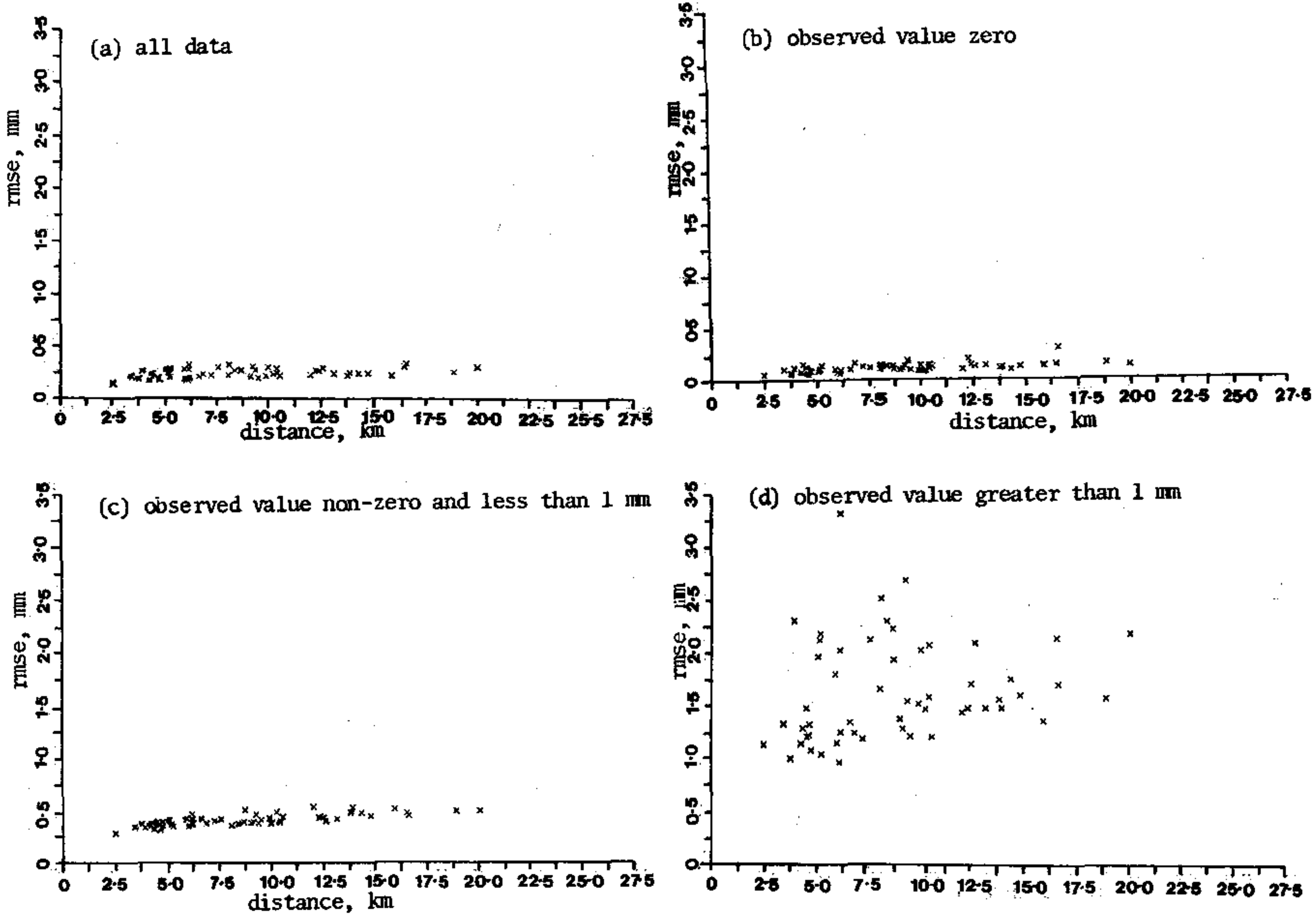


Figure 3.11 Sample root mean square errors for the empirical estimator : half-hourly totals, Ceiriog

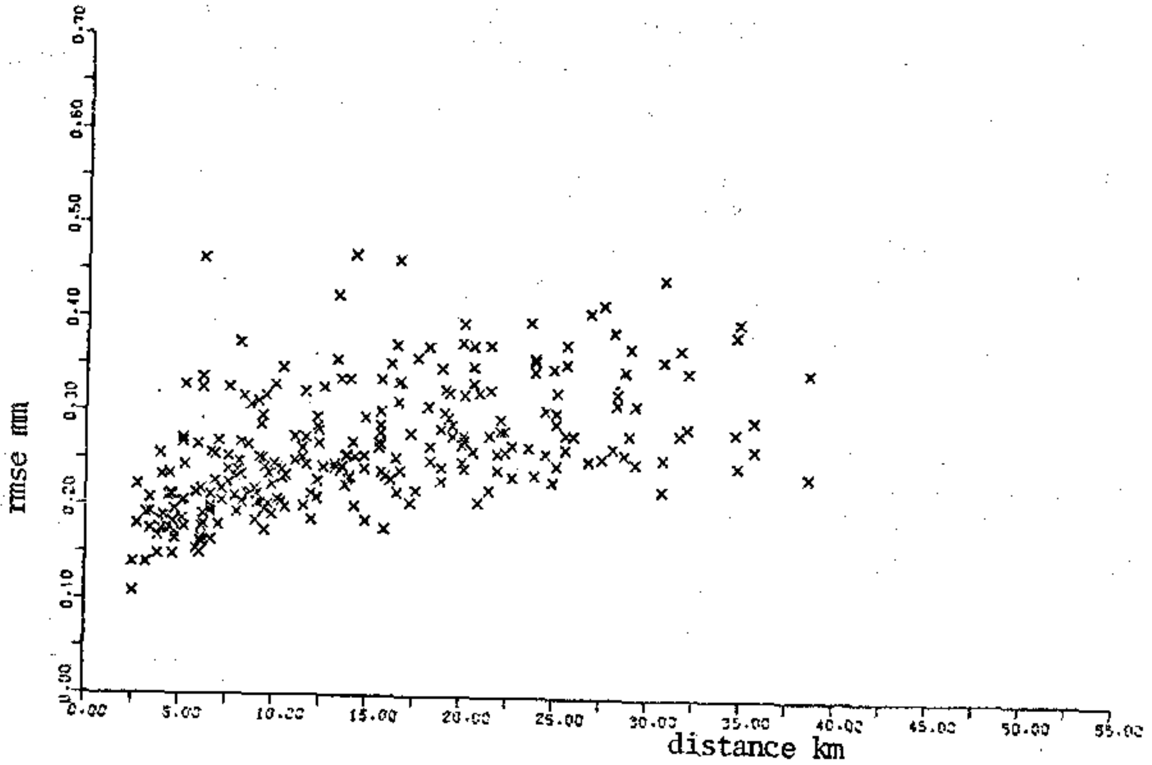
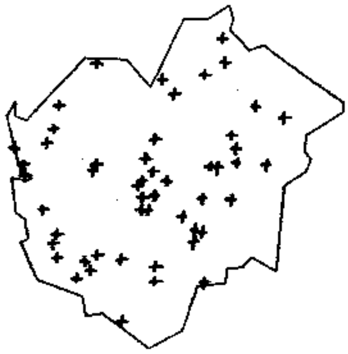
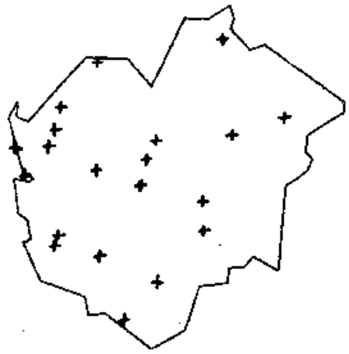


Figure 3.13 Sample root mean square errors for estimates of half-hourly rainfalls, redistributed from daily totals. Ceiriog and Hirnant catchments combined.



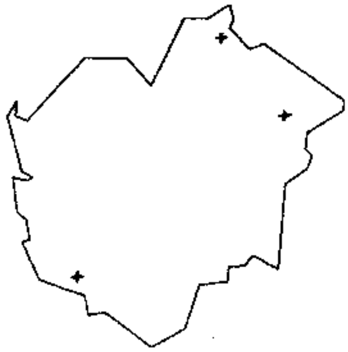
1978 Network : 51 gauges

(i) monthly totals: rmse = 1.0 mm
(ii) daily totals : rmse = 0.17 mm
(iii) days rain > 1 mm: rmse = 0.30 mm
(iv) days rain > 5 mm: rmse = 0.40 mm



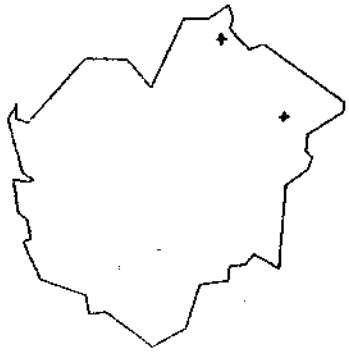
20 gauges selected at random from 1978 Network

monthly totals : rmse = 1.6 mm



3 gauges selected at random from 1978 Network

(i) monthly totals : rmse = 5.7 mm
(ii) days rain > 1 mm: rmse = 1.6 mm

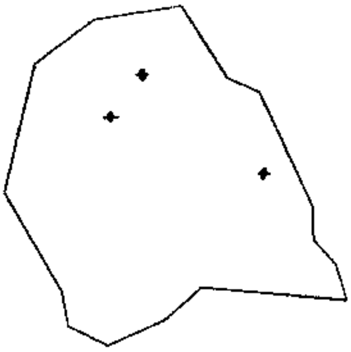


2 gauges selected at random from 1978 Network

monthly totals : rmse = 8.3 mm

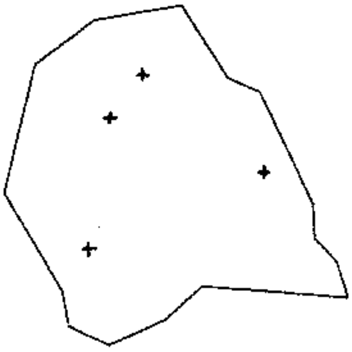
OTHERS: 1 gauge centrally sited, monthly totals : rmse = 9.1 mm
20 gauges regularly distributed, monthly totals : rmse = 1.2 mm

Figure 3.15 Bristol Avon catchment. Accuracies of optimal estimates of areal average rainfall using different sets of raingauges



1978 Network : 3 gauges

(i) monthly totals : rmse = 3.5 mm
(ii) daily totals : rmse = 0.65 mm
(iii) days rain > 1 mm : rmse = 1.1 mm
(iv) days rain > 5 mm : rmse = 1.4 mm



A Network of 4 gauges
(1978 network with fictitious additional gauge)

monthly totals : rmse = 2.3 mm

OTHERS : 1 gauge centrally sited, monthly totals : rmse = 5.0 mm
3 gauges regularly distributed, monthly totals : rmse = 2.5 mm

Figure 3.17 River Brit catchment. Accuracies of optimal estimates of areal average rainfall using different sets of raingauges.

4. NETWORK EVALUATION : APPLICATION OF INDIRECT METHODS

4.1 Introduction

The distinction drawn here between direct and indirect methods of network evaluation is ascribed to the use made of rainfall data for decision-making. Where an estimated rainfall quantity is itself the direct basis of a decision this is termed a direct use of rainfall data, and the accuracy of estimation will govern how 'good' a decision is, measured in terms of the expected benefits or losses accruing from the decision. In practice, however, the quantification of such benefits and losses is usually not feasible, and the decision-maker reverts to providing some subjective measure of required accuracy. Most of the accuracies specified in Tables 2.1 - 2.3 in Section 2 fall in this category. Network evaluation can then proceed using the methods described in Section 3.

Where rainfall represents but one input to a complex decision-making process governed by several variables, then the forthright specification of an accuracy criterion for the rainfall input becomes complicated. If the decision variable can be related to the various input variables, then the sensitivity of benefits accruing from a decision to the accuracy of the rainfall input could be evaluated; this would then represent an indirect method of network evaluation. Inevitably, information on benefits and losses will again be lacking; nevertheless, the model can be used to gain insight into how accurate each of the input variables need be to achieve the desired accuracy in the decision variable. For the present study, the input variable of interest is rainfall, measured or estimated from an existing network of gauges.

In Section 4.2, some possible approaches to indirect network evaluation within the WWA area are considered. For a variety of reasons, only one modelling approach proves viable and this is described in Section 4.3.

4.2 Possible approaches to indirect network evaluation for the Wessex Water Authority area

The survey of Wessex Water Authority (WWA) user requirements conducted by the Institute of Hydrology identified a number of problems requiring a rainfall-runoff modelling approach; these are described briefly in Section 2.2.3.9. They are now considered in turn as possible bases for indirect network evaluation.

(a) Gauging low-lying rivers in Somerset : the objective here would be to determine flows by modelling. A daily rainfall-runoff model could be used as sufficiently long records of mean daily flows are available for a number of catchments in the Somerset area. The sensitivity of flow estimation to the number of gauges used to define the daily rainfall input could then be explored using the fitted model.

(a) Which type of model should be used, with the related question of whether or not to use lumped or spatially distributed inputs?

(b) What criterion should be used to measure the goodness of fit of the model, and the effect of raingauge density on this?

(c) How should model inputs reflecting different raingauge densities be defined?

With regard to (a) the CLS (Constrained Linear Systems) 'black-box' model (Todini and Wallis, 1977) was adopted for the present exercise. This model had been used in Phase I of the study, and the arguments underlying this choice are given in Ph1R. Essentially the model consists of a multiple-input single-output linear system, where the response of the output to each input is described by an impulse response. Each of the ordinates of the impulse responses is treated as a parameter to be estimated; estimation is performed using a least squares criterion of fit subject to various constraints on the fitted parameter values:

(i) the estimated ordinates of each impulse response should all be greater than or equal to zero, in accordance with physical hydrological principles.

(ii) the model should preserve continuity; this is achieved by incorporating an equality constraint which states that the sum of the ordinates of each impulse response should equal the coefficient of runoff (i.e. the proportion of rainfall that becomes runoff) for that input.

The minimization of the least squares criterion of fit subject to either constraint (i) or constraints (i) and (ii) is performed using quadratic programming, which is both a computationally and statistically efficient approach to parameter estimation. Further details of the CLS model formulation, and of the objective function to be minimized, are given in Ph1R.

While the CLS model can handle spatially distributed inputs, only lumped inputs were considered for the present exercise. By applying a threshold mechanism to the lumped rainfall input, P_t, two separate rainfall inputs can be generated, and corresponding impulse responses estimated for each of these. The threshold mechanism has the effect of introducing non-linearity into the model, and operates as follows. An antecedent precipitation index API_t for day t is calculated as

$$API_t = K_t \; API_{t-1} + P_{t-1} \qquad (4.1)$$

where

$$e_i = \frac{1}{N} \sum_{i=1}^{N} (P_{t,i} - \bar{P}_t)^2$$

where $P_{t,i}$ denotes the rainfall at gauge i, $\bar{P}_t$ is the overall catchment average, and N is the length of record available at each gauge. The e_i values were then ranked from largest to smallest; this was then taken to be the order in which gauges should be deleted from the network. Further details of this approach are furnished in Ph1R.

Once the model had been calibrated using the lumped input corresponding to the maximum number of gauges, the parameter values were fixed and the input for each sub-set of gauges was used to generate a set of predicted discharges; the coefficient of determination R^2 was then calculated with reference to observed discharge. This differs slightly from the appraoch used in Ph1R; there, R^2 was computed with reference to discharge predicted by the model when all gauges were used to define the model input. The difference is largely one of detail, although the present approach has the advantage of the same scale of reference for values of R^2 from different catchments.

4.3.2 Catchments used

The catchments selected for modelling lay in the western region of the WWA area, as shown in Figure 4.2, and were chosen to identify as far as possible with the problems (a) and (d) described in Section 4.2. The catchments, their reference numbers and some of their basic hydrological properties are listed in Table 4.1; their areas ranged from 7 km^2 to 213 km^2. The main channel slopes for catchments 52/10 and 52/11 are smaller than for the remaining catchments; the other hydrological characteristics in Table 4.1 do not show any great contrasts between the catchments. The soil index and measure of stream frequency are defined in the Floods Studies Report (Natural Environment Research Council, 1975). A brief description of each catchment is given in Appendix E.

The four year period January 1970 - December 1973 was chosen over which to calibrate the CLS model on each catchment. Daily rainfall data for a set of gauges within and adjacent to each catchment were retrieved from the national archive of daily rainfall data subject to the criterion that each gauge did not have any missing data over the four year period. The number of gauges available for each catchment are listed in Table 4.1 and their location on the catchment maps is shown in Figures 4.3 - 4.8. For catchment 52/5, the Tone at Bishops Hull, the distribution of gauges shown in Figure 4.4 reflects the fact that some of the perimeter of this catchment borders on the South West Water Authority area, and gauges from that region were not included in the rationalization exercise for the WWA area. A better spatial distribution of gauges is observed for catchments 52/3, 52/6 and 52/7 than for catchments 52/10 and 52/11.

Mean daily flows for the six catchments had previously been obtained from the Water Data Unit archive of hydrometric data for the IH Low

Flows Study.

4.3.3 Results and conclusions

For calibration of the CLS model, the lumped daily rainfall input $\bar{P}_t (t=1,2,\ldots,N)$ was calculated as the arithmetic mean daily rainfall over the total number of gauges on each catchment. The model was then calibrated as described in Section 4.3.2 using a trial and error approach to the estimation of the incidental parameters in the first instance; a 'hill-climbing' routine was then used to try to improve on these estimates but on the whole little improvement was derived from applying this latter step. This was mainly due to the fact that the response surface was found to be highly irregular locally, and not amenable to a search by routines which assume that the response surface is essentially smooth.

