Project 394

Rainfall Frequency Estimation in England and Wales

Phase 1a: Survey

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National Rivers Authority

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Phase 1a: Survey

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EXECUTIVE SUMMARY

This report details the work carried out in Phase 1a of the project "Rainfall frequency studies: England and Wales" funded by the National Rivers Authority under R & D Contract 394. The objective of the project as a whole is to review the methods of rainfall frequency estimation currently in use in England and Wales and to develop new procedures. The final outcome of the project will be the production of a set of new guidelines for rainfall frequency estimation for durations from one hour to eight days, as well as algorithms to allow the new methods to be incorporated into existing software packages.

The project has been divided into three phases: feasibility, production and implementation. The first phase, of which this report forms a part, is concerned with a survey of the scope of the analysis (Phase 1a) and a pilot study of rainfall frequency in the East Midlands (Phase 1b).

Details of the terms of the project are given in the Project Investment Appraisal (Appendix A). In view of the unique requirement of the project for rainfall data held by both the National Rivers Authority (NRA) and the Meteorological Office (Met. Office) to be transferred to the Institute of Hydrology (IH), a Memorandum of Understanding has been agreed by all three parties (Appendix B).

Current practice in UK rainfall frequency estimation follows the procedure set out in Volume II of the Flood Studies Report (Natural Environment Research Council, 1975) based on research carried out at the Met. Office. A related development has been the Focused Rainfall Growth Estimation (FORGE) technique which has been applied to 1 and 2-day durations in south-west England (Reed & Stewart, 1989), but in recent years relatively little research has been undertaken on short-duration extremes. Recent methodological developments in the fields of spatial and temporal dependence show the potential for building on the FORGE technique to allow the estimation of rainfall growth rates over a range of return periods, as well as the production of consistent estimates at different durations.

A review of the extent of the rainfall data available to the project has been undertaken. Use will be made of the extensive, computerized records of daily rainfall totals for gauges throughout England, Wales and southern Scotland, which are already held at IH. In the case of sub-daily durations, information from a number of sources is likely to be exploited during the project. The longest records of sub-daily data available in England and Wales in computerized form amount to about 1100 station years from 78 gauges held by the Met. Office and about 560 station years from 40 gauges held by the NRA. In addition, over 3500 annual maximum 1-hour values computerized by May & Hitch (1989b) are now held at IH, and up to 3400 annual maxima of durations between two and 24 hours are available in manuscript form. Some further raingauge data of high temporal resolution from southern England and north Wales may also be incorporated into the final analysis.

A limited appraisal of samples of sub-daily rainfall data from a number of sources has been carried out. The results suggest that, although it is sometimes difficult to reconcile daily and hourly raingauge readings at the same site, the analysis of continuous hourly records will serve as a check on the proposed analyses of pre-existing annual maxima, especially where date information is lacking.

Finally, a number of options for proceeding with the analysis are presented based on different data inputs. Attention is drawn to recent advances in the quantification of spatial and temporal dependence, which will allow the development of methods to better integrate daily and hourly extremes and to determine the relative value of the various sources of data. Provided that the most extensive data set possible is made available to the analysis in Phase 1b, the application of these techniques should allow the most cost-effective exploitation of the data available throughout England and Wales during Phase 2.

1. INTRODUCTION

1.1 Background to the project

The analysis of rainfall frequency is an important tool in engineering design. Rainfall frequency estimates form one of the key inputs to the rainfall-runoff method of flood estimation, and other applications lie in reservoir, balancing pond, storm sewer and building design. A further application arises in the retrospective analysis of particular flood-producing storm events.

In the UK, current practice in rainfall frequency estimation relies on the method presented in Volume II of the Flood Studies Report (Natural Environment Research Council, 1975). However, since the publication of the Flood Studies Report (FSR), a number of deficiencies in the rainfall synthesis have come to light, notably the tendency of the method to underestimate the frequency of extreme events in Somerset (Bootman & Willis, 1981). More recently, Dales & Reed (1989) noted that the FSR II procedure is overgeneralized and, for example, can lead to overestimates in north-west England. For this reason, a reassessment of methods of rainfall frequency is urgently required and will be able to take advantage of the longer raingauge records now available.

The main objectives of this project are to review the methods of rainfall frequency estimation currently in use in England and Wales and to develop new procedures where the current methods give unsatisfactory results. A necessary end-product of this work will be the production of guidelines and software to allow the new procedures to be widely and easily implemented. The project has been divided into three phases, the first of which is a feasibility study incorporating an initial survey of the scope of the analysis and a pilot study of a small region. The analysis will be extended to the whole of England and Wales during the second (production) phase of the project, and the final phase will involve the implementation of the new methods. In this report details are given of the survey of the scope of the study undertaken as Phase 1a of the project.

Details of the terms and scope of the project are given in the Project Investment Appraisal (Appendix A). In view of the unique requirement of the project for rainfall data held both by the National Rivers Authority (NRA) and the Meteorological Office (Met. Office) to be transferred to the Institute of Hydrology (IH), a Memorandum of Understanding has been agreed by all three parties (Appendix B).

1.2 Structure of the report

This report details the work carried out in Phase 1a of the project. In Chapter 2 methods of rainfall frequency estimation from both the UK and elsewhere are reviewed. Chapter 3 gives details of regional holdings of raingauge records as well as annual maximum data and other sources of rainfall data and sample sub-daily rainfall data from both the NRA and the Met. Office are appraised in Chapter 4. Chapter 5 presents the options available in the later phases of the project, and conclusions and recommendations are set out in Chapter 6.

2 METHODS OF RAINFALL FREQUENCY ESTIMATION

2.1 Introduction

The assessment of rainfall frequency is fundamental to design flood estimation using a rainfall-runoff approach. In many parts of the world, records of rainfall depths are relatively long and reliable when compared to river flow data. Thus an indirect method of design flood estimation is commonly adopted. An initial analysis of rainfall frequency is used to define the design storm which, together with other associated design inputs, can be transformed into a flood hydrograph of the desired frequency by means of a rainfall-runoff model.

Another application of rainfall frequency estimation is in the analysis of the rarity of particular damaging storms; this is especially useful in assessing present levels of flood protection.

The methods of rainfall frequency estimation commonly in use around the world are generally based on regional frequency analyses of the longest available raingauge records. This chapter describes the development of the techniques currently recommended for hydrological design in the UK and reviews recent literature concerning frequency analysis and related themes.

2.2 Development of techniques in the UK

2.2.1 Early approaches to frequency estimation

In the UK, the earliest formal frequency analysis of rainfall was carried out by Bilham (1935) using data for ten years from 18 stations. The results were only applicable to rainfall of durations between five minutes and 120 minutes, although extrapolations were made to durations of up to 24 hours. Bilham's formula provided estimates of rainfall depth-duration-frequency for a typical site in lowland Britain. A revision of Bilham's analysis was carried out by Holland (1964), although this led to only minor changes in the formula.

2.2.2 The Flood Studies Report (FSR)

The basis of current UK practice in rainfall frequency estimation is Volume II of the Flood Studies Report (FSR II) which was published in 1975. For any location, an estimate can be derived of the rainfall depth of a specified duration from a few minutes to several days for return periods of up to 10 000 years. The analysis on which FSR II is based was carried out at the Met. Office. The data were mainly observations of annual maximum rainfalls for a variety of durations, extracted from autographic records, tabulations and computer data sets originating from daily and recording raingauges. Records from over 6000 daily gauges and about 200 autographic raingauges were utilized in the analysis.

The method of rainfall frequency estimation set out in FSR II was based on an extensive statistical analysis of annual maximum rainfalls for a range of durations. Frequencies were assigned to rainfalls of different durations using a quartile analysis. Two basic statistics underlie the method, namely the 60-minute and 2-day rainfalls of five year return period (termed M5) and the rainfalls of intermediate durations are related to them. The 2-day duration was used in preference to the 1-day duration to avoid the discretization problem associated with the definition of the observational rain day; a large rainfall total may appear to be less significant if it spans two rain days than if it is well synchronized with the observational day, defined from 0900 h on one day to 0900 h on the next. Sets of growth factors are used to determine the rainfall of any return period relative to the M5 value.

After the publication of FSR II, research continued at the Met. Office into ways of refining the methodology (Folland et al., 1981) although no major changes were recommended. The most important uncertainty in the model was felt to lie in the estimation of short-duration rainfalls in upland areas where data were scarce. More recent work at IH has considered the applicability of the areal reduction factors and storm profiles presented in FSR II to upland areas (Stewart, 1989a; Stewart & Reynard, 1993) but no requirement to issue new guidelines has been identified, except in the case of profiles of sequences of severe storms in north-west Scotland (Stewart & Reynard, 1991).

From FSR II, Keers & Wescott (1977) developed a computer-based method for calculating design rainfalls which uses digitized versions of the original maps. The procedure has subsequently been implemented in the Met. Office's ITED package (Keers & Wescott, 1977) and the RAINARK database system (Hydro-Logic Ltd, 1991); version 2 of the Micro-FSR package (Institute of Hydrology, 1991) includes an improved numerical representation of the standard FSR storm profiles, but leaves the user to enter values read from maps.

If the FSR method has a serious weakness, it is that the procedure is overgeneralized. For 1 and 2-day rainfall maxima, it has been shown that the FSR growth factors lead to systematic over- or underestimates of rainfall frequency in specific regions. Bootman & Willis (1981) expressed concern about the applicability of the FSR II growth factors to Somerset and the surrounding region, demonstrating that the method seriously underestimates the frequency of 2-day rainfalls. Historically, the region has experienced a relatively high frequency of heavy rainfall events, often associated with summer thunderstorms. As a result, engineers are advised not to use FSR II for dam design in Somerset without performing extra local analyses (Institution of Civil Engineers, 1989). More recently, the derivation of regional growth curves for 1-day rainfall (Dales & Reed, 1989) has shown that the FSR method leads to underestimates of rainfall frequency in the West Country and Eastern England and overestimates in North West England.

2.2.3 Focused Rainfall Growth Estimation (FORGE)

The Focused Rainfall Growth Estimation (FORGE) method was developed in a problem-oriented study of south-west England in order to overcome the recognized limitations of the FSR model in the region (Stewart, 1989b; Reed & Stewart, 1989). The technique retains the two-stage approach used in the FSR, but adopts the mean of at-site annual maxima (termed RBAR) as the standardizing variable; in this way the method is analogous to the index flood methodology which is widely used for flood frequency estimation.

A key feature of the FORGE technique is that it makes allowance for spatial dependence in rainfall extremes using a modification to the station-year method. Successive applications of the modified station-year method allow the rainfall growth curve to be defined over the full range of return periods required for design applications. A further advantage of the technique is that the rainfall growth curve can be focused on any location without requiring the prior definition of homogeneous regions.

The simple station-year approach to frequency analysis allows short records from a number of different sites to be combined to form an equivalent long record at a single site. The method has been widely criticized because it assumes that rainfall extremes are independent in space. In the modified station-year method, an existing model of spatial dependence in extreme rainfalls developed by Dales & Reed (1989) is used to define an equivalent number of independent sites, N_e, over which independent, standardized annual maxima can be pooled. Applied to the network of gauges operating in each year of record, the effective number of independent station years, M_e, can be accumulated as

$$M_e = \sum N_{e,i} \qquad (2.1)$$

where $N_{e,i}$ is the equivalent number of independent sites for year i. The value of M_e is used to define the plotting positions of the largest, independent, standardized annual maxima. Figure 2.1 provides an example of the application of the FORGE method to Wimbleball Reservoir for the 1-day duration. Details of the implementation of FORGE in south-west England are given in Stewart & Reed (1989b).

The second stage of the method requires an estimate of the value of the standardizing variable (RBAR) to be derived for the site of interest. Geostatistics provides a set of techniques for analysing the spatial structure of random variables and for performing interpolation and areal estimation (Cooper & Istok, 1988). In south-west England the geostatistical technique known as kriging has been used to produce detailed maps of RBAR for the 1 and 2-day durations (Stewart & Reed, 1989a). In areas of complex topography it may be advantageous to exploit digital elevation data by the use of cokriging as demonstrated recently by Phillips et al. (1992).

2.2.4 Analysis of short durations

Since publication of the FSR in 1975, relatively little research has been undertaken into the frequency of rainfall of durations shorter than one day in the UK. This reflects the relative difficulty of obtaining long data series in computer-compatible form when compared to daily data.