The results of the CLS model calibrations are given in Table 4.2, where runoff coefficients for the total period of record, defined as

$$\phi = \frac{\sum_{t=1}^{N} Q_t}{\sum_{t=1}^{N} \bar{P}_t} \qquad (4.7)$$

are also presented. The similarity in runoff regime of the six catchments is reflected in the uniformity in the runoff coefficients. For all catchments, only one threshold was used, as in all cases this led to values of R_d^2, the coefficient of determination of daily flows, greater than 0.70, and values of R_m^2 for monthly flows in excess of 0.800, which were considered adequate. Monthly flows were derived by aggregating daily flows predicted by the fitted daily model, and then computing R_m^2 using the observed monthly flows as a reference basis. The values of R_d^2 and R_m^2 obtained for catchments 52/5, 52/10 and 52/11 do not suggest that the rather poor spatial distribution of gauges on these catchments has an adverse effect on the model fit achieved.

It is considered that a much more complicated model formulation would be required to achieve results better than those presented here: the formulation and fitting of such a model would be beyond the scope and time-scale of the present study. Nonetheless, the level of complication of the present model is thought to be consistent with the level of complication of a model which a water authority might use in practice.

The values of the incidental parameters presented in Table 4.2 for each of the six catchments show a heartening similarity suggesting that the model could possibly be extended for use on ungauged catchments with similar runoff regimes. The values of the API parameters reflect a high level of seasonality in the parameter K_t in (4.2), which results in the threshold T operating to provide a seasonal

Order of Deletion	52/3	52/5	52/6	52/7	52/10	52/11
1	401668	402819	401005	398896	405455	401005
2	403115	401668	348684	351190	414415	404988
3	398081	401620	343207	400158	-	-
4	402819	398081	398505	398505	-	-
5	398063	402542	351256	-	-	-
6	402190	398063	351190	-	-	-
7	398276	402190	398512	-	-	-
8	404552	-	-	-	-	-
9	398022	-	-	-	-	-
10	402542	-	-	-	-	-
Remaining gauge	402553	402553	400158	398512	406177	404979

Table 4.3 Order of deletion of raingauges for six catchments

reduction for decreasing numbers of gauges, and the fluctuations observed may reflect the uneven spatial distribution of gauges for this catchment. For catchment 52/6, a drop in R_m^2 and R_d^2 occurs for less than 3 gauges, although the overall decrease is again not significant; this is also true of catchment 52/7. For catchments 52/10 and 52/11, the values of R_m^2 and R_d^2 drop away relatively quickly, suggesting that if further gauges were available on these catchments, better results would be obtained. These results tend to reflect the general non-uniform distribution of gauges in the WWA area which a redesign would be expected to eliminate.

These are two main factors which govern the goodness of fit obtained for a rainfall-runoff model; one is the extent to which the model can accurately represent the underlying rainfall-runoff process, and the other is the accuracy with which the rainfall input can be defined. In general, it is difficult to separate the effects of these two factors; however, the results presented in Figures 4.9 - 4.14 suggest that the number of gauges could be reduced on some WWA catchments and should be increased on others. This conclusion is deduced from the hypothesis that, for example, in the case of catchment 52/3, a better model would be required to achieve a better fit initially, while, for catchments 52/10 and 52/11, a better fit could probably be obtained with more gauges to define the rainfall input.

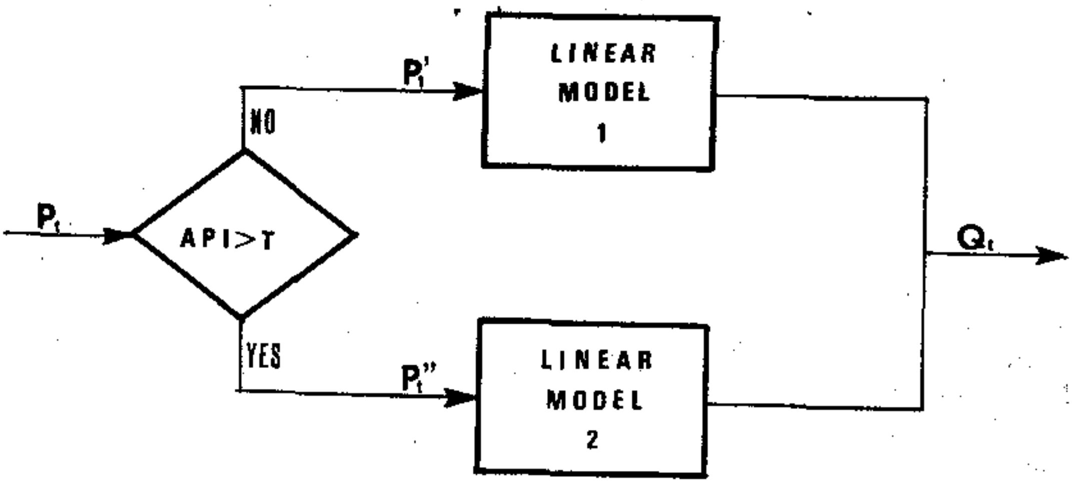


Figure 4.1. Schematic representation of CLS model with threshold

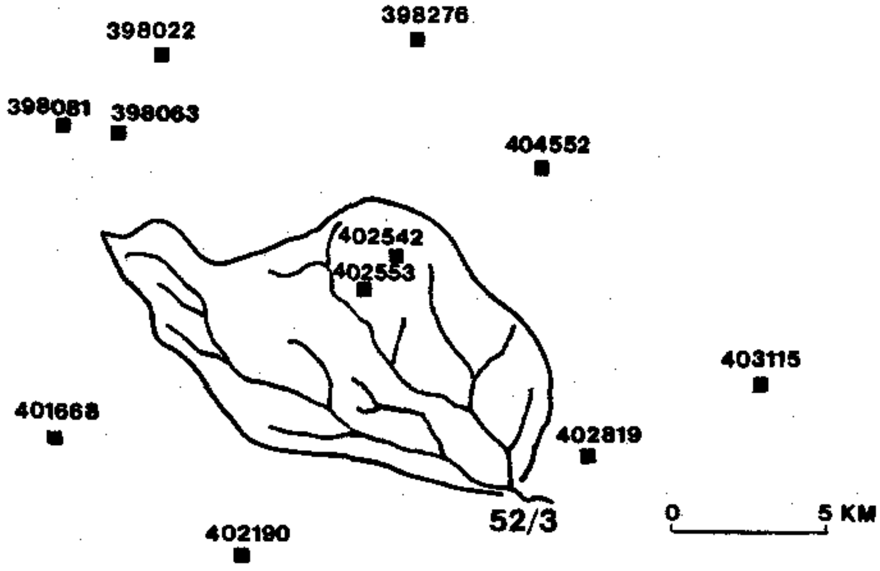


Figure 4.3. Catchment map for Halse Water at Bishops Hull (52/3) with locations of gauges used (Area = 87.8 km^2)

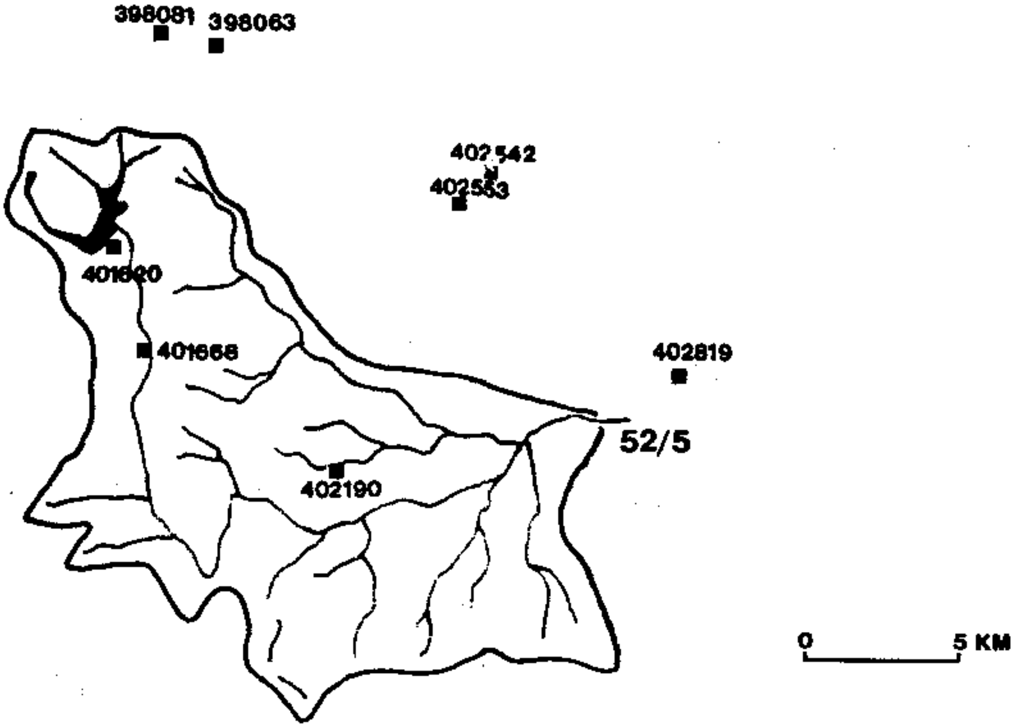


Figure 4.4. Catchment maps for the Tone at Bishops Hull (52/5) with locations of gauges used (Area = 202.0 km^2)

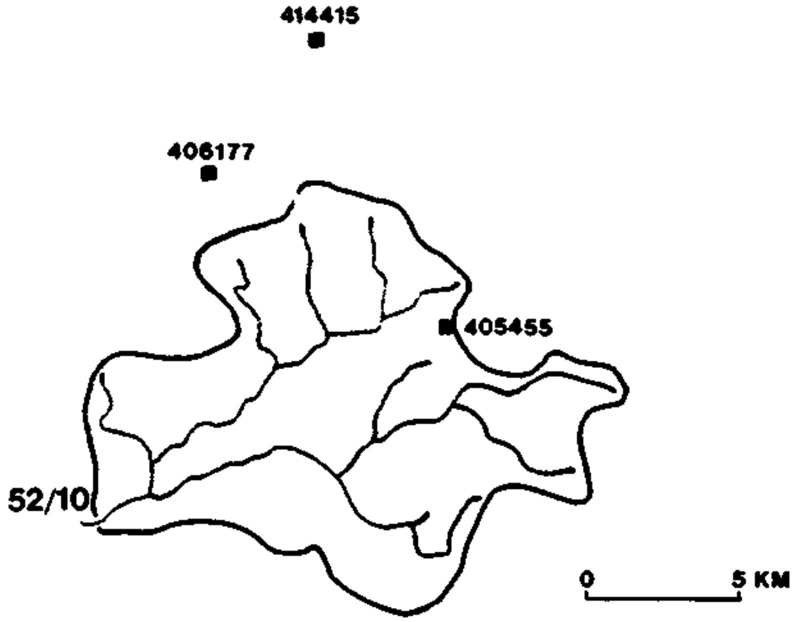


Figure 4.7. Catchment map for the Brue at Lovington (52/10), with locations of raingauges used (Area = 135.2 km^2)

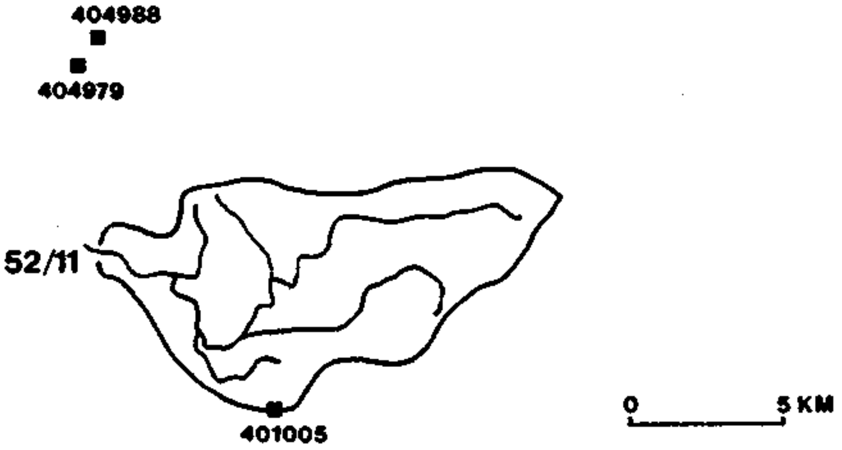


Figure 4.8. Catchment map for the Cary at Somerton (52/11), with locations of raingauges used (Area = 82.4 km^2)

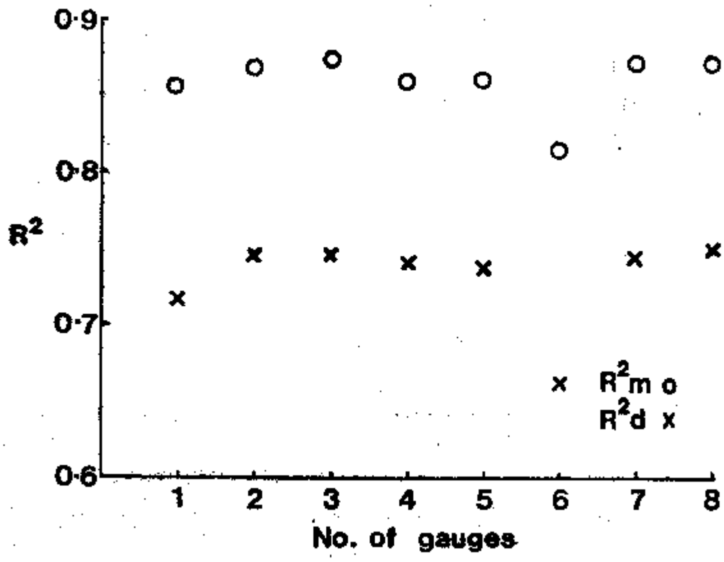


Figure 4.10. Relationship between R^2d, R^2m and number of gauges for the Tone at Bishops Hull (52/5)

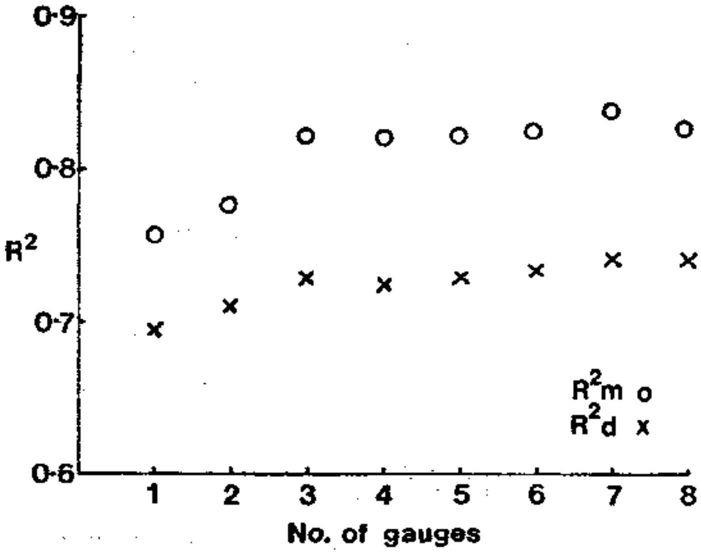


Figure 4.11. Relationship between R^2d, R^2m and number of gauges for the Yeo at Pen Mill (52/6)

5. NETWORK EVALUATION : OPERATIONAL ASPECTS

5.1 Introduction

There are two major factors which govern whether or not a raingauge network fulfils its purpose in supplying estimates of rainfall quantities of a desired accuracy to users: one of these is network density and configuration, as discussed in Section 3, and the other is the extent to which point measurements of rainfall provide a reliable and accurate representation of 'true' rainfall. The quality of observations is governed by the following major factors:

(i) the selection and maintenance of the raingauge and its site,

(ii) care and accuracy in measuring and reporting,

(iii) quality control of the data.

The proper maintenance of a raingauge site can be achieved by having regular inspections of the site, while the degree of care and accuracy in measuring and reporting depends largely on enthusiasm and care on the part of the observers. Good quality control can still only partially counteract the effect of poor observational practice.

Section 5.2 describes the methods employed to ensure that the data from raingauges are of a satisfactory standard. Section 5.3 reviews the network of gauges within the Wessex Water Authority (WWA) area in the light of the requirements described in Section 5.2.

5.2 Standards of rainfall measurement

5.2.1 Siting and maintenance of raingauges

The effectiveness of a raingauge in collecting precipitation will depend on a number of factors including the nature of the collector (i.e. its shape and size, the height of the orifice above the ground, and whether the rim of the gauge is level), and the nature of the site (i.e. the degree of over-sheltering from surrounding objects, or over exposure, and whether the surrounding ground is level).

The correct measurement and reporting of precipitation are equally important, since inaccuracy in either step will detract from the value of the observation. For this reason it is necessary for the gauge and rain measure to be carefully maintained and for there to be proper procedures to ensure that the measurements are made and reported correctly. The quality of the observations will be dealt with in Section 5.2.2.

The Meteorological Office (MO) provides guidance to observers on the choice of a raingauge, on its correct siting, on the care of

However, it is inevitable that the correct procedures will not always be followed (for example by an assistant observer), and that mistakes in observing or reporting will be made. Thus it is necessary to quality control the data before they are archived at the main collecting centre, which, for much of the daily and monthly data, is at the Meteorological Office, Bracknell. The data are subjected to a series of manual and computer checks (Shearman, 1975) in order to identify and correct any obvious errors. The errors are identified by a comparison of the indicated rainfall totals with data from nearby gauges, taking into account the variation in the annual average rainfall between them. Five kinds of errors occur most frequently:

(i) Wrong days: the rainfall is assigned to the wrong day for all or part of a month;

(ii) Indicated accumulations: the observations for a number of days are missed resulting in an accumulation of rainfall over several days when the gauge is eventually read, the accumulation being indicated by the observer;

(iii) Unindicated accumulations: as for (ii) but not reported by the observer as an accumulation;

(iv) Transposed values: the observations for two days are transposed when the rainfall card is being completed by the observer;

(v) Incorrect time of observations: sometimes it is impossible for the observer to read the gauge at the standard time. This will be important when significant rain has fallen between the standard time and the time of observation.