In south-west England, implementation of the results of the FORGE analysis of rainfall growth rates for 1 and 2-day durations required a "bridge" to the FSR model for shorter durations to enable consistent frequency estimates to be derived (Stewart & Reed, 1989b). In the absence of sub-daily gauge data, the assumption was made that the FSR model gave an adequate representation of rainfall frequency at short durations, but that FORGE estimates should be given progressively more weight relative to FSR estimates as duration increased to one day. Clearly the validity of the final results depends on the adequacy of the FSR model at shorter durations.

Some recent work at the Met. Office has attempted a limited reassessment of the FSR results for short durations. May & Hitch (1989a) computerized the FSR data set of annual maxima for the 1-hour duration and studied periodic variations in the data between 1881 and 1986. The results show roughly sine-wave variations with approximate periods of 7, 11, 20 and 50 years and amplitudes of 7%, 10%, 5% and 7% respectively. May & Hitch also looked at 2-hour rainfall maxima in south-east England and found good correspondence with the periodic variation of Stringfellow's annual lightning incidence index. However, the effects of such variations on rainfall frequency estimates would probably be small and thus would be unlikely to have serious implications for flood design.

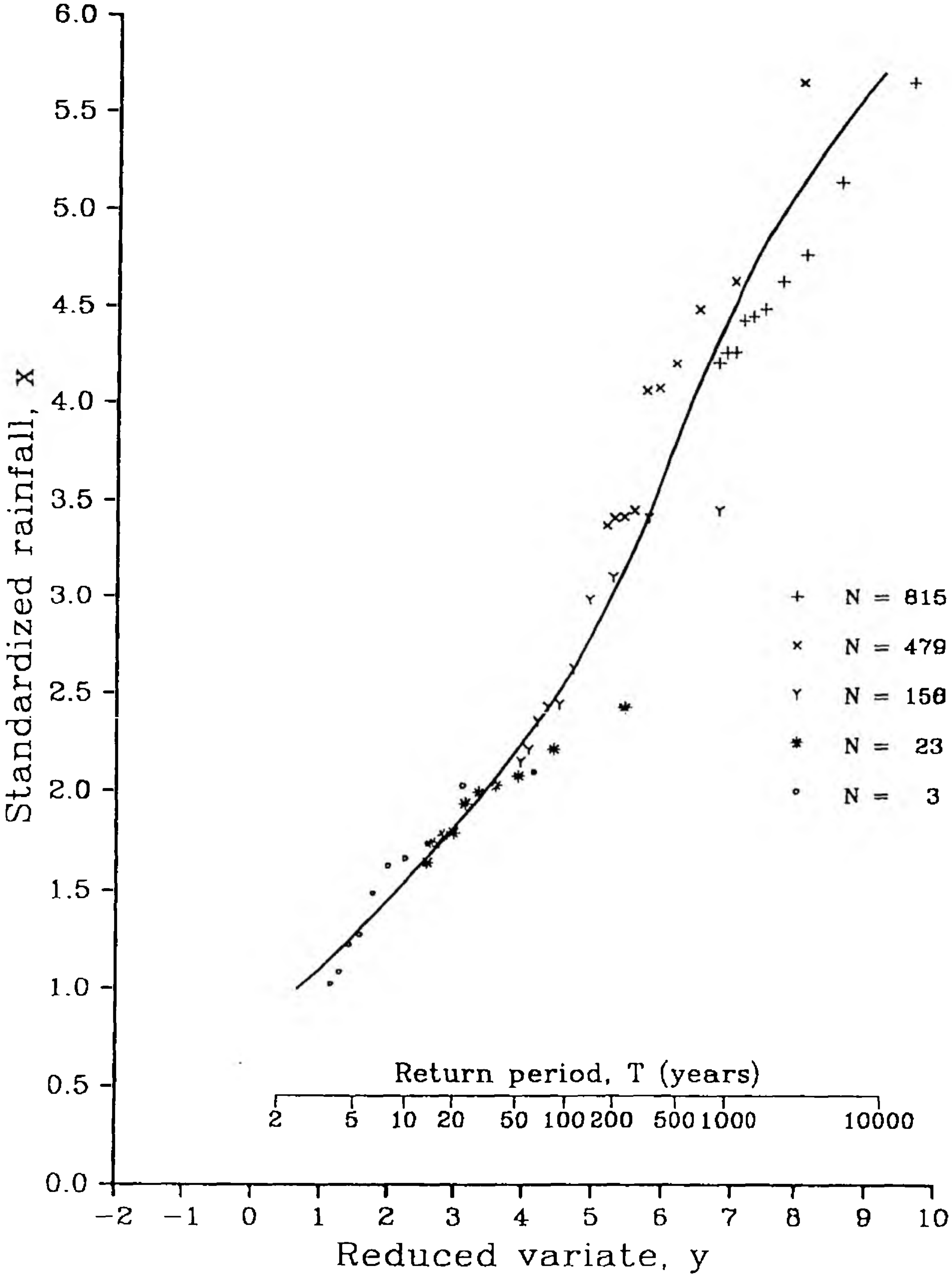

Figure 2.1 **Focused rainfall growth curve for Wimbleball Reservoir (1-day duration)**

Further work by May & Hitch (1989b) has investigated whether there is evidence to suggest that the FSR recommendations for the 1-hour duration require amendment or can be improved. They have extended the original FSR data set of annual maximum 1-hour and 60-minute rainfalls from 2284 to 4532 station years for the whole of the UK. This allowed improved estimates of 1-hour M5 rainfalls to be derived and new estimates for additional stations to be evaluated, thus enabling finer resolution of the M5 map which appears in the FSR. As a result, May & Hitch detected an undulating pattern of 1-hour M5 values in south-east England which appears to follow the topography. The main conclusion is that the 1-hour M5 map is oversmoothed owing to the way in which climatological data were used in the mapping process, thereby indicating that there is a general need to reassess the FSR model for short durations.

Clark (1991) proposed a model of rainfall frequency for south-west England based on hourly data for a network of 44 autographic raingauges with an average record length of 14.5 years. His results imply that both the FSR and FORGE methods cause return periods for rainfall over a range of durations to be underestimated in the region. However, the assumption of a log-Gumbel distribution underlies Clark's model and there is evidence to suggest that this may be inappropriate for daily rainfall in south-west England. Nevertheless, the requirement for a re-evaluation of rainfall frequency for short durations throughout the UK is clear.

2.3 Review of related research

Although the techniques discussed so far have all been applied to annual maximum data, peaks-over-threshold (POT) techniques are also relevant to rainfall data, particularly where record lengths are insufficient for an annual maximum analysis. An example of the application of POT techniques to daily rainfall data is given by Fitzgerald (1989). Reed (1992) discusses the relative merits of annual maximum and POT approaches, concluding that they share the fundamental weakness that the observed extremes may be peculiar to the particular period of record at the subject site, making some form of regionalization, or pooling of data, desirable.

The problem of regionalization is discussed by Schaefer (1990) who conducts a rainfall frequency analysis of Washington State using an index flood methodology. He introduces the concept of a heterogeneous superregion to eliminate problems at the boundaries between regions and fits generalized extreme value (GEV) distributions to homogeneous subregions. Buishand (1991) reviews several methods of extreme rainfall estimation which combine annual maximum data from several sites. Fitzgerald (1989) describes both single site and regional analyses of daily rainfall extremes using a peaks-over-threshold approach. However, data from different stations are pooled together without first being standardized, and some sites are arbitrarily excluded from the regional analysis.

Another related concept is spatial dependence in rainfall maxima which leads to increased uncertainty in growth curve estimation (Hosking & Wallis, 1988). Pooling data from several sites where spatial dependence exists can cause particular historical events to have an unreasonably large influence on the resulting growth curves. Reed & Stewart (1991) give an example of a flood analysis in south Wales in which a single widespread extreme event leads to a very large change in the regional flood growth curve, despite the pooling of annual maxima from 18 stations. The way in which the FORGE technique allows for the spatial dependence in rainfall extremes has already been discussed. Schaefer (1990) also considers intersite dependence in rainfall maxima using an approach similar to that of FORGE, evaluating an "equivalent independent record length" by counting independent events observed in the region.

Current research is attempting to characterize the effects of temporal discretization on extremes of rainfall and other environmental variables. This is important in deriving adjustment factors to correct for the difference between maximum rainfalls over a fixed period, such as the observational rain day, and those for a variable period, such as any 24-hour period. A factor of 1.14 was proposed by Weiss (1964) to convert estimates of 1-day maximum rainfall to estimates of 24-hour maximum rainfall and is still widely used. Dwyer & Reed (1993) demonstrate that this value is slightly low for rainfall and that much smaller corrections are appropriate for wind or temperature maxima, showing that the correction factors can be related to the temporal "roughness" of the variable.

Another problem is that of temporal dependence in rainfall maxima of differing durations. Existing practice is to analyse, for example, 1-day rainfall maxima separately from 2-day maxima, an approach which can lead to inconsistencies. Buishand (1992) presents a method of generalization based on maximum likelihood estimation which makes allowance for dependence between rainfall maxima at different durations. Revfeim (1992) also discusses temporal dependence problems in rationalizing rainfall depth-duration-frequency relationships.

2.4 Conclusions

This review has underlined the important role that FSR II has played in flood design in the UK. Now that the FSR is nearly 20 years old, the development of new techniques and the increased length of rainfall records both point to the need to update the recommended methods of rainfall frequency estimation. Recent research has indicated ways in which rainfall frequency estimates may be improved using daily data, but there has been little corresponding research based on shorter durations. Finally, recent publications indicate that the importance of dependence, both spatial and temporal, must be recognized and taken account of within the new techniques.

3. AVAILABILITY OF DATA IN ENGLAND AND WALES

3.1 Introduction

This study is concerned with the analysis of rainfall frequency in England and Wales for durations ranging from one hour to eight days. To avoid inconsistencies in frequency estimates close to the Scottish border, gauges in southern Scotland will be included in the analysis. The following sections give details of a survey carried out to assess the sources of rainfall data potentially available to the later phases of the study.

3.2 Daily raingauge data

The Institute of Hydrology holds an archive of some 13,000 short-term daily raingauges in the UK with data covering the period 1961 to 1990. In addition, there is an archive of 400 long-term daily raingauges with records of over 40 years commencing before 1961. The Met. Office has given permission for the long-term data to be used in the project as set out in the Memorandum of Understanding (Appendix B).

Previous studies of rainfall frequency using daily data (for example, Stewart, 1989; Reed & Stewart, 1989) have been based on the analysis of annual maxima. Such an analysis requires data records to be relatively long. For this reason, the survey of available daily rainfall data has concentrated on the gauges that can provide at least ten annual maxima.

Table 3.1 gives a breakdown of the number of daily raingauges with at least ten years of record in each region of the NRA. An indication is given of the number of short-term gauges with complete 30-year records (1961 to 1990) and also the number of long-term gauges with over 40 years of record. In each region there are larger numbers of short-term gauges than long-term gauges, but generally the availability of daily raingauge data is good. Some regions of the NRA (for example, Thames Region) hold a small amount of daily data from unregistered gauges. It is likely that quality control considerations would preclude the inclusion of these stations in the analysis.

The total number of station years represented by the data shown in Table 3.1 is of the order of 117 000.

3.3 Sub-daily raingauge data

Rainfall totals recorded at intervals of less than one day are available from two sources, namely the Met. Office and the NRA. The situation is more complex than in the case of daily rainfall data because of the past and present use of a number of different types of gauges, recorders and loggers. Assessment of the amount of data available for analysis has been further complicated by the diverse methods of archiving in use for both manuscript and computerized records.

Separate assessments have been made of the extent of potentially utilizable sub-daily data from each source.

Table 3.1 Regional breakdown of the number of daily raingauge records held at IH

Region	Record length			Total
	10 - 29 years	30 years	≥ 40 years	
Anglian	568	100	44	712
Northumbria	161	27	15	203
North West	362	77	37	476
Severn-Trent	571	81	58	710
Southern	343	102	36	481
South West	340	41	29	410
Thames	443	147	56	646
Welsh	410	68	24	502
Wessex	263	44	26	333
Yorkshire	281	66	20	367
Total	3742	753	345	4840

3.3.1 Hourly raingauge data held by the Met. Office

The Met. Office holds hourly data for just over 200 raingauges in England, Wales and the Scottish borders in computerized form. Fewer than half of these gauges have record lengths greater than ten years, the longest being 22 years. For about 20 gauges, the length of record is not clear but is likely to be less than five years. Further details of the record lengths of the remaining gauges are given in Table 3.2.