It is possible to identify sites where an improvement in observational practice is needed, by considering the number and types of errors at each gauge over an extended period.

5.3 Operational evaluation of the Wessex Water Authority network

5.3.1 Methods of evaluation

In order to indicate gauges which could or should be removed or retained during a rationalization exercise, three procedures can be used as parts of the evaluation

(a) Inspection of the sites,

(b) Inspection of the quality of the data,

(c) Consideration of the length and continuity of the records.

These procedures have been carried out for the gauges in the Wessex Water Authority area, with the following results.

Very Good quality data	≤ 5 indicated errors or 'flags'
Good quality data	Between 6 and 15 'flags'
Fair quality data	Between 16 and 30 'flags'
Poor quality data	Between 31 and 60 'flags'
Very Poor quality data	≥ 61 'flags'

The number of sites within each category of data quality are shown in Table 5.2 showing a rather disturbing incidence of faults at many stations.

Quality of Data	Number of Sites
Very Good	59
Good	51
Fair	33
Poor	20
Very Poor	56
Total	219

Table 5.2 Quality control error analysis for daily registered sites (Open 1975-1978)

5.3.4 Consideration of record lengths

For some purposes, very long data records are desirable, and it is therefore necessary to assess the importance of a gauge in terms of the length of its record. However, the length of record consideration will generally be less important than the quality of a site and the data it supplies, except in the case of extremely long records. Normally it will be preferable to retain a good site which is carefully maintained and provides good quality data even if it has operated for only a short period, rather than a poor site providing poor quality data but which has operated for many years. Sometimes, however, a good degree of overlap between two such sites is desirable.

The records for each daily and monthly station open in 1978 were categorised according to their lengths, using the following criteria:-

Very Long Records	≥ 60 years
Long Records	Between 30 and 59 years
Moderate length records	Between 20 and 29 years
Short Records	Between 10 and 19 years
Very Short Records	≤ 9 years

The number of stations with record lengths in each category are shown in Table 5.3.

5.4 Conclusions

Based on the operational factors described, 95 gauges of above average standard are available in the WWA area which could be considered as a basis for a rationalized network. However, as these gauges are rather unevenly distributed, they do not provide a particularly good initial basis for a design. There is probably considerable scope for improving the classifications of the remaining sites either by resiting gauges and/or changing observers. Such improvements to existing sites should be considered before closing down sites and introducing totally new sites into the network.

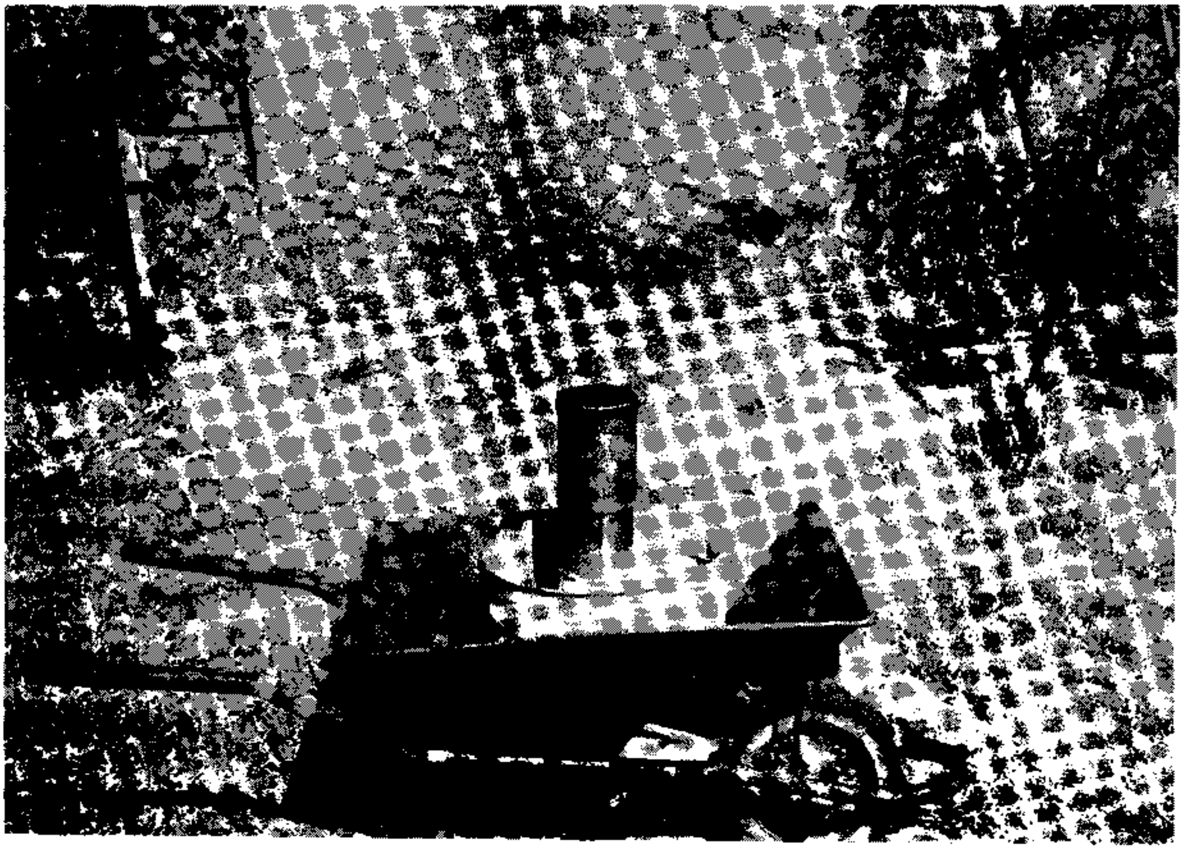


Figure 5.3 A poor quality site with a non-standard exposure (this site has been improved since inspection).

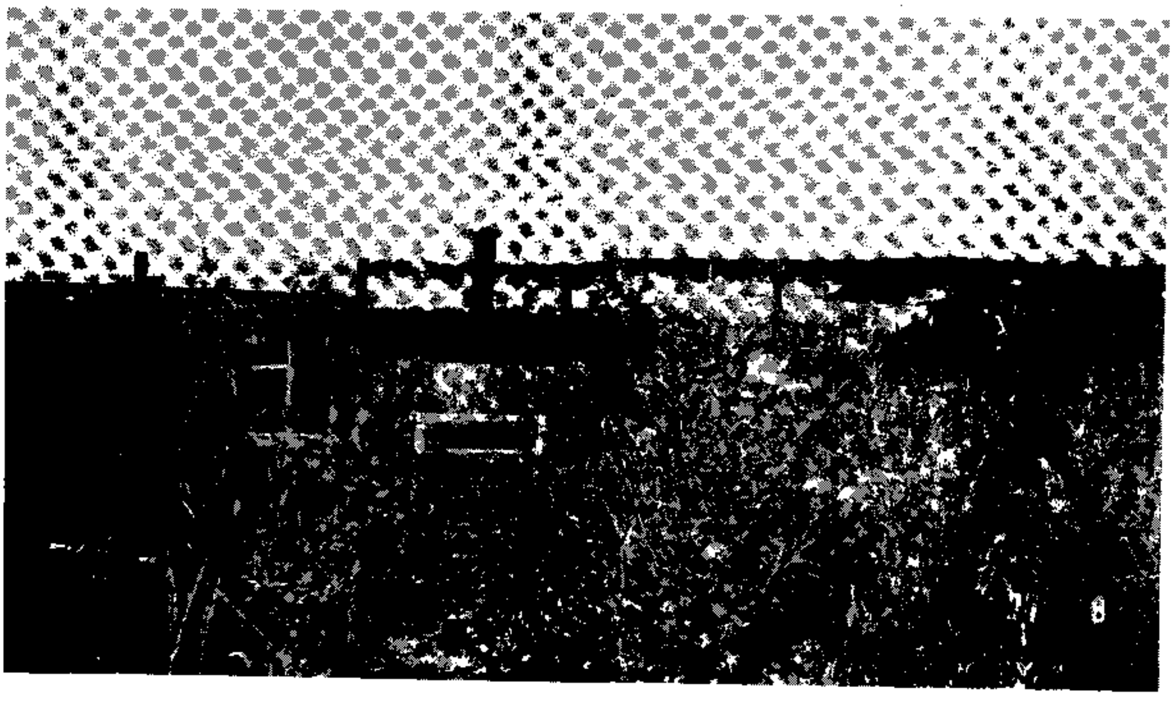


Figure 5.4 A poor quality site with a non-standard exposure (this site has also been improved since inspection).

6. NETWORK DESIGN

6.1 Introduction

In Sections 3 and 4 statistical procedures were described for evaluating the accuracy of estimation of various rainfall and streamflow quantities for a specified network of raingauges. However, such procedures are not in themselves sufficient to evaluate the performance of a network; the quality of the data supplied by a network is also important, and this is governed by raingauge siting, observational practice and quality control of the data. Procedures for evaluating the operational performance of a network have been described in Section 5.

Three basic approaches to the design of a raingauge network are possible:

(i) Ignore the existing network and design a new network on a regular grid, taking into account the correlation structure of the rainfall process

(ii) Keep the existing network and add gauges to fill in gaps. The network would be modified only when gauges close through natural wastage. In this event, the replacement of each gauge would be considered individually and it might be decided not to replace a gauge or to replace by more than one new site in order to improve the local distribution of gauges

(iii) Base a redesigned network on a selection of the existing gauges, using these where possible and filling in any gaps with new sites. Thus some existing gauges might not be used in the redesigned network.

Of these, the second approach is probably closest to the current situation in the WWA area although gaps have developed in the network and usually no objective procedures are applied to fill these. The first approach would obviously lead to a network which would be very costly to implement in practice. Here the third approach is adopted as this gives some control over the number of gauges appearing in the design network and thus allows considerable reductions on the existing number of gauges to be accommodated. As will be seen, the number and, more importantly, distribution of gauges in a network, together with the quality of the measurements, determine its adequacy in meeting user requirements for rainfall data. To what extent this is achieved for any design network can be evaluated using the techniques for calculating point and areal estimation errors described in Section 3, and by considering the quality of existing sites as described in Section 5. If, for some areas, special requirements for the use of rainfall data in modelling studies exist, then such studies can be used to provide guidance on network requirements in these areas. The type of modelling study carried out in Section 4 can be used to

(iv) the final network should include as many as possible of those gauges designated in Section 5 as Class A sites. As the Class A sites are not uniformly distributed, they could not be adopted initially to form part of the basic network.

(v) the final network should include a sufficient number of sites with long records.

6.3 Step-by-step approach to design of WWA network

6.3.1 Network of daily and monthly gauges

The total number of daily gauges currently operating in the WWA area is 333; of these 232 are registered with MO, the remaining sites being unregistered. The total number of monthly (including daily) gauges is 379, of which 262 are registered. Rather than attempting to arrive at a single final redesigned network, it was decided to produce a range of three possible designs as the final decision about which design should be adopted would probably be the subject of some negotiation between WWA, MO and MAFF. At the outset, the three designs were envisaged as follows:

(i) a skeleton network which would illustrate the effect of a radical reduction in the number of gauges in the WWA area. This will subsequently be referred to as Design Network 1.

(ii) a network which would satisfy all of the WWA requirements listed in Table 2.1 and meet MO and MAFF requirements over a percentage of the WWA area - this will subsequently be referred to as Design Network 2.

(iii) a larger network which would meet WWA requirements and also satisfy MO and MAFF requirements over most of the WWA area - this will be referred to as Design Network 3.

A step-by-step procedure was then applied, either wholly or in part, to evolve Design Networks 1-3; the steps were as follows:

Step 1

A gauge spacing was selected for the Basic Network; the choice of this spacing could be determined by a global background requirement for point or areal rainfall, or simply by a maximum gauge spacing acceptable to users. Then, using a map of all of the current registered daily gauges a set of gauge-sites from the existing network was identified which satisfied as closely as possible the inter-gauge spacing criterion. Where possible, Class A sites were included at this stage but as previously noted, their non-uniform distribution precluded selection of all of them at this stage.

Step 2

The network identified in Step 1 unavoidably contained areas where the gauge spacing exceeded that required; using a map on which all the calculating areal rainfall estimation errors. If user requirements were not met in certain areas, then the network was enhanced locally while some reduction in network density could be afforded in areas where user requirements were more than adequately met. In adding further new gauges to the Preliminary Design Network, a certain amount of deletion or movement of theoretically new sites in the Preliminary Design Network was carried out; the gauges involved may be categorized as follows:

(a) new gauges in the Preliminary Design Network to be deleted or moved to new grid references nearby

(b) existing registered gauges to be added

(c) existing unregistered gauges to be added

(d) further new sites to be added

(e) registered sites to be deleted

Following the modification of the Preliminary Design Network as described above, point and areal estimation errors were then re-evaluated; if the performance of the network in meeting user requirements was still found to be unsatisfactory, further iterations of Step 8 were carried out.

The above step-by-step design procedure was applied to produce the three Design Networks for the WWA area referred to earlier; while the application of the overall procedure can be summarized here, the detailed description of the evaluation of the various networks (Step 8) is deferred to Section 6.3. Details of the numbers of gauges introduced at each step for each of the three networks are given in Table 6.1; lists of the reference numbers (and for new gauges, grid references) are supplied in Appendix G.

Table 6.1(a) Number of gauges added at each step of design procedure for Design Network 1.

Step No.	No. of gauges added	Notes
1	72	Gauge spacing of 15 km
2	3	
Total	75	

Table 6.1 <u>Numbers of gauges after each step of design procedure</u> (continued overleaf)

As Design Network 1 was viewed as a skeleton network at the outset, only steps 1 and 2 of the full procedure were applied. A gauge spacing of 15 km was adopted and this produced a total of 75 gauges. A map of this network is shown in Figure 6.1. For Design Network 2, the breakdown of gauges for each of steps in the design procedure is given in Table 6.1(b). A gauge spacing of 10 km was adopted for the Basic Network to satisfy the necessity of a gauge every 10 km stipulated in Table 2.2; this resulted in a total of 133 gauges for the Basic Network (Figure 6.2), of which 23 were at new sites. Sites with greater than 50 years of record were selected at Step 5. The Preliminary Design Network contained 181 gauges; two iterations of Step 8 were required, resulting in a final total of 220 gauges for Design Network 2 (Figure 6.3).

In the case of Design Network 3, a gauge spacing of 7 km was adopted in Step 1; had a spacing of 5 km been adopted, suggested as desirable in Table 2.2, this would have resulted in an excessive number of gauges compared to the present network. The Basic Network resulting from the application of Steps 1-3 contained 221 gauges, of which 64 were at new sites. Sites with records longer than 25 years were selected at Step 5; the total number of gauges in the Preliminary Design Network was 280. One iteration of Step 8 was applied and this added 17 gauges to give a total of 297 gauges for Design Network 3 (Figure 6.4). Details of this network are given in Table 6.1(c) and Appendix G.

6.3.2 Network of recording gauges

The design procedure for daily and monthly networks described in Section 6.3.1 essentially depends on the quantification of the spatial correlation structure of rainfall over the whole of the WWA area; this was achieved using the RAINMASTER archive of daily and monthly data available at MO. While a total of 70 recording gauges (the term recording is here taken to cover all types of continuously recording and telemetering gauges) currently exist in the WWA area, no data from these gauges were available in computer compatible form for the present study. This largely precluded the use of any quantitative techniques at the design stage. However, by transposing some results obtained in other areas (Sections 3.4, 3.5 and 3.7) some general guidelines have been obtained.

Of the 70 recording gauges currently operating or installed in the WWA area, 31 are telemetering rainfall gauges. A large number of these (24) are sited in the Bristol Avon catchment and are specifically intended for use in flood warning. It is possible, however, that the data received from these sites will eventually be archived. The distribution of recording gauges in the WWA area is shown in Figure 2.4, where gauges at MO climate stations are distinguished from other gauges.

Sections 3.4, 3.5 and 3.7 describe relationships between root mean square error and distance for half-hourly totals of rainfall. These may also be used to give an indication of errors at different gauge spacings, although none of the data used came from within the WWA area.

Step 1

Using a map of the daily and monthly Design Network, and a map of all the existing recording gauges in the WWA area, possible recording raingauge sites at daily gauge sites were identified across the WWA area at a 20 km spacing to give a basic recording raingauge network. If no recording gauge already existed at these sites or nearby, then a new recording gauge was tentatively introduced at that site.

Step 2

All MO and Climat stations with recording gauges and which were not included at Step 1 were added here.

Step 3

All telemetering gauges, the data from which it is proposed to archive in the future, were added.

Step 4

Extra sites in urban areas and areas prone to flooding were identified. The towns needing recording gauges were judged to be Bristol, Bath, Keynsham, Chipping Sodbury, Radstock/Midsomer Norton, Frome, Trowbridge, Melksham, Salisbury, Bournemouth, Poole, Christchurch, Weymouth, Taunton, Yeovil, Bridgwater and Weston-super-Mare. For flood warning purposes, extra gauges were added in certain catchments in South-west Dorset and West Somerset. Sites with existing recording gauges were selected where possible.

Step 5

Recording gauges at sites in the daily/monthly Design Network which had not been already included were added.

Step 6

Those daily sites which were designated in Step 1 to have a recording gauge, but which do not at present, were reviewed. If these sites were within 4 km of a site added in Steps 2-4, then the sites added in Step 1 were replaced by the sites added in Steps 2-4.