Table 3.2 Record lengths of hourly gauges held by the Met. Office

Record length (years)	Number of gauges
< 5	43
5 - 10	55
11 - 15	44
16 - 20	26
> 20	8
Total	176

The locations of the 78 gauges having records of greater than ten years are shown in Figure 3.1. It can be seen that they are fairly evenly distributed, although north Wales and north-east England are not well represented. The number of station years represented by

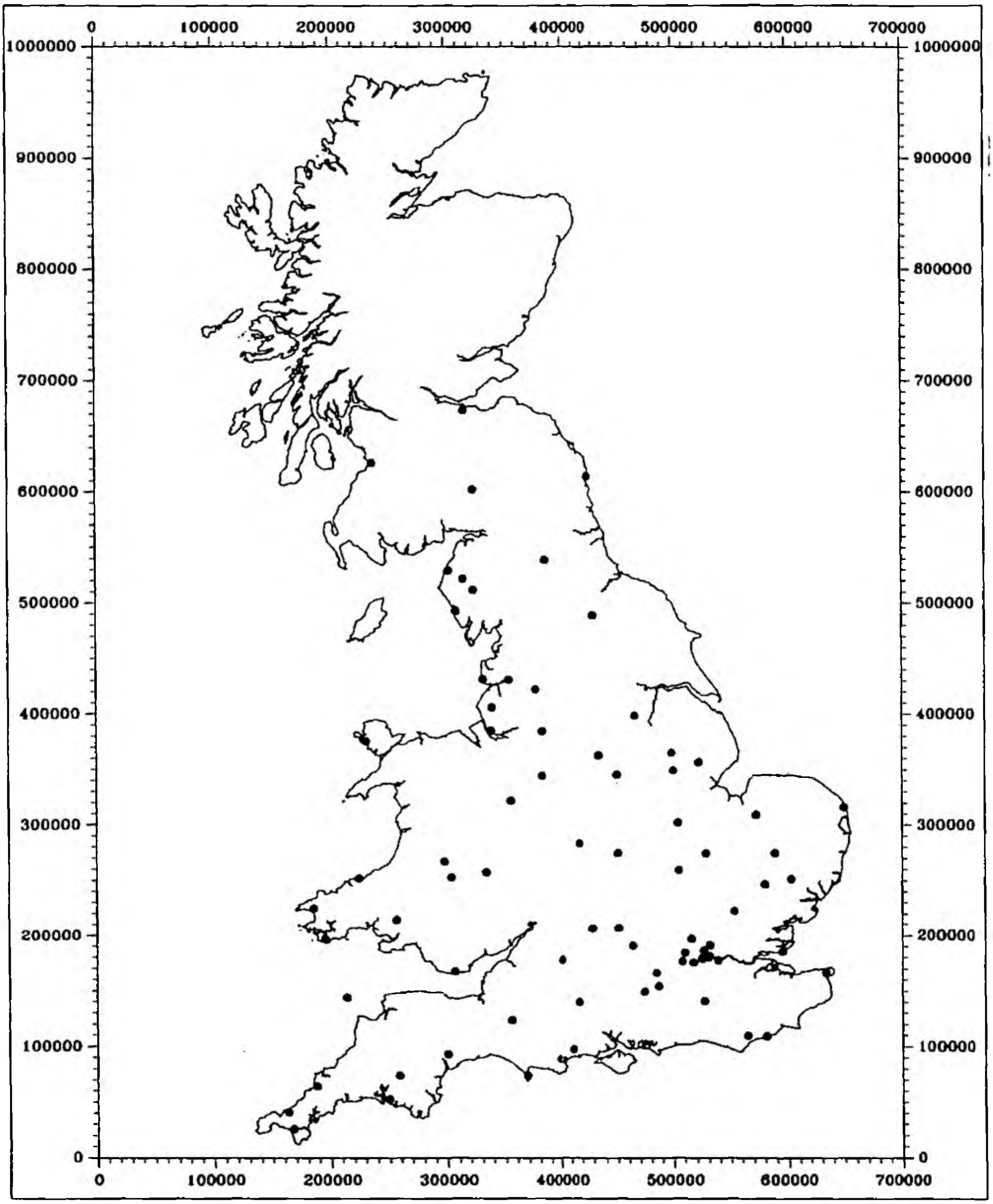

Figure 3.1 Locations of hourly gauges held by the Met. Office with computerized record lengths of at least ten years.

these gauges is approximately 1100. A notable feature of the hourly gauge network is the relatively high proportion of airfields and coastal sites, making the use of additional data from other sources desirable to ensure that the results of the analysis are representative.

Records of less than ten years in length are unlikely to be suitable for frequency analysis using annual maximum techniques unless they can be extended in some way. If hourly values have already been tabulated at the Met. Office, it would be feasible, though time-consuming, to enter them into the computer by hand. Extracting hourly totals directly from raingauge charts is a more difficult task and again would be time-consuming. A third means of extending the records would be to use annual maxima of specified durations, together with their dates of occurrence.

Use of peaks-over-threshold (POT) methods might allow records of less than ten years to be exploited. However, the effort given to integrating POT and annual maximum approaches might be better expended in extracting additional years of annual maximum data from non-computerized sources. Annual maximum data are discussed in the following section.

3.3.2 Annual maximum data

May & Hitch data

As part of the analysis carried out for FSR II, a series of 1-hour annual maxima was constructed by the Met. Office. The data set was made up of 112 stations in the UK mainly covering the period 1951 to 1970. At 33 of the stations, 60-minute annual maxima were extracted, with 1-hour rainfalls being produced at the remaining sites. The difference between these two durations is discussed in Appendix C.

More recently, May & Hitch (1989b) have used additional Met. Office archives to fill gaps in individual annual maximum records. Many of the records have been extended back to the start of the observations and forward to 1989. Annual maxima have also been extracted at additional stations for which data were not available at the time of the FSR analysis. A computer data set of all these annual maxima has been created at the Met. Office and is updated annually. The archive includes information about the month of occurrence of most of the annual maxima. The number of stations contributing to the series in 1989 was 234 (more than double the initial number) producing an annual maximum archive of some 4532 station years compared to 2284 used in FSR II (May & Hitch, 1989b).