Recording raingauge networks for Design Networks 1*-3*

As in the case of the daily and monthly network, only a skeleton network of recording gauges was considered for Design Network 1*. This was evolved by applying Step 1 only of the above procedure. The resulting network contained 32 gauges, of which six were at existing sites. As this network would in any case by supplemented by the 31 existing telemetry gauges, this brings the total number of gauges to 63. The numbers of gauges added at each step for Design Networks 2* and 3* are summarized in Table 6.2; detailed lists of the gauge reference numbers are given in Appendix G. The total number of

6.4 Evaluation of Design Networks

6.4.1 Networks of daily and monthly gauges

6.4.1.1 Evaluation of existing network

In Tables 2.1-2.2, the accuracy requirements of users of point and areal daily and monthly rainfall data have been specified. By mapping point interpolation error over the WWA area for the various design networks using the procedure described in Section 3.4, and comparing the maps of error with the requirements for interpolation accuracy specified in Table 2.2, areas of deficient accuracy were identified. Similarly, the procedures described in Section 3.6 for evaluating the accuracies of optimal areal rainfall estimates were also applied within the areas in the WWA area outlined in Figure 2.1.

As noted in Section 2.3, the MO survey of user requirements showed that users could only specify the accuracy required for gauge-site rainfall measurements, and were unable to specify reliably what a reasonable accuracy requirement would be for ungauged points. Accordingly, a map of point interpolation error for daily rainfall ≥ 1 mm was prepared for the network of all 333 daily gauges (both registered and unregistered) within the WWA area. A level of accuracy was then identified which could be met over a large proportion of the WWA area (of the order of 90%). The percentage of area with root mean square error (rmse) less than 1.5 mm was found to be 88.2%. In theory, therefore, point interpolation errors less than 3 mm for daily rainfall ≥ 1 mm can be achieved over approximately 90% of the WWA area, using the present network of all daily gauges. A similar exercise was carried out for monthly rainfall; for the existing network of 379 registered and unregistered gauges the percentage of area with rmse less than 6.5 mm was found to be 92.9%. Maps of daily and monthly point interpolation error are shown in Figures 6.9 and 6.10. Taking the viewpoint that any rationalized network should ideally not result in a reduction in accuracy to users, the figures of 1.5 mm rmse for daily rainfall > 1 mm and 6.5 rmse for monthly rainfall were adopted as user requirements to be satisfied over 90% of the WWA area; these are the figures quoted in Table 2.2. Accuracy levels for the remaining categories of daily rainfall given in Table 3.1 have also been derived and these are quoted in Table 6.3, while the results for monthly data are quoted in Table 6.4.

To explore the accuracies of areal rainfall estimates for the existing networks, three regions were selected to correspond to the major WWA requirements for areal rainfall estimates. These regions are shown in Figure 6.11 and correspond to the use of data for aquifer recharge (total area 1085 km^2), reservoir yield (total area 228 km^2) and flood design (total area 393 km^2) for which the required accuracies have been quoted in Table 2.1. The optimal areal estimation procedure was applied to the existing network of all daily gauges to establish the accuracies currently obtainable; these are given in Table 6.5 for each region. Results are also presented for sub-areas of each region, as, for a given network density, areal estimation error

Network	No. of gauges	% area ≤ 6.5 mm rmse
Network of Existing Registered Gauges	262	88.7%
Network of All Existing Gauges	379	92.9%
Design Network 1	75	43.6%
Design Network 2	220	90.2%
Design Network 3	297	96.1%

Table 6.4 Percentages of WWA area with rmse less than 6.5 mm for monthly data

An overall WWA areal accuracy requirement for monthly rainfall estimates has also been quoted in Table 2.1. Any arbitrary area within the WWA area could have been selected to see if this requirement is met by the network considered; for convenience, the River Avon catchment area used in Section 3.6 was selected. A section of this catchment was broken up into ten sub-areas and the estimation errors for optimal average monthly rainfall for each sub-area calculated for each network considered. A number of sub-areas of the same size have been selected to illustrate the effect of network configuration on these estimates. The results of these calculations for the existing networks, and for Design Networks 1-3, are given in Table 6.6.

6.4.1.2 Evaluation of Design Network 1

A map of point interpolation error for daily rainfall ≥ 1 mm was prepared for this network of 75 gauges. Figure 6.15 illustrates those areas for which the point interpolation error is less than 1.5 mm rmse: these amount to 41.9% of the total WWA area. Similarly, the corresponding percentage areas for the other categories of daily and monthly data in Table 3.1 were evaluated and are tabulated in Table 6.3 for daily rainfall and in Table 6.4 for monthly rainfall. These results illustrate that the accuracy supplied by the present network would not be attained over roughly 60% of the WWA area for all categories of data using Design Network 1. Figure 6.15 shows that for daily rainfall > 1 mm, the deficient areas lie to the west of the WWA area; a similar pattern was observed for the other categories of daily data and for monthly data.

	Root mean square error of optimal areal rainfall estimates					
Area (km^2)	Network of registered gauges	Network of all gauges	Design Network 1	Design Network 2		Design Network 3
				Basic	Total	
600	1.21	1.07	2.44	1.30	1.10	0.88
500	1.34	1.18	2.70	1.29	1.11	0.99
450	1.46	1.25	2.86	1.42	1.24	1.02
225	1.79	1.67	3.02	1.77	1.42	1.28
225	1.77	1.63	3.85	2.16	1.86	1.22
100	1.54	1.44	3.84	2.15	1.64	1.50
100	1.89	1.85	4.84	2.61	2.46	1.75
25	5.91	5.55	6.24	2.85	2.81	2.45
25	5.65	5.64	5.67	4.65	4.44	4.54
25	2.60	2.59	5.11	3.42	3.19	2.56

Table 6.6 Background optimal areal estimation errors for monthly data

of the design procedure (Iteration 1), resulting in the map of interpolation error shown in Figure 6.19 (% area $\leq$ 1.5 mm rmse = 90.7%). This network now satisfied the user requirement in Table 2.1 of having 90% of the WWA area with rmse $\leq$ 1.5 mm.However, it was felt that the remaining areas with deficient accuracy were relatively important, and so a further 19 gauges were added in these areas (Iteration 2). It is not possible to predict the exact effect of adding gauges on the map of interpolation error and so one or more iterations of mapping error and adding gauges are necessary in practice. Figure 6.20 shows that the areas of residual deficient accuracy are now almost all at the boundaries. In preparing the maps presented here, gauges from adjacent Water authority areas have not been included for interpolation near boundaries, as such gauges could in the future be the subject of a rationalization exercise. If and when this had been carried out, there is no reason why gauges in neighbouring water authorities could not be used to improve the present accuracies near the WWA boundaries.

At this stage, maps of interpolation error for the remaining categories of daily data and for monthly data were prepared; for all of these categories of data, the percentages of area with errors less than the specified level were all greater than 90%, and the distribution of areas of deficient accuracy was deemed to be acceptable. In Tables 6.3 and 6.4, a comparison can be made between Design Network 2 and the existing network of all 333 gauges, which shows that for the levels of interpolation error considered, the performance of Design Network 2 (220 gauges) is equal to that of the present network of 333 gauges. This illustrates the value of a proper design procedure.

Optimal areal estimation errors were calculated for the regions and subareas shown in Figure 6.12-6.14; the results in Tables 6.5 and 6.6 illustrate that the estimation errors for Design Network 2 are generally smaller than those observed for the existing network of all gauges. This essentially results from the better spatial distribution of gauges in Design Network 2. Also presented in Table 6.6 are results for the Basic Network, which represent the minimum areal accuracy attainable over the WWA area with Design Network 2. This compares favourably with the accuracy attained by the present networks.

Other attributes of Design Network 2 are that (i) the necessary requirement of a 10 km spacing between gauges is satisfied, (ii) all the Class A sites and (iii) a sufficient number of sites with long records are retained.

6.4.1.4 Evaluation of Design Network 3

Point interpolation error for daily rainfall $\geq$ 1 mm was again used initially in evaluating this design. Figure 6.21 is a map of point interpolation error for the Preliminary Design Network of 280 gauges detailed in Table 6.1(c); only a few small areas exist with rmse > 1.5 mm and the percentage of area with errors, $\leq$ 1.5 mm is 94.1%. To improve further the performance of this network, 17 gauges were added in areas of deficient accuracy, resulting in the map of interpolation error shown in Figure 6.22. Having obtained further maps resources a similar exercise would require if carried out at some time in the future. The figures quoted here are in terms of man-days and MO computer units (the current charge for 1 unit is £1), and are based on the experience acquired from the WWA case study. The MO resources required to design a hypothetical network of 500 gauges are broken down as follows:

(a) Computing

	No. of MO units		
	Monthly data	Daily data (3 categories)	Total
Creation of Data Sets	150	150	300
Calculation of sample correlations	300	900	1200
Fitting correlation functions	300	1500	1800
Error mapping	500	1500	2000
			5300

(b) Manpower

Inspection of sites	63 days - Higher Scientific Officer (HSO) time
Computing	20 days - Higher Scientific Officer (HSO) time
Analysis and Network Design	26 days - Senior Scientific Officer (SSO) time
General Support	5 days - Higher Scientific Officer (HSO) time 15 days - Assistant Scientific Officer (ASO) time
TOTAL	15 days ASO time 88 days HSO time 26 days SSO time

Some of the above resources may, in any case, be deployed by the MO in the future, for example, to estimate the correlation structure of rainfall on a country-wide basis for use in the MO quality control program. There would also be the possibility of a water authority sharing the manpower resources required for site inspection. Thus, the figures quoted above should be regarded as flexible.

The water authority input to a rationalization exercise would to some extent depend on the level of involvement in the site inspections. The resources provided by WWA for the present study were entirely in terms of manpower and can be broken down as follows:

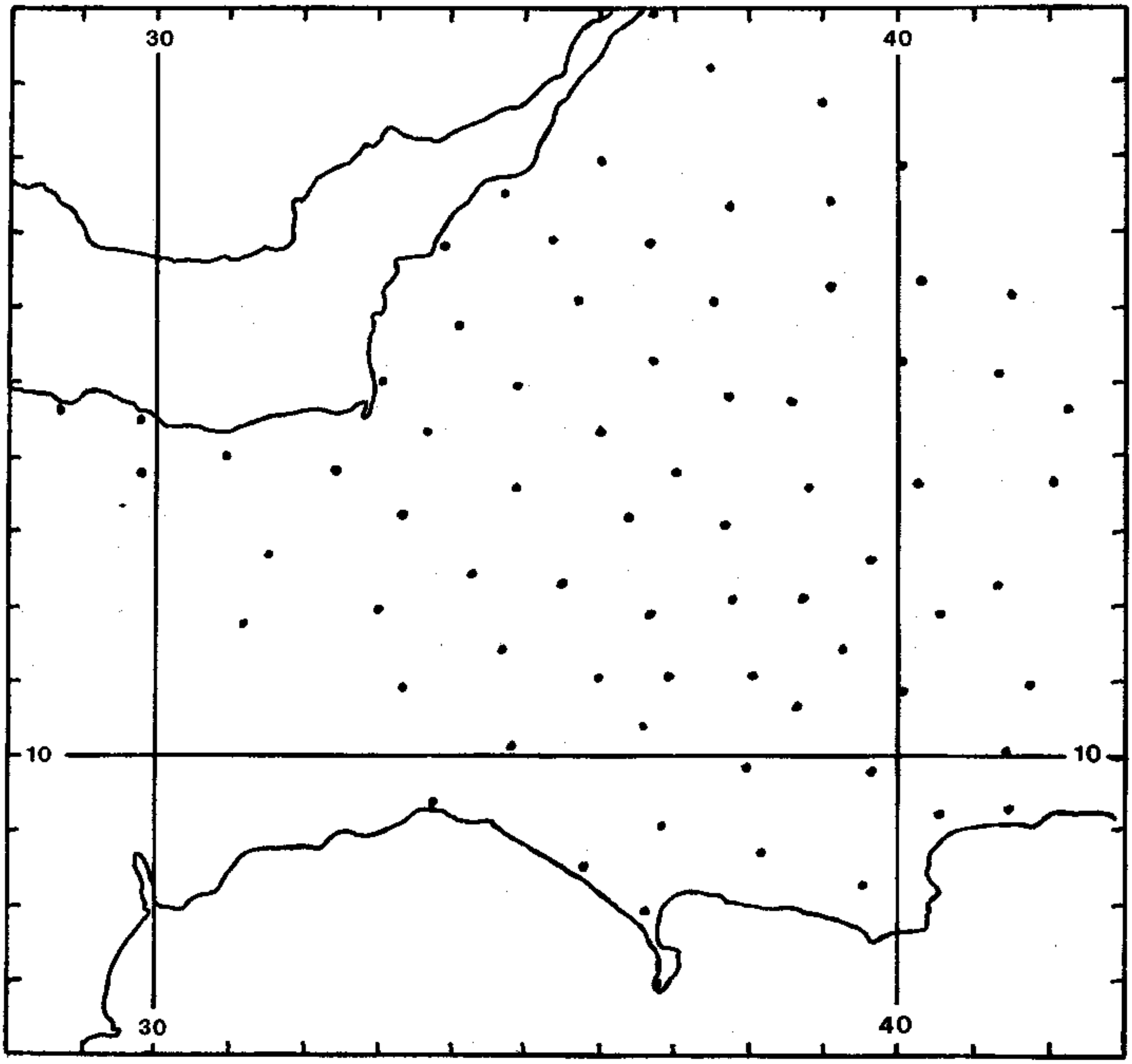


Figure 6.1 Positions of gauges in Design Network 1

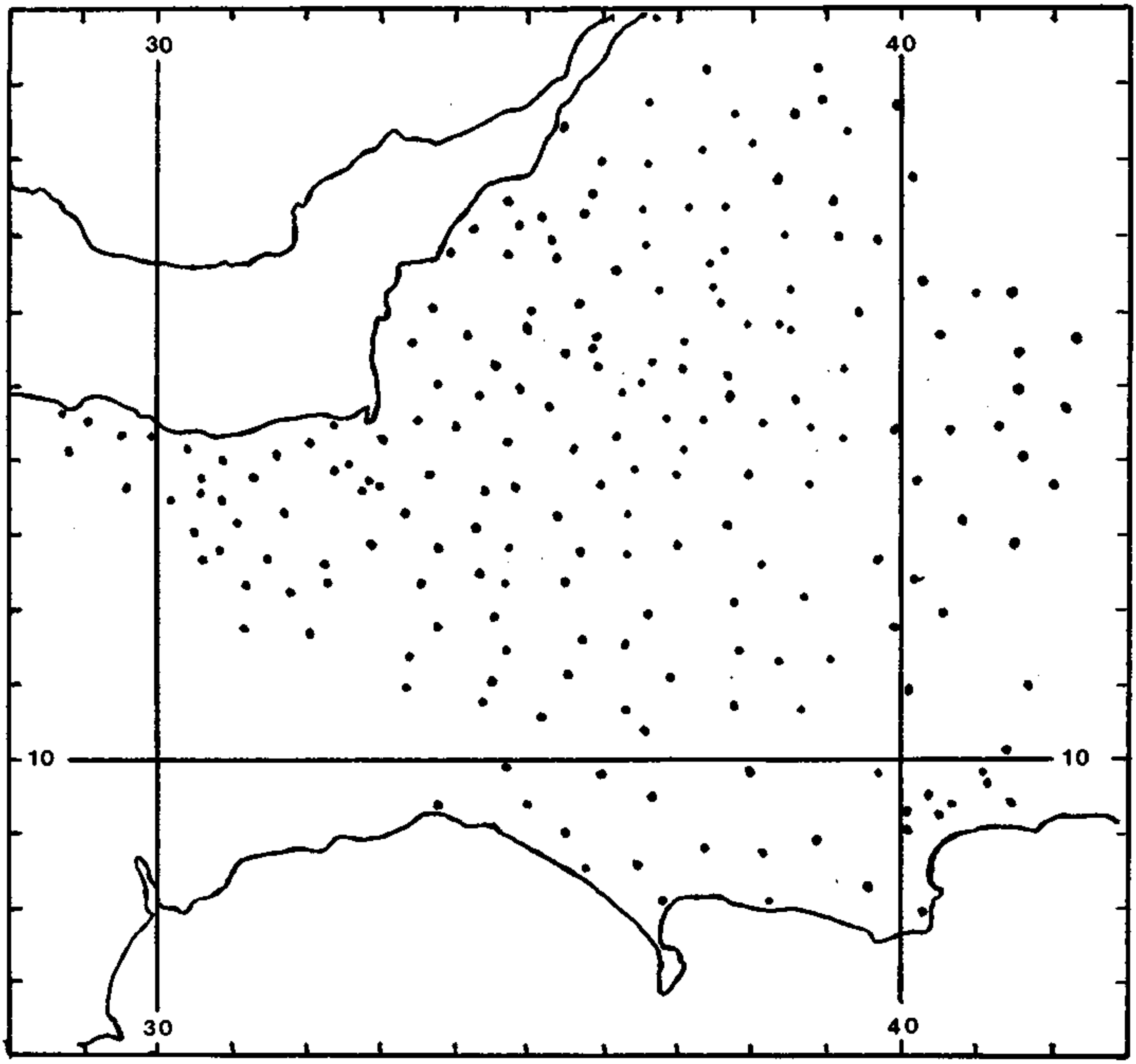


Figure 6.3 Positions of gauges in final Design Network 2

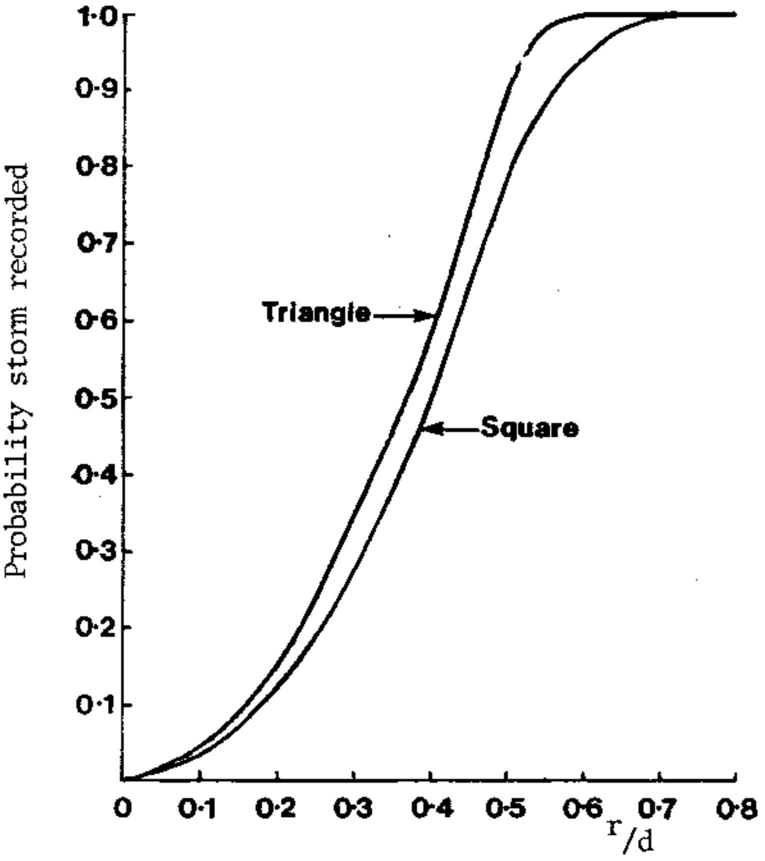


Figure 6.5 Relationship between the probability that a symmetric, stationary storm is recorded at one or more gauges in a network, the radius of the storm (r) and the distance (d) between gauges. For regular triangular or square lattice networks.