The updated computer data set of 1-hour and 60-minute annual maxima together with their months of occurrence has been made available to the present study by the Met. Office. The May & Hitch total of 234 gauges has been increased to 285 by the inclusion of some records which start in 1987, allowing the total number of station years to be increased to 4910. However, these additional records are too short as yet to be relevant to a formal frequency analysis. Out of the 234 May & Hitch gauges, 185 are situated in England, Wales or southern Scotland and have a combined record length of 3785 station years. The locations of these gauges are shown in Figure 3.2. Of these, 132 have at least ten annual maxima and have a combined record length of 3434 station years.

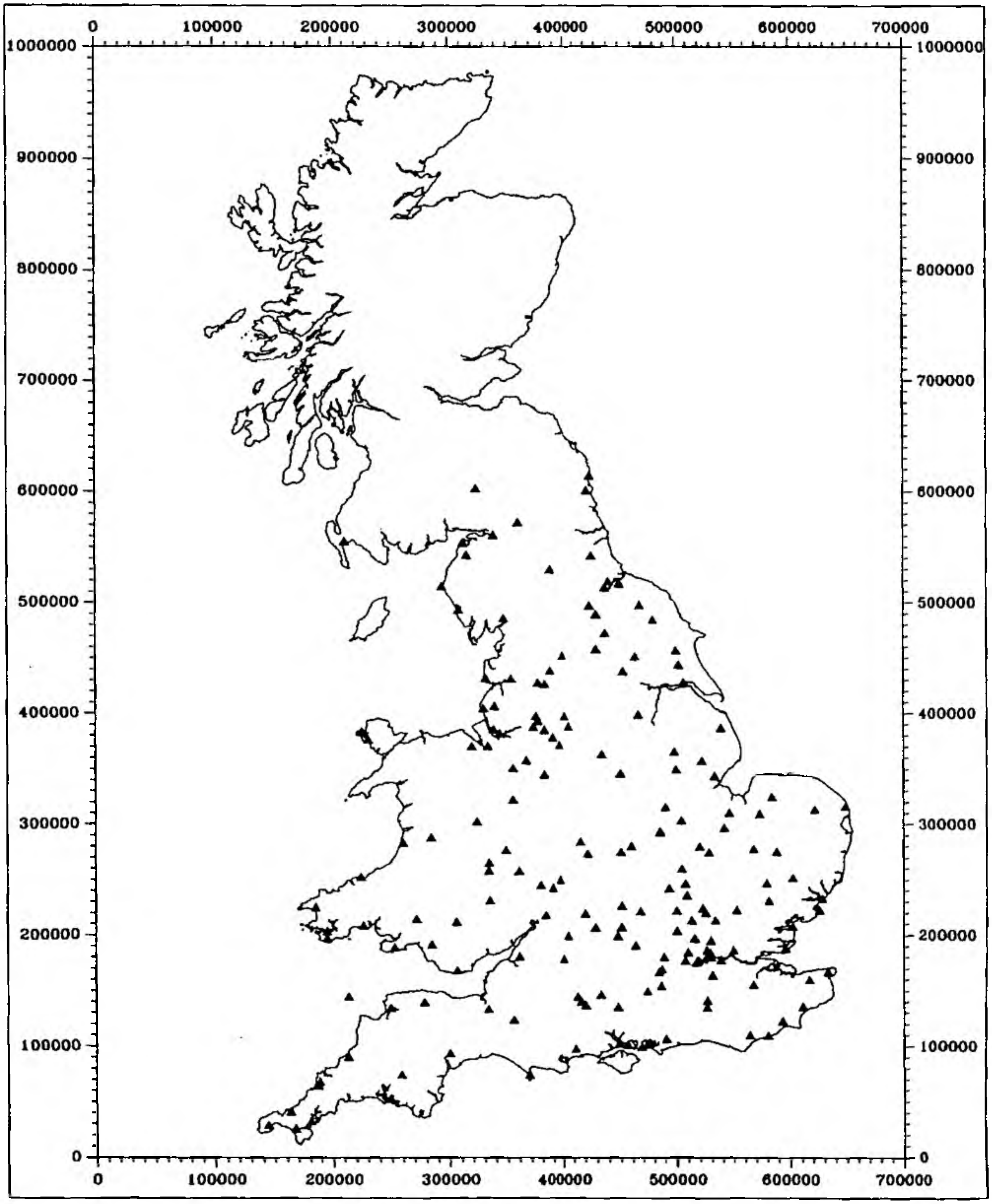

Figure 3.2 Locations of May & Hitch gauges.

Annual maxima for other durations

Tabulations of annual maximum rainfall depths for durations ranging from one hour to eight days are held at the National Meteorological Archive in Bracknell. It is likely that these data were used as the basis of the May & Hitch data set of 1-hour maxima which was subsequently extended using other data sources. The quality of the tabulated records is variable and the dates of individual maxima are not always indicated, but nevertheless they contain a great deal of information. Estimates of the total number of station years of data available at each duration are given in Table 3.3.

Table 3.3 Estimated station years of annual maxima available for sub-daily durations

Duration	Number of station years
60 minutes	749
120 minutes	657
240 minutes	20
360 minutes	29
1 hour	1067
2 hours	1067
3 hours	190
4 hours	301
6 hours	1050
12 hours	413
24 hours	413

Data for a total of 94 gauges have been obtained and their locations are shown in Figure 3.3. The map indicates that most of the gauges are situated in central England and that Wales is not well represented in the data set.

The annual maxima mainly cover the period from 1951 to 1971. It would be feasible to extend the records by extracting annual maxima and their associated dates manually from hourly tabulations held at the Met. Office, as was carried out by May & Hitch (1989b) for the 1-hour duration. However, the need to accumulate several hourly readings makes the process more difficult for durations greater than one hour.

3.3.3 Sub-daily data held by the NRA

The ten regions of the NRA hold a considerable amount of recording raingauge data in a variety of forms. Before the widespread introduction of the tipping bucket raingauge in the mid-1980s, most of the sub-daily data were derived from Dines tilting siphon raingauges in the form of charts. More recently, charts have been replaced by solid-state loggers or telemetry systems, allowing event data to be transferred quickly and easily to computers for permanent storage. Most regions of the NRA now use the RAINARK computer package (Hydro-Logic Ltd) to store daily, hourly and event data. Some regions, for example Severn-Trent, are also transferring historic data to the archive system.