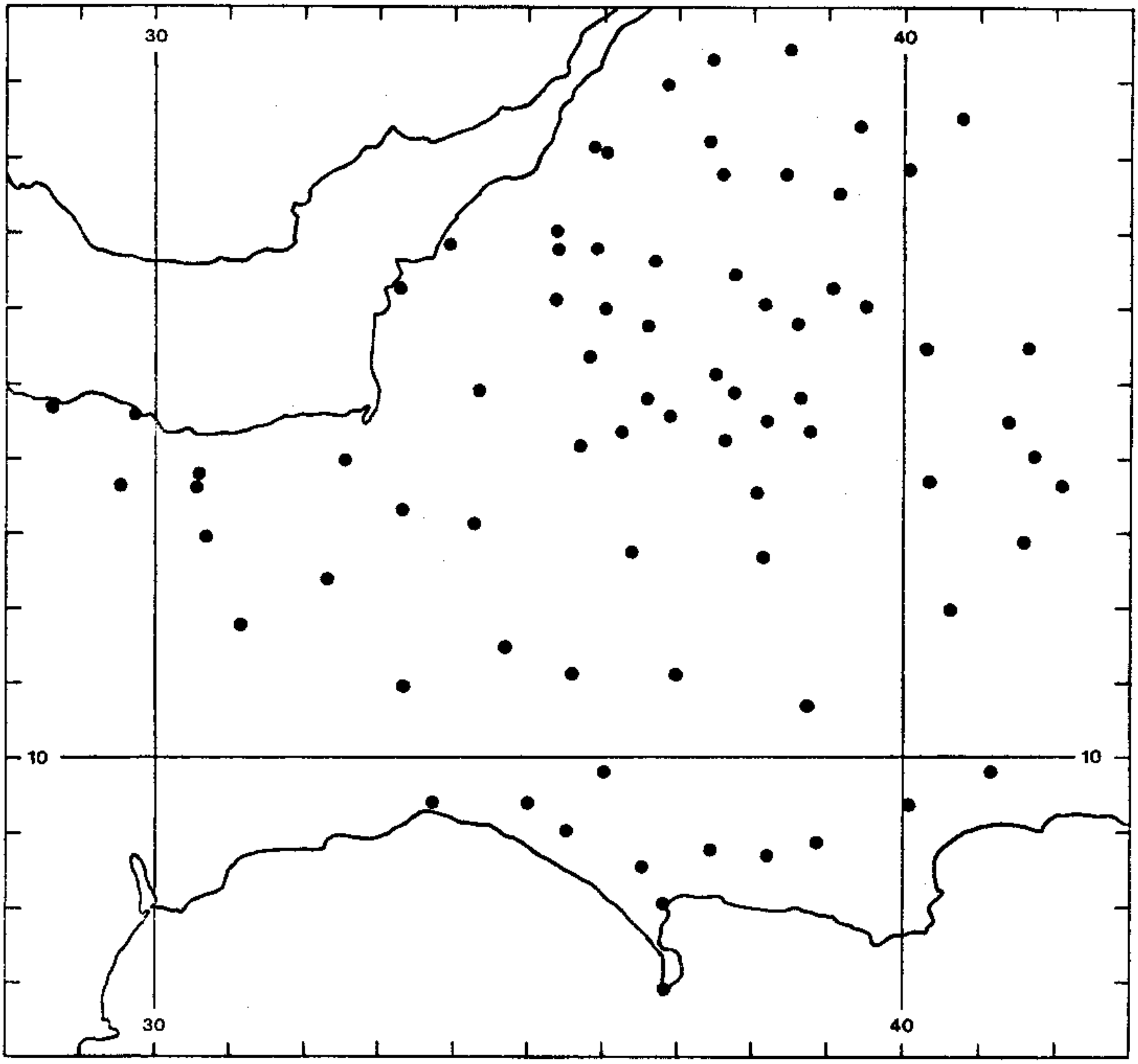


Figure 6.7 Positions of recording gauges in Design Network 2*

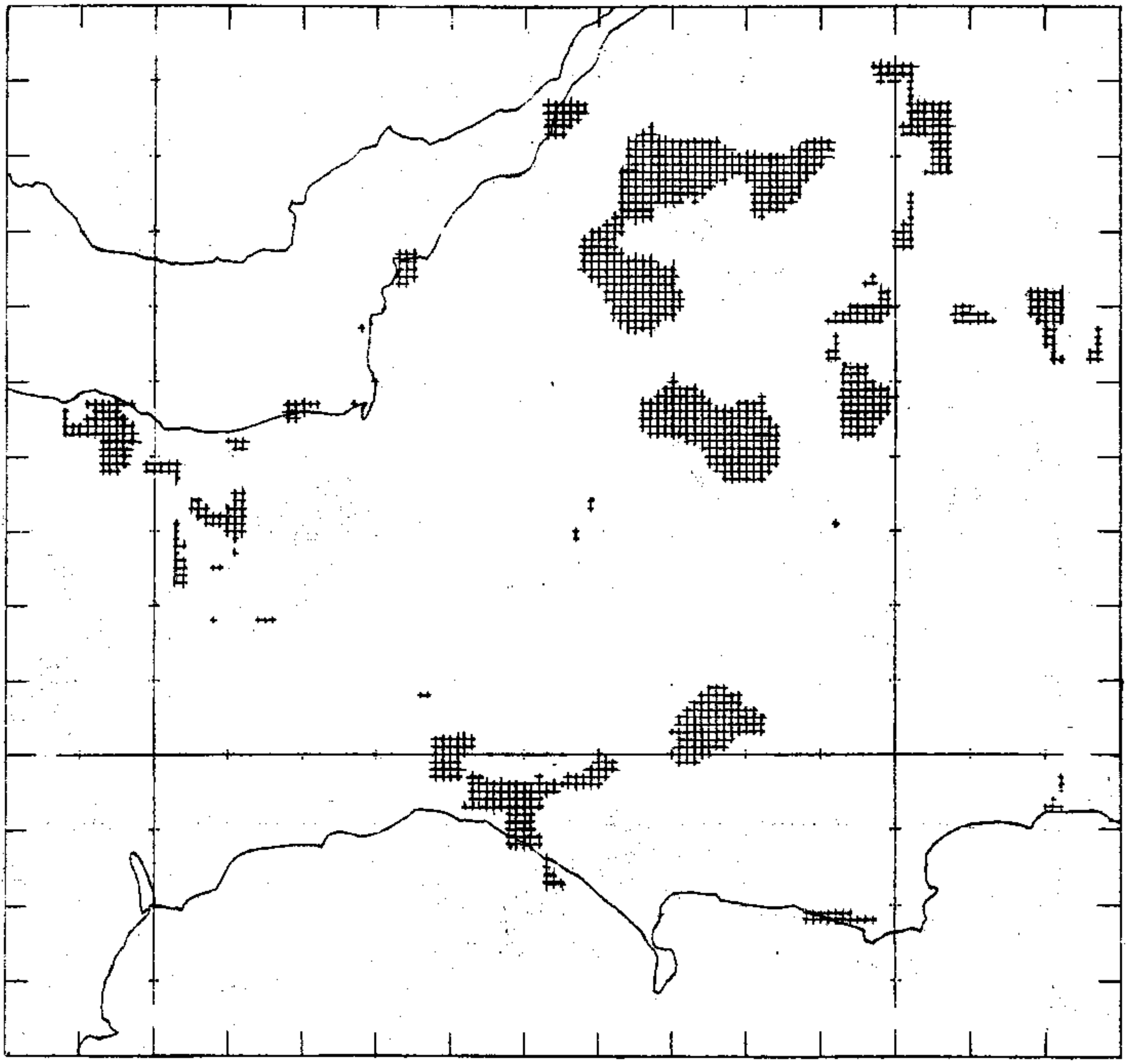


Figure 6.9 Regions (shaded) for which the rmse of optimal interpolation is greater than 1.5 mm for days with widespread rainfall of over 1 mm

The existing network (333 gauges)

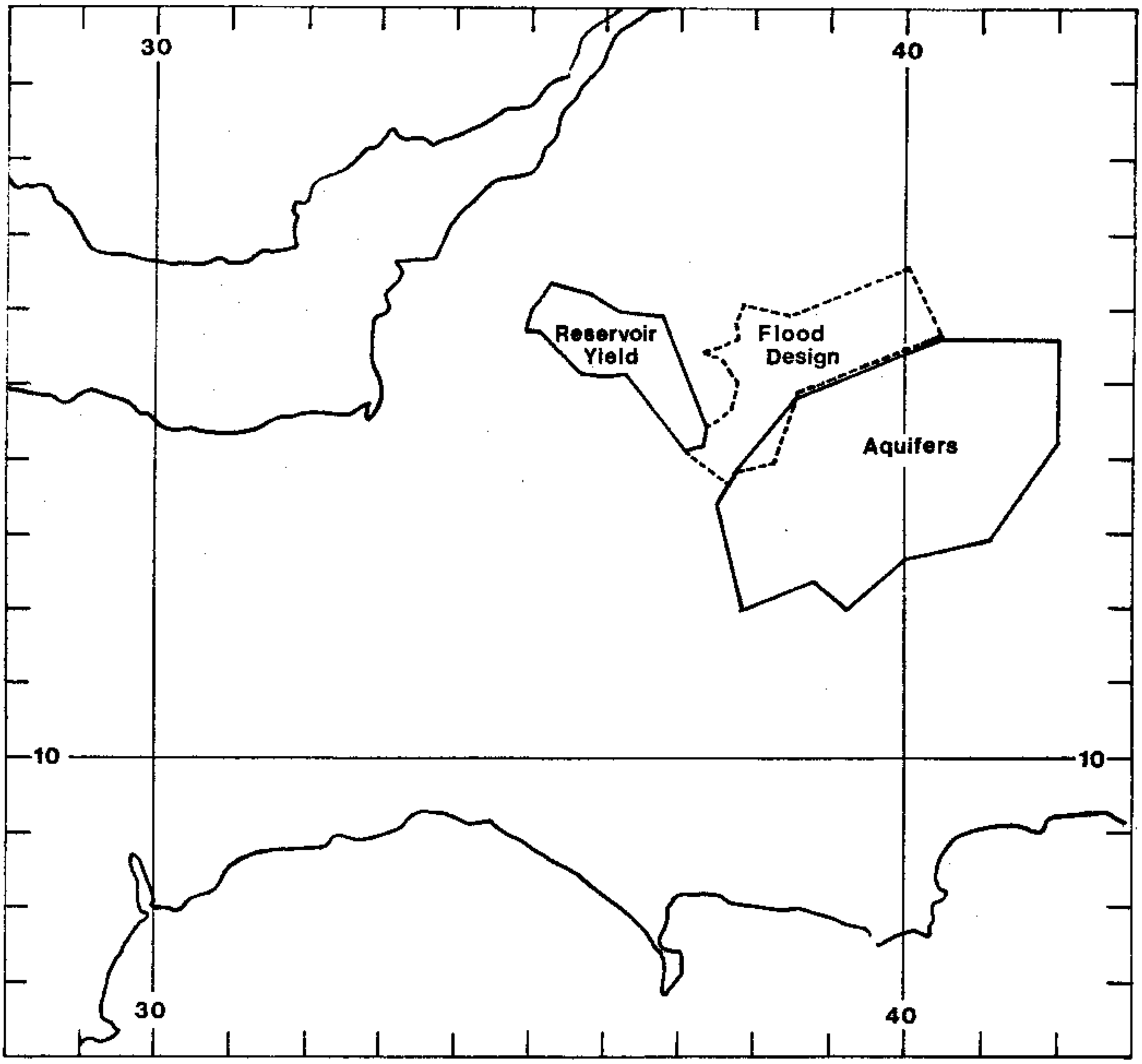


Figure 6.11 Regions chosen to assess the accuracy of average areal rainfalls. Different accuracies are required for the different applications.

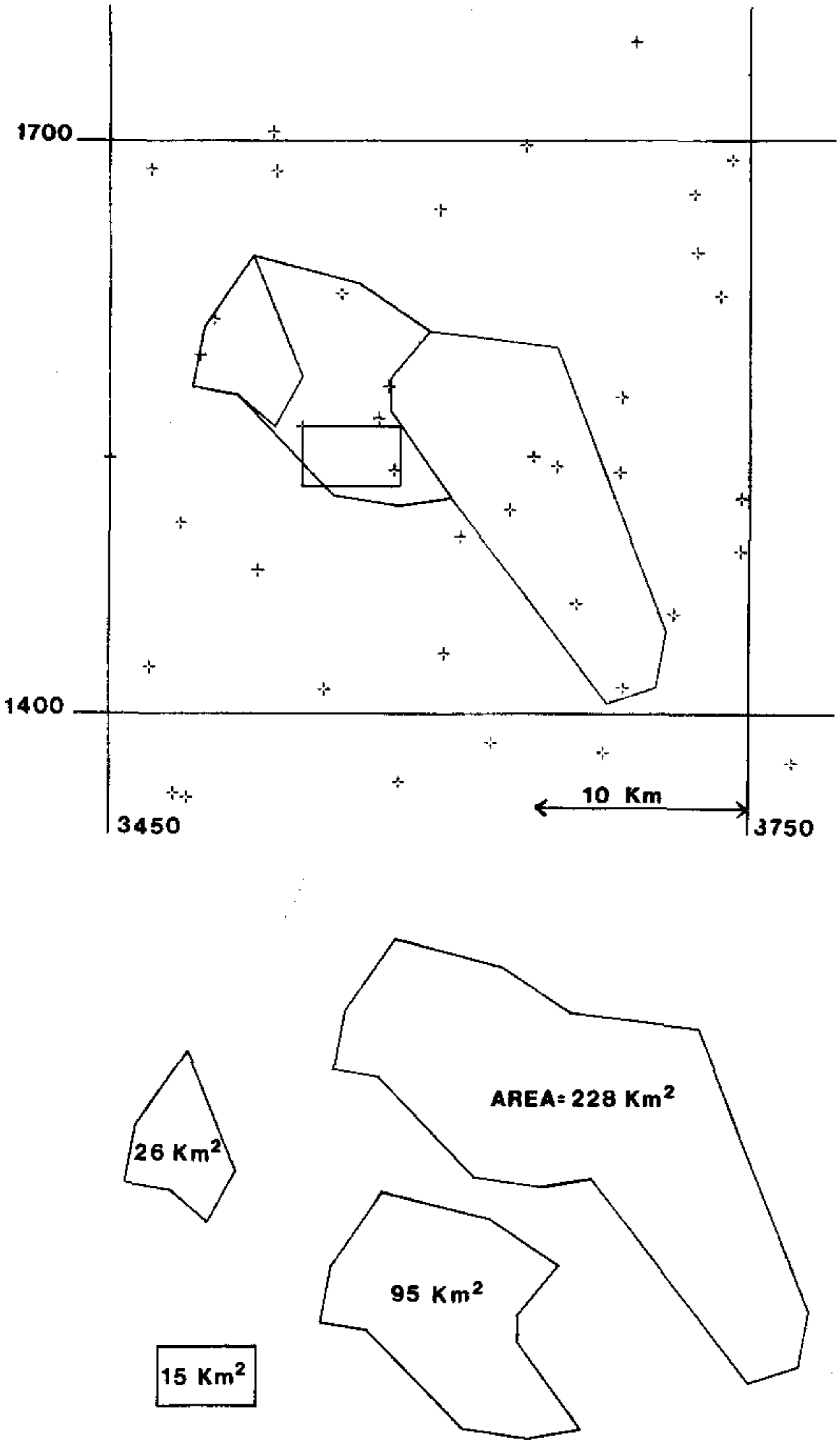


Figure 6.13 The subregions of the 'Reservoir Yield' region used. The gauges shown are those in the *final Design Network 2*.