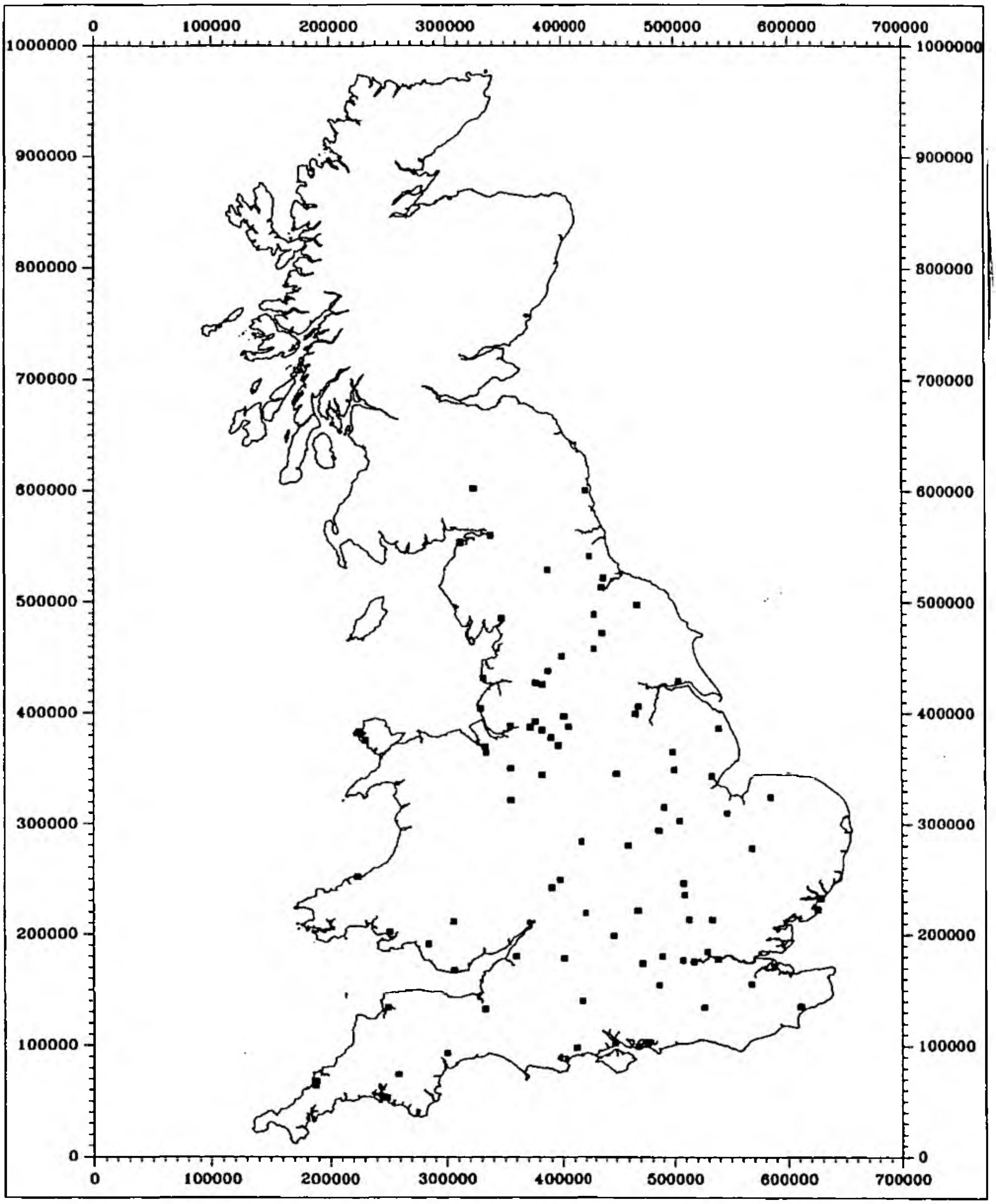

Figure 3.3 Locations of gauges with tabulated annual maxima.

A survey of the recording raingauge data held by the ten regions of the NRA was undertaken in order to ascertain the nature of the data and the means of storage. Computerized records tend to be relatively short, but in some cases it would be possible to extend them by digitizing autographic charts. Currently, historic records are being digitized systematically in Severn-Trent Region. Also, in most regions event data will continue to be added to the existing data during the course of the study, allowing some gauge records to be included in the analysis in later phases of the project.

The lengths of recording raingauge records currently held on computer are given in Table 3.4 and the locations of the 40 gauges with computerized records of at least ten years in length are shown in Figure 3.4. These represent a total of about 560 station years. Anglian and Severn-Trent Regions hold the most data for short durations and both use the RAINARK system. Thames and Northumbrian Regions also have reasonably long computerized records but use different database systems. Yorkshire Region is currently loading data since 1988 from 32 tipping bucket raingauges onto RAINARK. Data before 1988 exist as hardcopy only. North West, Welsh and Wessex Regions have relatively short computerized records, but in many cases record lengths could be extended by digitizing autographic charts. Only two regions, namely Southern and South West, have no significant computerized holdings of short-duration data.

Table 3.4 Number of computerized sub-daily raingauge records held by NRA regions

Region	Type of data	< 5 years	5 - 10 years	> 10 years	Total
Anglian	RAINARK	44	37	16	97
North West	RAINARK	63	0	0	63
Northumbria	HYDATA	12	8	6	26
Severn-Trent	RAINARK	46	41	11	98
Southern		0	0	0	0
South West		0	0	0	0
Thames	Argus/Vax	68	18	7	93
Welsh	RAINARK	28	0	0	28
Wessex	RAINARK	22	0	0	22
	Other computerized	37	0	0	37
Yorkshire	ASCII files	32	0	0	32
Total		352	104	40	495

Thames Region of the NRA operates an additional network of recording raingauges in London for use in local calibration of the Chenies weather radar. Currently the network consists of 56 gauges with data recorded at 15-minute intervals (Table 3.5). These data are held on computer at IH, but record lengths do not yet exceed five years.