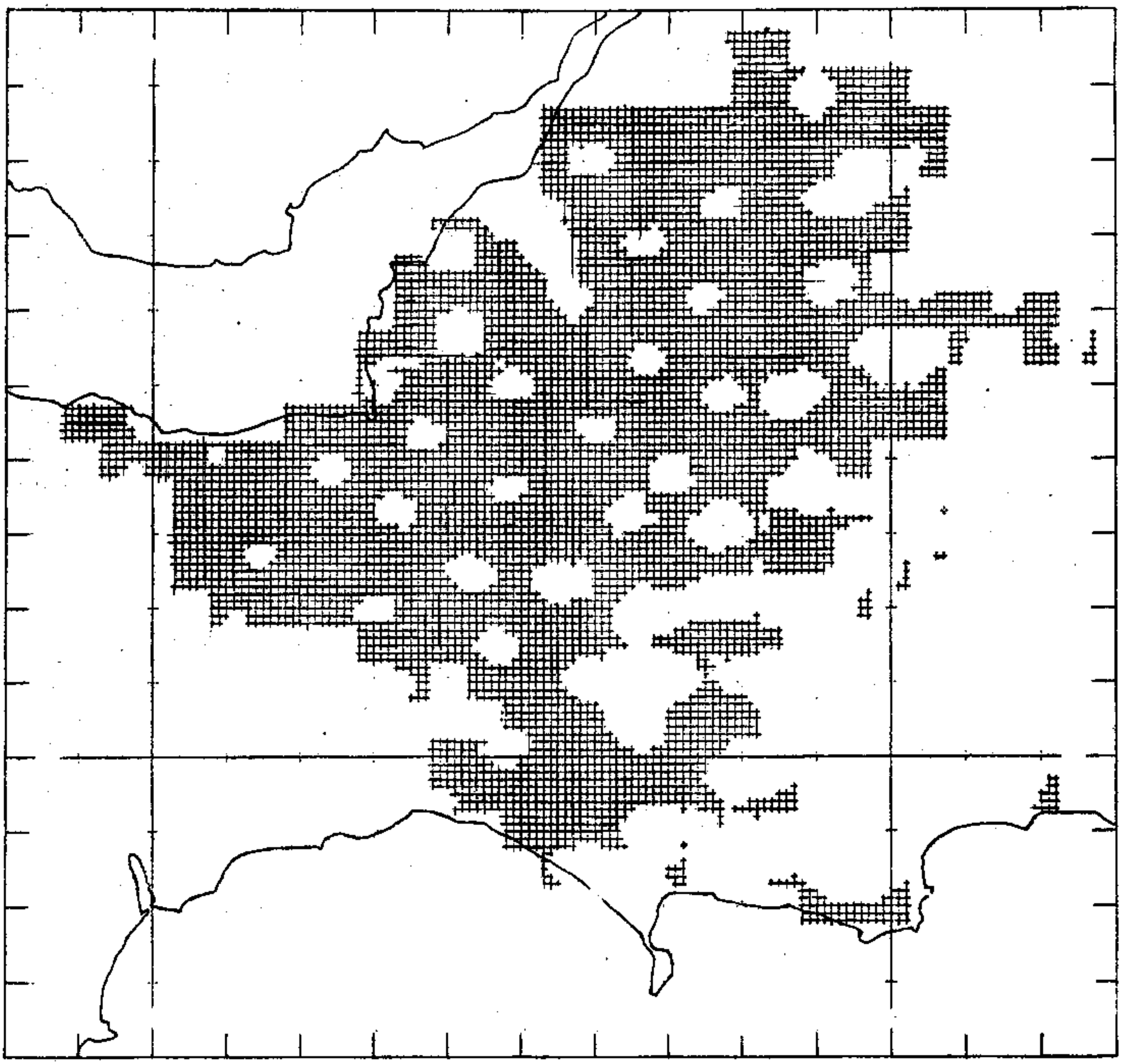


Figure 6.15 Regions (shaded) for which the rmse of optimal interpolation is greater than 1.5 mm for days with widespread rainfall of over 1 mm.

Design Network 1 (75 gauges)

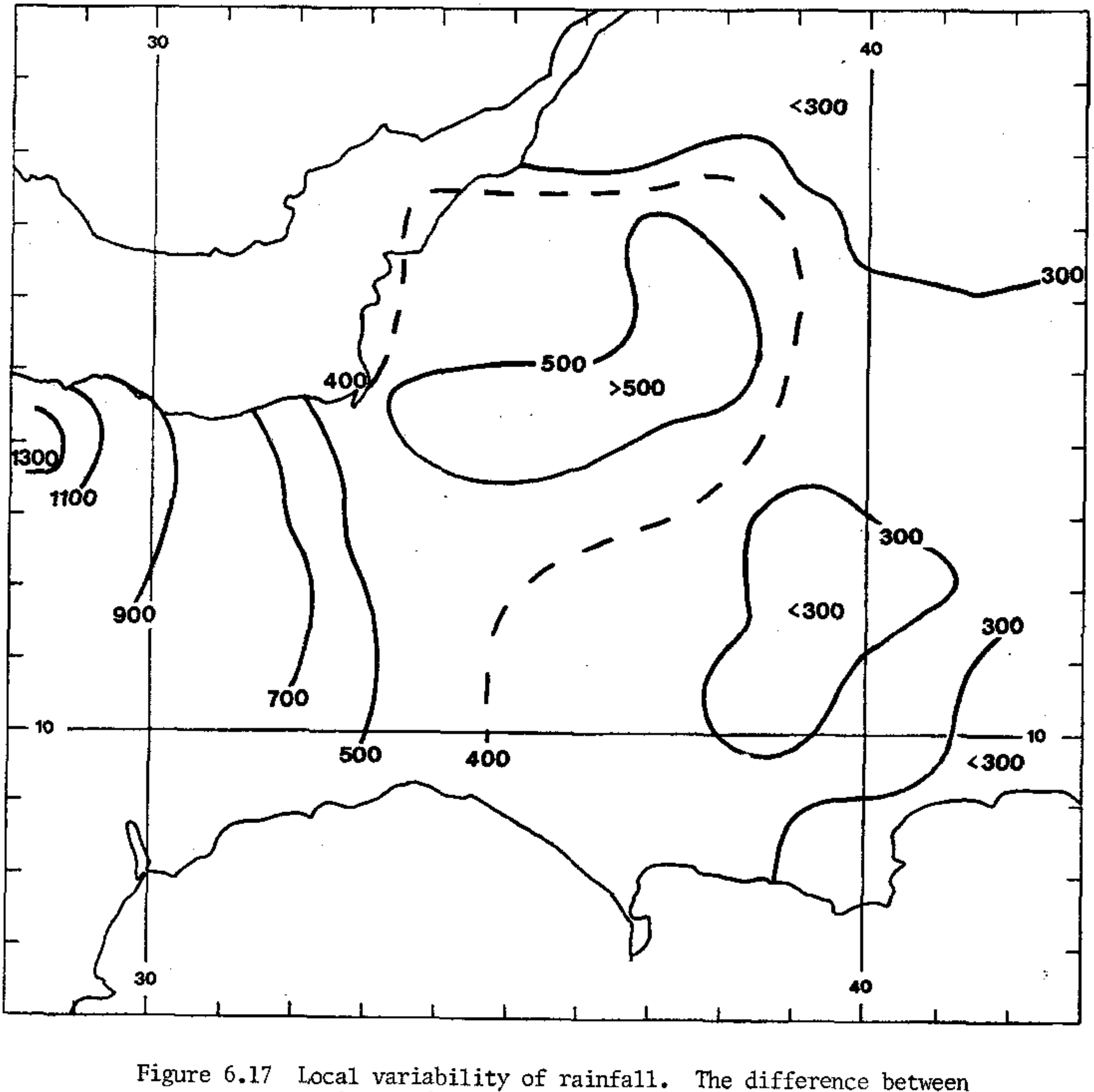


Figure 6.17 Local variability of rainfall. The difference between maximum and minimum annual average rainfall in regions of diameter 35 km.

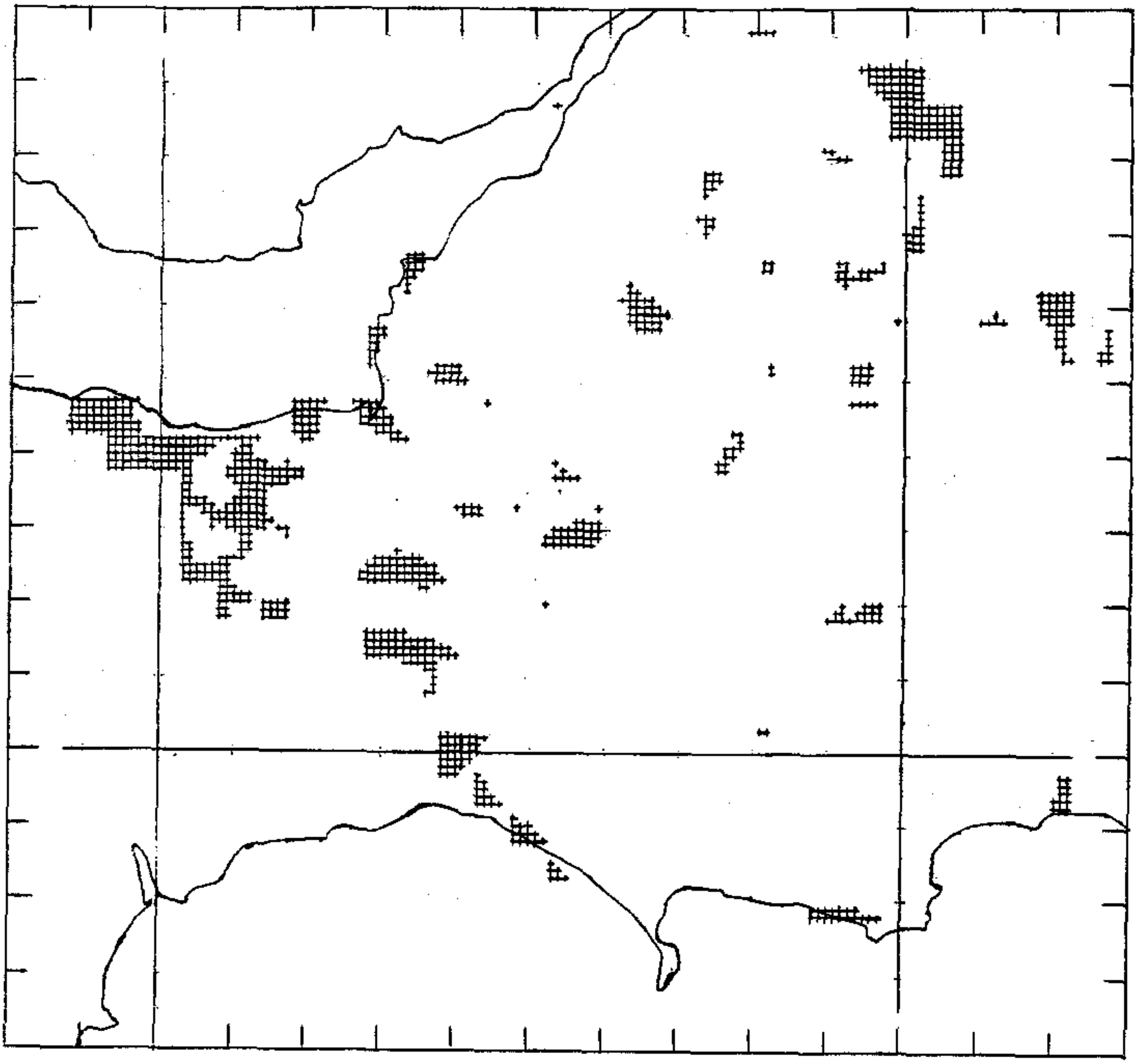


Figure 6.19 Regions (shaded) for which the rmse of optimal interpolation is greater than 1.5 mm for days with widespread rainfall of over 1 mm.

First iteration of last step in producing Design Network 2 (201 gauges)

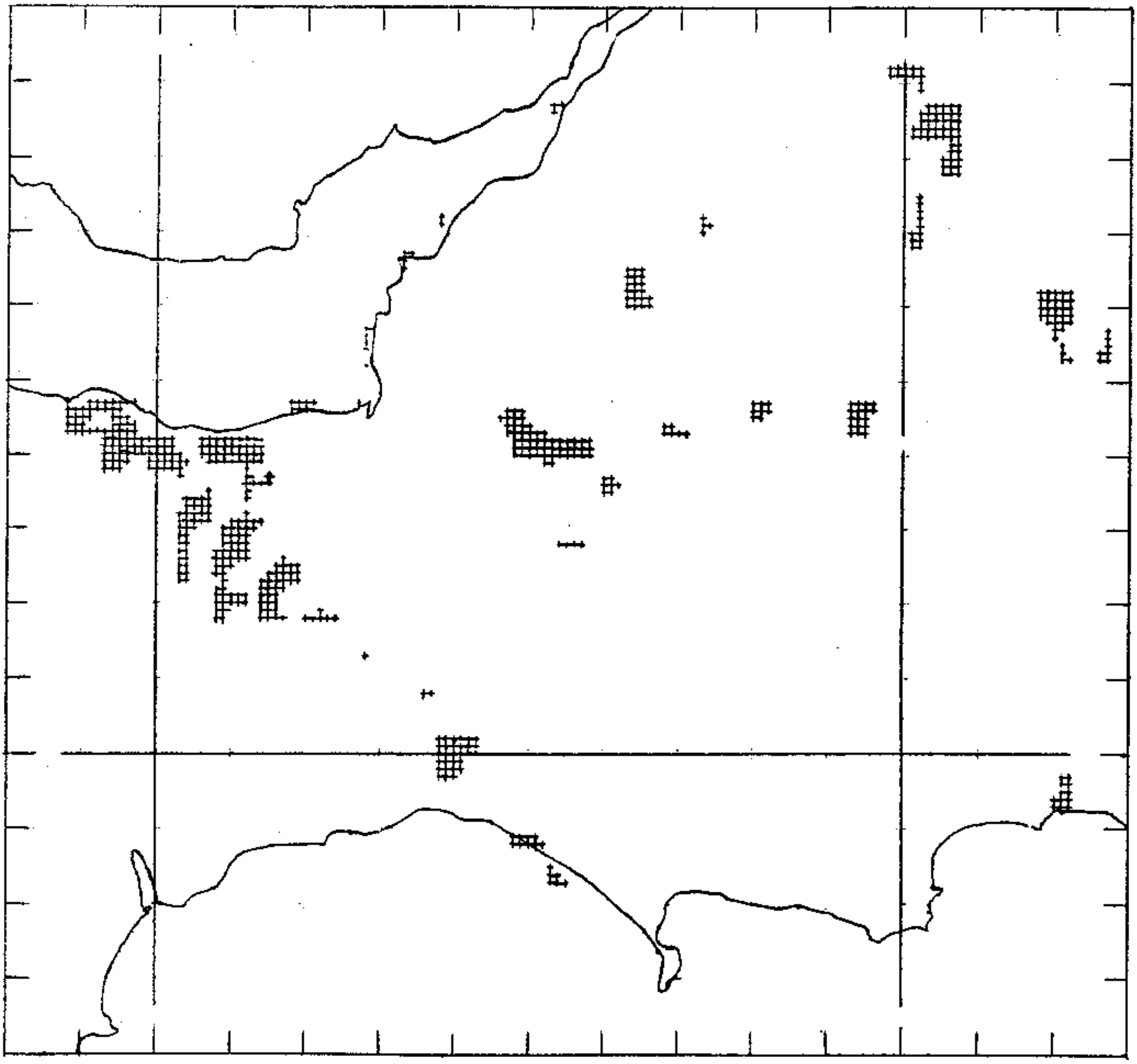


Figure 6.21 Regions (shaded) for which the rmse of optimal interpolation is greater than 1.5 mm for days with widespread rainfall of over 1 mm.

Preliminary Design Network for Design Network 3 (282 gauges)

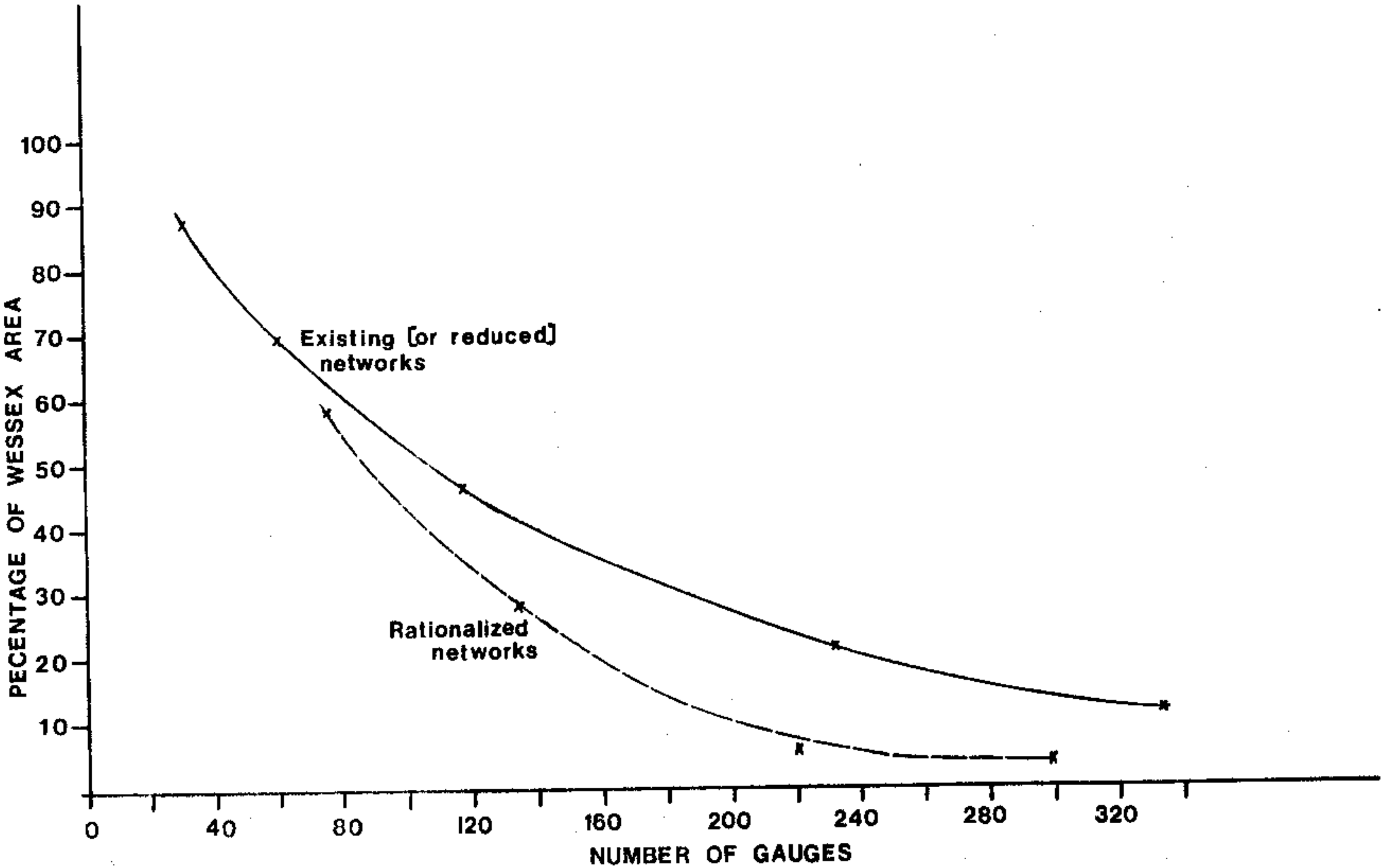


Figure 6.23 Percentage of WWA region having a root mean square error of interpolation greater than 1.5 mm (for days with more than 1 mm rainfall) for different networks considered in this report.

7. NETWORK OPERATION: LOGISTICS AND COSTS

7.1 Background of Wessex Water Authority Network

At the present time (June, 1978), the raingauge network within the Wessex Water Authority (WWA) region consists of 379 daily and monthly read gauges and 70 recording gauges. This represents a reduction of approximately 70 daily and monthly gauges over the past four years since the reorganisation of the water industry in 1974. During the same period the number of gauges recording short duration data has increased by 30, most of these being telemetering gauges installed in the Bristol Avon catchment. Of the daily and monthly gauges 262 are registered with the Meteorological Office (MO). The MO are currently considering the possibility of registering other sites on the basis of the site inspections undertaken during this study. Other meteorological parameters, besides rainfall, are measured on a regular basis at 30 sites in the region: these can vary from wet and dry bulb temperature readings to manual or automatic climatological stations recording all variables required for the calculation of potential evapotranspiration.

In any network of this size changes are occurring almost continuously and, as has already been seen, there has been a substantial net reduction in the raingauge network density since 1974.

7.2 Maintenance of network

Many changes in the network are unplanned, as observers move away from the area or die, and it is necessary to keep a close check on the receipt of records so that the reasons for a missing return may be established and the difficulty overcome as quickly as possible. With a daily-read raingauge network the observer is as important, if not more important, than the site and it is often the case that when one observer leaves another suitable person cannot be found in the area even though satisfactory sites exist. This emphasis is highlighted in Figure 7.1 which shows diagrammatically the procedure adopted for establishing a suitable rainfall measuring station. Changes in the network may also be necessary as a result of continued vandalism or damage even though the observer and site are otherwise satisfactory.

Regular inspections of the network are fundamental to its operation; these are undertaken by WWA staff at intervals of one to two years and by the Meteorological Office inspectors less frequently. As a result of such visits repairs or replacements to raingauges or measures may be required, changes of site or improvement to the area surrounding a gauge may be recommended to reduce over- or under-exposure, and further instruction to the observers may be necessary to improve the procedure followed in taking and reporting the measurements.

7.3 Control of network

Control of the WWA network is exercised in two ways, firstly by the

	Cost per year (£)		
	Existing	Design Network 1*	Design Network 2*
Postcards - daily gauges	100	20	60
Charts - autographic gauges	280	230	320
Postage (1st class - postcards monthly, charts weekly)	590	230	450
Total Stationery	970	480	830
Replacement gauges - daily	750	200	400
- autographic	600	500	700
Installation	120	50	70
Total Replacement	1470	750	1170
Site inspections	600	200	300
Maintenance of gauges	120	50	70
Total Upkeep	720	250	370
Checking of raw data	600	130	330
Corrections and coding	450	100	250
Quality control	1200	250	650
Analysis of charts	650	530	770
Computer time (inc. data preparation)	8000	2700	5000
Total Processing	10900	3710	7000
TOTAL ANNUAL COST	14060	5190	9370

Table 7.2 Operation and data processing costs for the three networks in Table 7.1

The numbers of replacement gauges, inspection and maintenance costs, and data processing costs have been estimated from experience gained in operating the WWA network but may vary substantially in other areas. The cost of telemetering raingauges has not been included in Table 7.2 because the marginal costs of raingauges in a telemetering scheme are difficult to estimate, and because local siting factors may be very important in giving costings. It can be seen from Table 7.2 that, whilst some savings in stationery, inspections and maintenance are made in the operation of the smaller networks, the main financial benefits accrue from the reduced involvement in data processing. Savings in manpower costs associated with quality control, coding and data preparation as well as in computing time could result from the operation of a smaller network. The costs however are small in comparison with the overall expenditure of a

(iv) to create maps of point interpolation error for each network considered and to calculate accuracies of estimates of average areal rainfall.

It is clear that it will not be necessary to repeat all these steps if, at some time in the future, it is required to assess the WWA raingauge network as it then exists.

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* Note :- O'Connell et al (1977) contains an extensive bibliography of investigations of the spatial variability of rainfall processes, raingauge network accuracy considerations, the principles of network design, local and global direct methods of design and of indirect methods of design.

$$E(U^2) = \mu_u^2 + \sigma_u^2, \quad E(V^2) = \mu_v^2 + \sigma_v^2,$$

$$\mathrm{var}(U^2) = 2\sigma_u^2(\sigma_u^2 + 2\mu_u^2), \quad \mathrm{var}(V^2) = 2\sigma_v^2(\sigma_v^2 + 2\mu_v^2) \qquad (A.2)$$

$$\mathrm{cov}(U^2, V^2) = 2\sigma_{uv}(\sigma_{uv} + 2\mu_u\mu_v).$$

The maximum likelihood estimate of, for example, $\mathrm{cov}(U^2, V^2)$ is given by $2\hat{\sigma}_{uv}(\hat{\sigma}_{uv} + 2\hat{\mu}_u\hat{\mu}_v)$, where $\hat{\sigma}_{uv}$, $\hat{\mu}_u$, $\hat{\mu}_v$ are the usual maximum likelihood estimates of σ_{uv}, μ_u, μ_v derived from the distribution of (U,V).

The estimate $\hat{\mu}_u$, for example, is

$$\hat{\mu}_u = \frac{1}{N}\sum_{t=1}^{N} U_t.$$

Now if only (U_t^2, V_t^2) are observed, there is some ambiguity as to the sign of each U_t and V_t. However, if the standard deviations σ_u, σ_v are small compared with the corresponding means μ_u, μ_v (as in this case where $\hat{\mu}_u \sim 8$, $\hat{\sigma}_u \sim 2.5$), then there is a very small chance of a negative value of U or V arising from the underlying population. Therefore the U_t and V_t can always be taken to be positive with little effect when calculating the sample moments of (U_t, V_t). Maximum likelihood estimators for the means and variances follow similarly from equations (A.2).

In the case of daily data, application of a square root transformation leads to a set of data still containing a high proportion of zeros: the transformed data are therefore markedly non-Normal and the method suggested above for monthly data cannot be applied as the "underlying" Normally distributed data cannot be recovered

Marshall (1976) has suggested the use of a truncated square root transformation to describe daily total rainfalls. Thus if U has a Normal distribution with suitable mean and variance, the recorded daily total rainfall Y is modelled as

$$Y = \begin{cases} 0 & \text{if } U < c^{\frac{1}{2}}, \\ U^2 & \text{if } U \geqslant c^{\frac{1}{2}}, \end{cases} \qquad (A.3)$$

where c is a number describing the smallest rainfall that would be reported. This basic model was extended by Marshall to a multisite model for sequences of rainfall totals by using a multivariate

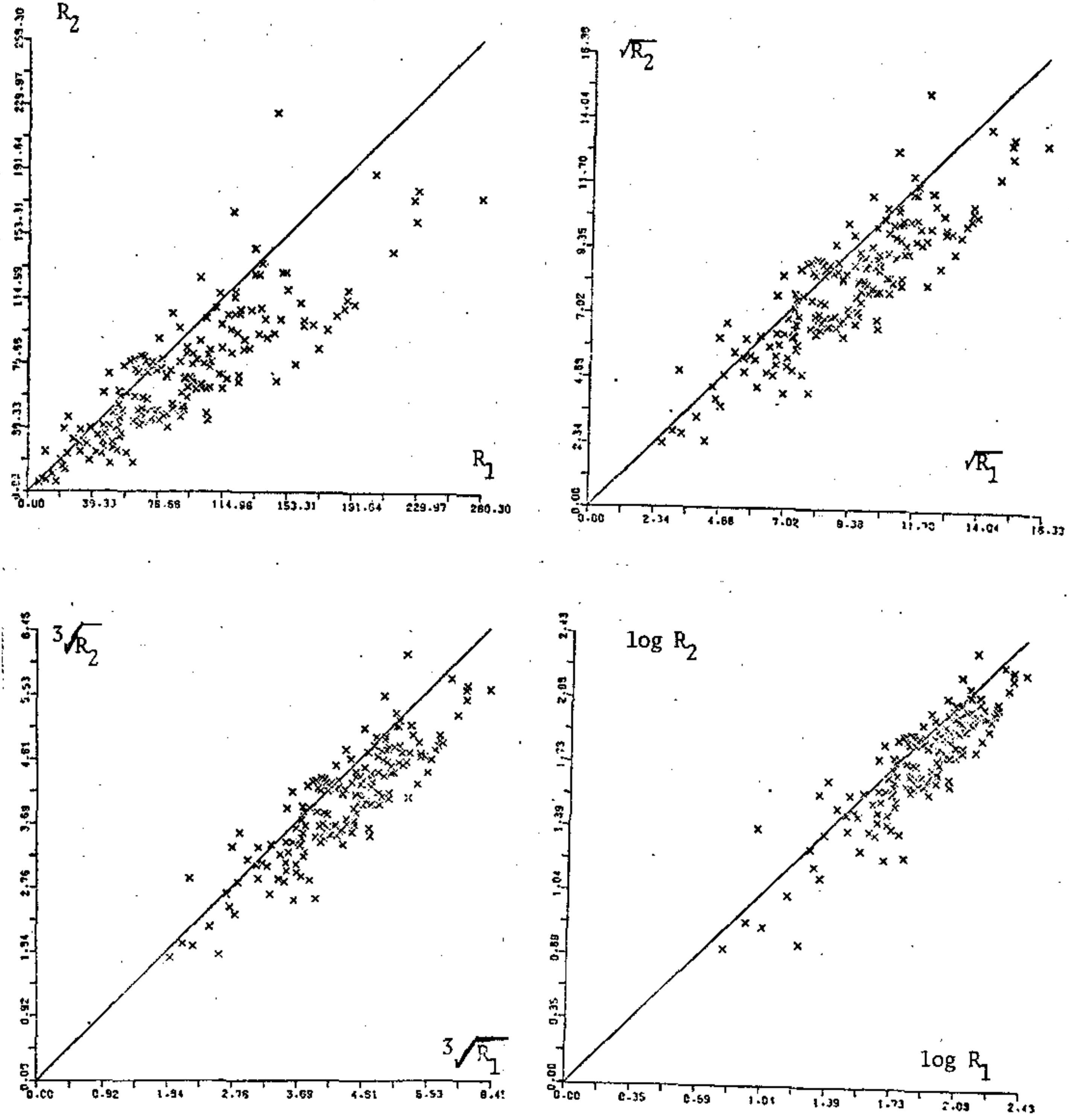

Figure A.1: Recorded rainfalls at two gauges plotted together under different transformations and finally

$$g(a, b, c_1, c_2, \varepsilon) = \sum_{j=1}^{Q} (n_j - k) (z_j - f_j)^2 \qquad (B.2)$$

where k is a particular constant. Section 4.4.2 of PhlR stressed that, while there is no strict justification for the above procedure, it is a reasonable fitting technique which gives less weight to those sample correlations calculated from fewer data pairs and which takes some account of the change of variance of the sample correlations as the true correlation changes. As in PhlR, k was given the value 36 for monthly data and 3 for daily data. An additional consideration was introduced into the computer implementation of the above calculations, namely that any sample correlation calculated from less than a given number of pairs of values was ignored: this avoids negative terms appearing in equation (B.2) but was essentially to save computation costs in calculating terms which have relatively little effect on the final answer. The minimum number of pairs allowed was 72 for monthly data and 10 for daily data.

The parameter values minimising the function (B.2) were obtained computationally by a call to a subroutine from the Harwell Library which minimises a sum of squares

$$s = \sum_{j=1}^{Q} h_j^2(q_1, \ldots q_n),$$

depending on n parameters $q_1, \ldots q_n$, given the values and first derivatives of $h_j (j = 1, \ldots Q)$.

the left hand side of (C.3) is multiplied by $\underset{\sim}{b}^T$, the following result is obtained

$$-\underset{\sim}{b}^T\underset{\sim}{\sigma}_{xy} + \underset{\sim}{b}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{b} = \lambda ,$$

and, using this expression, the minimum mean square error is

$$\begin{aligned}
\mathrm{mse}(\hat{Y})_{\min} &= \sigma_{yy} - \underset{\sim}{b}^T\underset{\sim}{\sigma}_{xy} + \lambda \\
&= \sigma_{yy} - (\lambda\underset{\sim}{1}^T + \underset{\sim}{\sigma}_{xy}^T)\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy} + \lambda \\
&= \sigma_{yy} - \underset{\sim}{\sigma}_{xy}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy}) + \lambda(1 - \underset{\sim}{1}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy}) \\
&= \sigma_{yy} - \underset{\sim}{\sigma}_{xy}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy} + (1 - \underset{\sim}{1}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy})^2/(\underset{\sim}{1}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{1}) \qquad \text{(C.6)}
\end{aligned}$$

which is the result reported in PhlR.

C.2 Computational refinements

The calculation of the minimum mean square error given in equation (C.6) involves the inversion of a P x P matrix of covariances. For rainfall data the corresponding correlations are often fairly high and there may then be a loss of numerical accuracy in the inversion. This can be overcome in the following case. Suppose that the covariances are of the form

$$\sigma_{ij} = w\{(1 - a^*)s_{ij} + a^*\} \qquad \text{(C.7)}$$

where $\{s_{ij}\}$ is another set of numbers; because of the form of the correlation function used (equation (B.1)), the fitted covariances have such a structure here. Then it can be shown, extending the notation in an obvious manner, that

$$\sigma_{yy} - 2\underset{\sim}{b}^T\underset{\sim}{\sigma}_{xy} + \underset{\sim}{b}^T\underset{\sim}{\sigma}_{xx}\underset{\sim}{b} = w(1-a^*)(s_{yy} - 2\underset{\sim}{b}^T\underset{\sim}{s}_{xy} + \underset{\sim}{b}^T\underset{\sim}{s}_{xx}\underset{\sim}{b})$$

if $\Sigma b_i = 1$, and, for the minimum mean square error in equation (C.6),

$$\begin{aligned}
&\sigma_{yy} - \underset{\sim}{\sigma}_{xy}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy} + (1 - \underset{\sim}{1}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{\sigma}_{xy})^2/(\underset{\sim}{1}^T\underset{\sim}{\sigma}_{xx}^{-1}\underset{\sim}{1})\}, \qquad \text{(C.8)} \\
&= w(1-a^*)\{s_{yy} - \underset{\sim}{s}_{xy}^T\underset{\sim}{s}_{xx}^{-1}\underset{\sim}{s}_{xy} + (1 - \underset{\sim}{1}^T\underset{\sim}{s}_{xx}^{-1}\underset{\sim}{s}_{xy})^2/(\underset{\sim}{1}^T\underset{\sim}{s}_{xx}^{-1}\underset{\sim}{1})\},
\end{aligned}$$

provided $\underset{\sim}{s}_{xx}$ is invertible. The above results may be derived by using the following matrix inversion result:

$$\text{if } \underset{\sim}{A} = \underset{\sim}{B} + \underset{\sim}{\alpha}\underset{\sim}{\beta}^T \text{, then } \underset{\sim}{A}^{-1} = \underset{\sim}{B}^{-1} - \lambda\underset{\sim}{\theta}\underset{\sim}{\phi}^T \text{ where}$$

$$\underset{\sim}{\theta} = \underset{\sim}{B}^{-1}\underset{\sim}{\alpha} \text{, } \underset{\sim}{\phi}^T = \underset{\sim}{\beta}^T\underset{\sim}{B}^{-1} \text{ and } \lambda = (1 + \underset{\sim}{\phi}^T\underset{\sim}{\alpha})^{-1}.$$

This may be checked by substitution.

APPENDIX D Calculation of mean square errors for estimates of average areal rainfall

D.1 Optimal estimates

If the true total rainfall over a given duration at each point $\underset{\sim}{u} = (u_1, u_2)$ in a region is denoted by $Y(\underset{\sim}{u}) = Y(u_1, u_2)$, then the average rainfall, $\bar{Y}$, over the area A is given by

$$\bar{Y} = \frac{1}{A} \int_A Y(u_1, u_2)\, du_1 du_2 = \frac{1}{A} \int_A Y(\underset{\sim}{u})\, d\underset{\sim}{u} \ , \qquad \text{(D.1)}$$

where the symbol A is used to denote the particular area as well as its areal extent. As in Appendix C, estimators $\hat{\bar{Y}}$, of $\bar{Y}$, of the following form are considered

$$\hat{\bar{Y}} = b_1 X_1 + \ldots\ldots\ldots + b_P X_P = \underset{\sim}{b}^T \underset{\sim}{X} \qquad \text{(D.2)}$$

where $\Sigma b_i = 1$ and $X_1, \ldots . X_P$ are the observations recorded at gauges with coordinates $\underset{\sim i}{u} = (u_{1i}, u_{2i})$ $(i=1, \ldots ., P)$. Here the observations X_i are assumed to be related to the corresponding true rainfall totals by

$$X_i = Y(\underset{\sim i}{u}) + \eta_i \qquad (i=1, \ldots P)$$

where the quantities η_i represent measurement errors and are considered as random variables, uncorrelated with the rainfall and amongst themselves, with variance σ_η^2. This model is therefore compatible with the correlation function fitted to monthly and daily rainfall totals in Section 3.2.2 and Appendix B. For daily data the fitted covariance function is of the form

$$\sigma_{XX}(\underset{\sim}{u}-\underset{\sim}{v}) = \begin{cases} \sigma^2 & (\underset{\sim}{u} = \underset{\sim}{v}) \\ \sigma^2\{a + (1-a-\varepsilon)\rho^*(\underset{\sim}{u}-\underset{\sim}{v})\} & (\underset{\sim}{u} \neq \underset{\sim}{v}) \end{cases}$$

where $\rho^*(\underset{\sim}{u})$ is an exponential function defined by equation (D.9) below. Thus the true variance of rainfall may be identified as $(1-\varepsilon)\sigma^2$ and the variance of the measurement errors as $\varepsilon\sigma^2$, where σ^2 is the variance of the observed rainfalls. The covariance function of observed rainfalls may be written as

Finally the matrix of covariances between the observed rainfalls themselves is

$$\underset{\sim}{\sigma}_{xx} = \{\mathrm{cov}(X_i, X_j)\} = \{\sigma_{xx}(\underset{\sim}{u}_i - \underset{\sim}{u}_j)\}.$$

With the quantities $\sigma_{\bar{y}\bar{y}}$, $\underset{\sim}{\sigma}_{x\bar{y}}$, $\underset{\sim}{\sigma}_{xx}$ defined in the above way, the formulae derived in Section C.1 give the mean square errors of linear estimators of areal average rainfall together with the coefficients of the best linear estimator, where $\underset{\sim}{\sigma}_{x\bar{y}}$, $\sigma_{\bar{y}\bar{y}}$ replace $\underset{\sim}{\sigma}_{xy}$ and σ_{yy}.

D.2 Computational refinements

The computations required to calculate the mean square error of an estimator of areal average rainfall can be modified in the same way as in Section C.2 to avoid unnecessary computations and to achieve a gain in numerical accuracy.

If

$$\sigma_{yy}(\underset{\sim}{u}) = w\{(1 - a^*)\ s_{yy}(\underset{\sim}{u}) + a^*\} \qquad \text{(D.7)}$$

and

$$\sigma_{xx}(\underset{\sim}{u}) = w\{(1 - a^*)\ s_{xx}(\underset{\sim}{u}) + a^*\}, \qquad \text{(D.8)}$$

where

$$s_{xx}(\underset{\sim}{u}) = \begin{cases} s_{yy}(\underset{\sim}{u}) & (\underset{\sim}{u} \neq 0), \\ 1 & (\underset{\sim}{u} = 0), \end{cases}$$

then the mean square error of the optimal linear estimator is

$$w(1 - a^*)\ \{s_{\bar{y}\bar{y}} - \underset{\sim}{s}_{x\bar{y}}^{T}\underset{\sim}{s}_{xx}^{-1}\underset{\sim}{s}_{x\bar{y}} + (1 - \underset{\sim}{1}^{T}\ \underset{\sim}{s}_{xx}^{-1}\underset{\sim}{s}_{x\bar{y}})^2/(\underset{\sim}{1}^{T}\underset{\sim}{s}_{xx}^{-1}\underset{\sim}{1})\}.$$

Here, for example,

$$s_{\bar{y}\bar{y}} = \frac{1}{A^2}\int_A\int_A s_{yy}(\underset{\sim}{u} - \underset{\sim}{v})\ d\underset{\sim}{u}\ d\underset{\sim}{v}.$$

In the case of daily total rainfalls the function $s_{yy}(\underset{\sim}{u})$ is given by

$$s_{yy}(\underset{\sim}{u}) = \frac{1-a-\varepsilon}{1-a}\ \exp\left[-b\ \{(u_1 + c_2u_2)^2 + (c_2u_2)^2\}^{\frac{1}{2}}\right]$$

and the region A is transformed to a corresponding region A*. Then the integrals (D.10), (D.11) become, respectively,

$$\frac{1}{A^{*2}} \int_{A^*}\int_{A^*} \exp\{ - [(x_1^* - x_2^*)^2 + (y_1^* - y_2^*)^2]^{\frac{1}{2}}\}\, dx_1^*\, dx_2^*\, dy_1^*\, dy_2^* \qquad (D.13)$$

and

$$\frac{1}{A^*} \int_{A^*} \exp\{ - [(x_1^* - u_{1i}^*)^2 + (y_1^* - u_{2i}^*)^2]^{\frac{1}{2}}\}\, dx^*_1\, dy_1^*. \qquad (D.14)$$

The integral (D.13) may be written

$$\int_{A^*}\int_{A^*} \gamma(x_1-x_2,\ y_1-y_2)\; dx_1 dx_2 dy_1 dy_2$$

$$= \int_{(y_1)}\int_{(y_2)} \sum_{j,k} \int_{x_1 = f_j(y_1)}^{g_j(y_1)} \int_{x_2 = f_k(y_2)}^{g_k(y_2)} \gamma(x_1-x_2,\ y_1-y_2)\, dx_1 dx_2 dy_1 dy_2 \qquad (D.15)$$

where a typical inner integral is

$$\int_{x_1=f_1(y_1)}^{g_1(y_1)} \int_{x_2=f_2(y_2)}^{g_2(y_2)} \gamma(x_1-x_2, y_1-y_2)\; dx_1 dx_2.$$

Making the transformation $z = x_1-x_2$, $u=x_1$ and, omitting the functional references to y_1 and y_2, this integral becomes

$$\int_{z=f_1-g_2}^{g_1-f_2} \int_{u=\max(f_1, z+f_2)}^{\min(g_1, z+g_2)} \gamma(z, y_1-y_2)\; du\; dz$$

$$= \int_{z=f_1-g_2}^{g_1-f_2} \{\min(g_1, z + g_2) - \max(f_1,\ z + f_2)\}\gamma(z,\ y_1 - y_2)dz$$

$$= \sum_{j,p} \frac{x^{r-2p}}{(x^2+y^2)^{(r-p+j)/2}} \quad C^r_{j,p} . \exp\{ - (x^2+y^2)^{\frac{1}{2}}\} \qquad (D.17)$$

where the coefficients $C^r_{j,p}$ ($0 \leqslant j \leqslant r-p-1$; $0 \leqslant p \leqslant r/2$) are defined recursively by

$$C^{r+1}_{j,p} = - C^r_{j,p} + (r - 2(p-1))\, C^r_{j,p-1} - (j + r - p - 1) C^r_{j-1,p} \qquad (D.18)$$

with $C^o_{j,p} = \begin{cases} 1 & (j=p=0) \\ o & (\text{otherwise}) \end{cases}$ and $C^1_{j,p} = \begin{cases} -1 & (j=p=0) \\ o & (\text{otherwise}). \end{cases}$

The above formulae may be checked by formally differentiating expression (D.17).

On making a Taylor series expansion about a point w, the following equations may be derived

$$\int_u^v \exp\{ - (x^2+y^2)^{\frac{1}{2}}\} \, dx = \int_u^v \sum_{r=o}^{\infty} f^{(r)}(w) \frac{(x-w)^r}{r!} \, dx$$

$$= \sum_{r=o}^{\infty} f^{(r)}(w) \left\{ \frac{(v-w)^{r+1} - (u-w)^{r+1}}{(r+1)!} \right\} ,$$

and, on choosing $w = (u+v)/2$, this becomes

$$2 \sum_{r \text{ even}} f^{(r)}(w) \left(\frac{v-u}{2}\right)^{r+1} \frac{1}{(r+1)!}$$

$$= 2 \sum_{r \text{ even}} \sum_{j,p} C^r_{j,p} \frac{w^{r-2p}}{(w^2+y^2)^{(r-p+j)/2}} \cdot \left(\frac{v-u}{2}\right)^{r+1} \cdot \frac{1}{(r+1)!}$$

$$\cdot \exp\{-(w^2+y^2)^{\frac{1}{2}}\}. \qquad (D.19)$$

Similarly, again with $w = (u + v)/2$,

APPENDIX E. Descriptions of catchments used for daily rainfall-runoff modelling

The general characteristics of the catchments show no great contrast, annual average rainfall (SAAR) ranging from 750 to 1000 mm, catchment area (AREA) in the range 75-213 km^2 and catchment geologies consisting of a mixture of permeable and impermeable rocks of Jurassic, Triasic, Permian and Devonian age. With the exception of one catchment (52/11) which has a low stream frequency and slope (Table 4.1) the topographic characteristics are relatively uniform and are typical of this region of the UK. The soil index reflects the infiltration rate of the soil, the higher the index the lower the infiltration rate. The index is closely related to the geology of the catchments which are described below.

Halse Water at Bishops Hull (52/3) and the Tone at Bishops Hull (52/5) draining from the west of the Vale of Taunton both have similar solid geologies, mainly of permeable Permo-Triassic and Devonian sandstones, the remainder (30%) consisting of relatively impermeable Keuper Marl. In common with other catchments drift is limited to local deposits of alluvium and river terraces. The main differences between the catchments derive from the larger area and higher rainfall of the Tone at Bishops Hull. The Yeo at Pen Mill (52/6) and the Parret at Chiselborough (52/7) drain north from the North Dorset Downs and have similar geologies of permeable Oolitic Limestone and impermeable clays. The smaller of the two catchments (52/7) has the larger proportion of permeable (75%) to impermeable rocks (25%); in other respects the catchments are the same.

The geology of the catchment of the Cary gauged at Somerton (52/11) is dominated by relatively impermeable clays and shales of the Keuper Marl and Lias series. In contrast the neighbouring catchment - the Brue at Lovington (52/10) has only a 70% covering of these impermeable rocks, the remainder of the catchment consisting of permeable Oolitic limestone. The annual average rainfall, stream frequency and slope are all lower for the smaller less permeable catchment of the River Cary.

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F.2 Class B stations which could be retained or removed

335893	337068	337202*	338349*	338488
338605	338751*	340465	341381	341737
341782	341874	342534	343447	343842
344052	344184*	344240	344314	344382
345017*	345126	345167*	345379	345394*
345717	345986*	346085	346481	346881
347355*	347748*	347819	347927	348294
348461*	348916	349326	349353*	349695
350079	350531	340858*	350918*	351053
351190	351523*	397135*	397169*	397680*
397758	398022	398202	398383	398505
398892*	398896	399368	399748	399758
399762	399863	400021	400158	400174
400347	400434	400616	401577*	401668
401899	402073	402190	402252	402542
402553	402606*	402745	402819*	403115
403138	403146	403168	403426	404552
404580	404978	405279	405455	405669
405817	406028	406177	406353	406525
406797	407021	407156	407234*	407398
407635	407733	407865	408323	408346
408414	408549	408723	408896	409013
409085	409224	410524	410498	411524
412209	412392	412576	412728	413747
413787	413886	414372	414564*	414829
415161	415176	415375	415583	415588
416056	416081	417005	417899	418367
419131	419364	419746	419751	420216

F.3 Class C stations which should be removed

336662	341501	343042	344255	345057*
345089	348586*	349122	351047	397752*
398512	398631	399307	400418	401622*
403143	405141	406209	407236	407368
408772	410444	412386	415086	416263

* denotes a monthly station

398512 398842 399190 399368 399569
399758 400021 400174 400347 400408
401005 401444 401668 401899 402252
402447 402542 402769 403115 403490
404124 405455 405669 406028 406525
407021 407635 407865 408772* 409224
410111 410598 411686 411950 412205
412728 413479 413787* 414829 415125
415176 415588 415725 416213 416743
417005 417634 417899 418317 419751
419869 420216

<u>Step 2</u>: additional unregistered gauges

950127 950901 960302 962306 970802
972201 972304 972803

<u>Step 3</u>: new sites

999401*	(3450 1450)	999402	(3550 1550)
999403*	(3650 1605)	999404	(3550 1850)
999405	(3660 1800)	999406	(3740 1820)
999407	(3840 1780)	999408	(3950 1600)
999409	(4060 1570)	999410*	(3630 1230)
999411	(3900 1300)	999412*	(4180 1180)
999413*	(3900 0990)	999414	(3600 0980)
99415	(3930 1430)	999416	(3850 1705)
999417	(4090 1320)	999418	(3780 1070)
999419	(3710 1000)	999420	(3370 1610)
999421*	(3802 1398)	999422	(3498 0940)
999432	(3690 1460)		

This is now the Basic Network for this design

<u>Step 4</u>: additional MO and Climat Stations

336402 339816 346474 347013 398081
398528 404585 407349 412297 413825
416242 417640 418120

<u>Step 5</u>: additional gauges with records over 50 years in length

345678 346481 346847 346876 348847
350921 400616 403426 404564 404988
404994 408323 408346 408723 409013
409085 410524 413747 414372 415375
416128 416771 416807 418367 418545

<u>Step 6</u>: substitutions for gauges in Basic Network

delete 407882 (replaced by long record gauge 408723)
delete 413787 (replaced by M.O. gauge 413825)

(c) additional unregistered gauges

950129 970101 970203 970601 970703
970806 971107 972302 972502 972701
972908

(d) additional new sites

999433	(2945 1435)	999434	(3102 1321)
999435	(3720 1745)	999436	(3930 1525)
999437	(3570 1280)		

This is the final Design Network 2.

G.1.3 *Design Network 3*

Step 1: registered gauges

335128 335663 335893 336376 336402
336662 337068 337630 337858 338605
338940 339374 339608 339816 339981
340164 340465 340766 341381 341501
341732 341874 342152 342282 342375
342534 343207 343447 343878 344052
344240 344314 344382 344939 345126
345379 345721 346085 346474 346842
347013 347819 347927 347973 348294
348684 348792 348847 349326 349492
350079 350278 350531 350593 350749
350776 350921 351053 351256 351827
397532 397758 398383 398528 399025
399190 399368 399569 399758* 400021
400128 400347 400418 400616 401005
401444 401899 402073 402190 402447
402542 402769 403115 403219 403490
403899 404124 404564 404988 405455
405817 406177 406353 407021 407156
407349 407635 407733 408346 408723
409085 409224 410111 411524 411686
411950 412205 412392 412576 413479
413747 414290 415125 415176 415583
415725 416213 416743 416807 417005
417640 417899 418120 418367 419751
419869 420254

Step 2: additional unregistered sites

950129 950502* 950604 950901 950902
951105 951303 952001 960302 970101
970104 970106 970315 970518 970524
970601 970717 970720 970802 970806
970905 970909 971107 971108 971302
971303* 971907 972301 972701 972801

Step 7: additional class A gauges

343690 343854 350570 398842 400408

This is now the Preliminary Design Network for this design.

Step 8:

(a) new sites moved or deleted

delete 999333 replace with additional new site 999367 (3625 1220)

(b) additional registered gauges

398022 402252 406525 416081

(c) additional unregistered gauges

970105 970203 970220 970505 970511
970517 970523 970526 970703 971001
972201 972502 972908

(d) additional new sites

999368 (3415 0990) 999369 (3705 1435)
999370 (3635 1620)

(e) delete registered and unregistered gauges

399758 950502 971303

G.2 Recording raingauges

G.2.1 Recording raingauge network for Design Network 1*

In this and the following sections, lists of the recording gauges included in the Design Networks at each stage of the procedure described in Section 6.3 are given. The convention used in adopting gauge numbers for unregistered sites was set

998XXX . telemetering sites in Bristol Avon flood warning scheme.
9998XX . telemetering sites not in Bristol Avon flood warning scheme.
9999XX . non-telemetering recording gauges.

The networks are based upon the corresponding Design Networks for daily and monthly gauges.

Step 1: Sites which already possess recording raingauges

339816 351190 399190 406209 418120
419869

Step 6: New sites deleted

340766 348847 342152 416242 417005

G.2.3 Recording raingauge network Design Network 3*

Step 1 Sites which already possess recording raingauges

339816 346474 398081 399190 411686
418120 419869

Sites which do not possess recording raingauges

335783 338605 340766 342152 343207
344052 347973 348847 350776 398842
401899 402769 404585 406177 416242
417005 970220 970806 971107 972201
999309 999312 999329 999337 999343

Step 2 Sites at Meteorological Offices and Climat stations

336376 336402 347013 349492 398074
417640

Step 3 Telemetering gauges, the data from which it is proposed to archive

416971 417634 998003 998004 998005
998007 998008 998009 998010 998011
998012 998013 998014 998016 998017
998018 998020 998021 998022 998023
998024 999414 999811 999812 999817
999818 999819 999820 999902 999903
999904

Step 4 Sites for flood warning at existing recording gauge sites

339981 350570 397532 414290 418317
999901

Sites which do not possess an existing recording gauge

351053 351827 413747 972801 999307

Step 5 Other sites in daily/monthly Design Network 3 which possess a recording raingauge, other unregistered recording gauge sites

346882 349695 351190 400408 402073
403219 404580 406208 407200 412392
999905 999906 999908 999909 999910
999913 999914 999915 999916

Step 6: New sites deleted

340766 347973 348847 342152 404585
416242 417005