3.3.4 Data available for East Midlands pilot study region

The first phase of the project constitutes a feasibility study and is divided into two sub-phases. This report gives details of the survey of data and methods carried out in Phase 1a of the

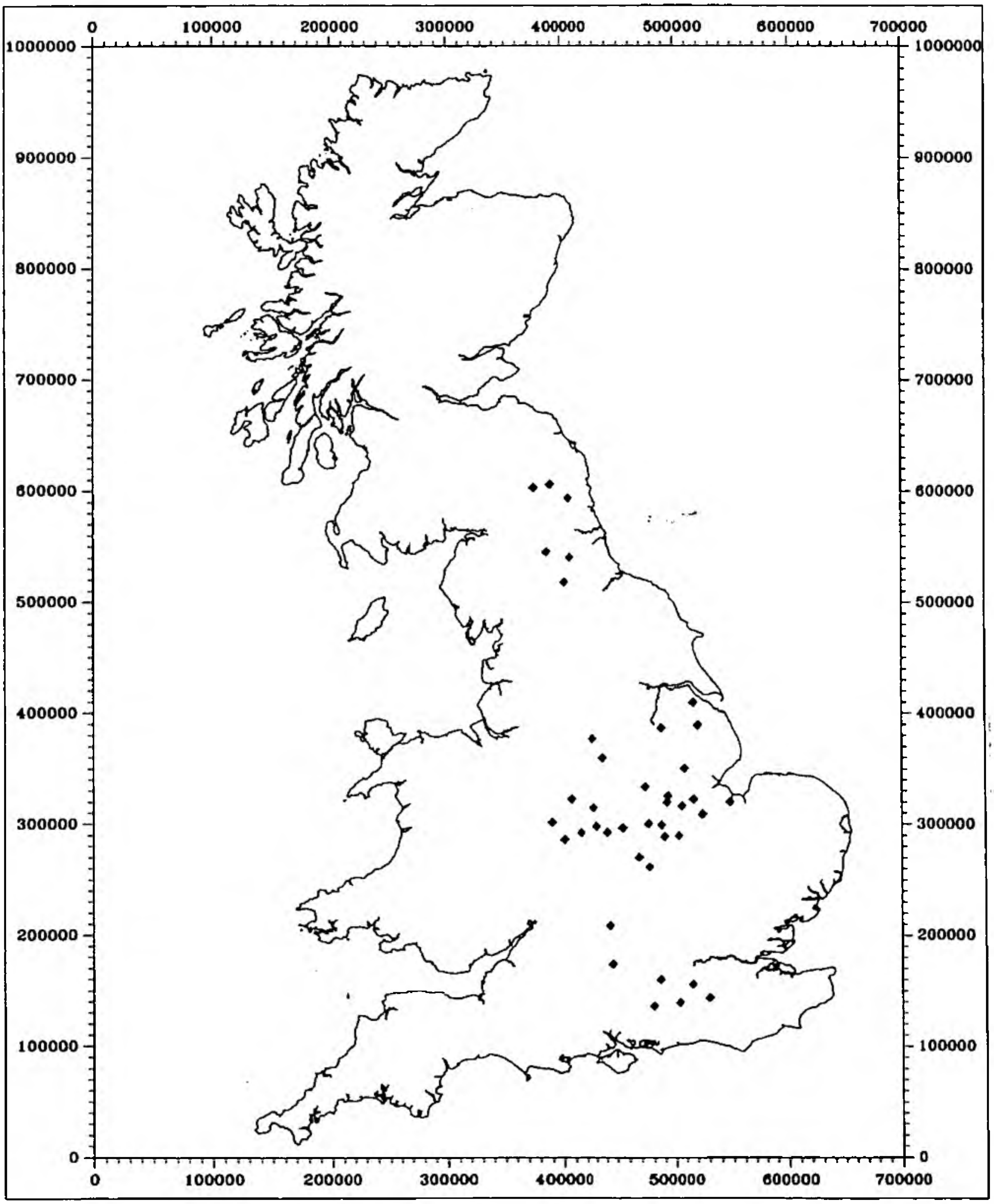

Figure 3.4 **Locations of recording raingauges held by the NRA with computerized record lengths of at least ten years**

Table 3.5 Development of the 15-minute recording raingauge network over London

Date	Number of gauges in the network
Dec 1987	20
Aug 1988	27
Dec 1989	30
Dec 1990	49
Aug 1992	56

project. Phase 1b is a pilot study of a region in the East Midlands; rainfall frequency will be analysed for durations from one hour to eight days and return periods between 0.5 and 200 years. Also included in Phase 1b is a mapping exercise of 1 and 2-day rainfall statistics in the Severn basin; in this case the region was chosen on the basis of the availability of digital terrain data.

As part of Phase 1a, the availability of sub-daily rainfall data in the main pilot region in the East Midlands has been investigated. The region has been defined on the basis of the longest raingauge records available on computer at the Met. Office and Anglian and Severn-Trent Regions of the NRA and is illustrated in Figure 3.5. The main "inner" area is a rectangular area of 120 km by 80 km which is relatively densely gauged. The "outer" area is shown in Figure 3.5 as a rectangular area of 180 km by 140 km, although in practice the boundary will not be rigidly defined. The locations of the recording raingauges with the longest computerized records operated by the Met. Office and the NRA are also shown in Figure 3.5. Eighteen gauges operated by the Met. Office are shown and these have a total of 267 station years of data on computer. Anglian Region of the NRA holds data for 30 gauges with a total of 311 station years, and Severn-Trent Region holds data for eight gauges with a total of 113 station years.

3.4 Other sources of data

3.4.1 PEPR data

The Precision Encoder and Pattern Recognition (PEPR) machine is a spot scanner used to digitize charts automatically. The machine was used to digitize over a million rainfall charts in a collaborative study involving the Greater London Council and the Met. Office. A copy of the database is currently held at IH and was provided by the NRA Thames Region for an NRA-funded project studying rainfall patterns over London.

The database is made up of point rainfall values at variable intervals held to an accuracy of 0.01 mm. Depending on the type and intensity of the rainfall, the data may be available at the 1-minute interval. Data are held from 77 raingauges in the Greater London area with the longest records covering over 20 years.

Data from a further seven PEPR stations are also held on computer at IH. Details of the locations and record lengths are given in Table 3.6.

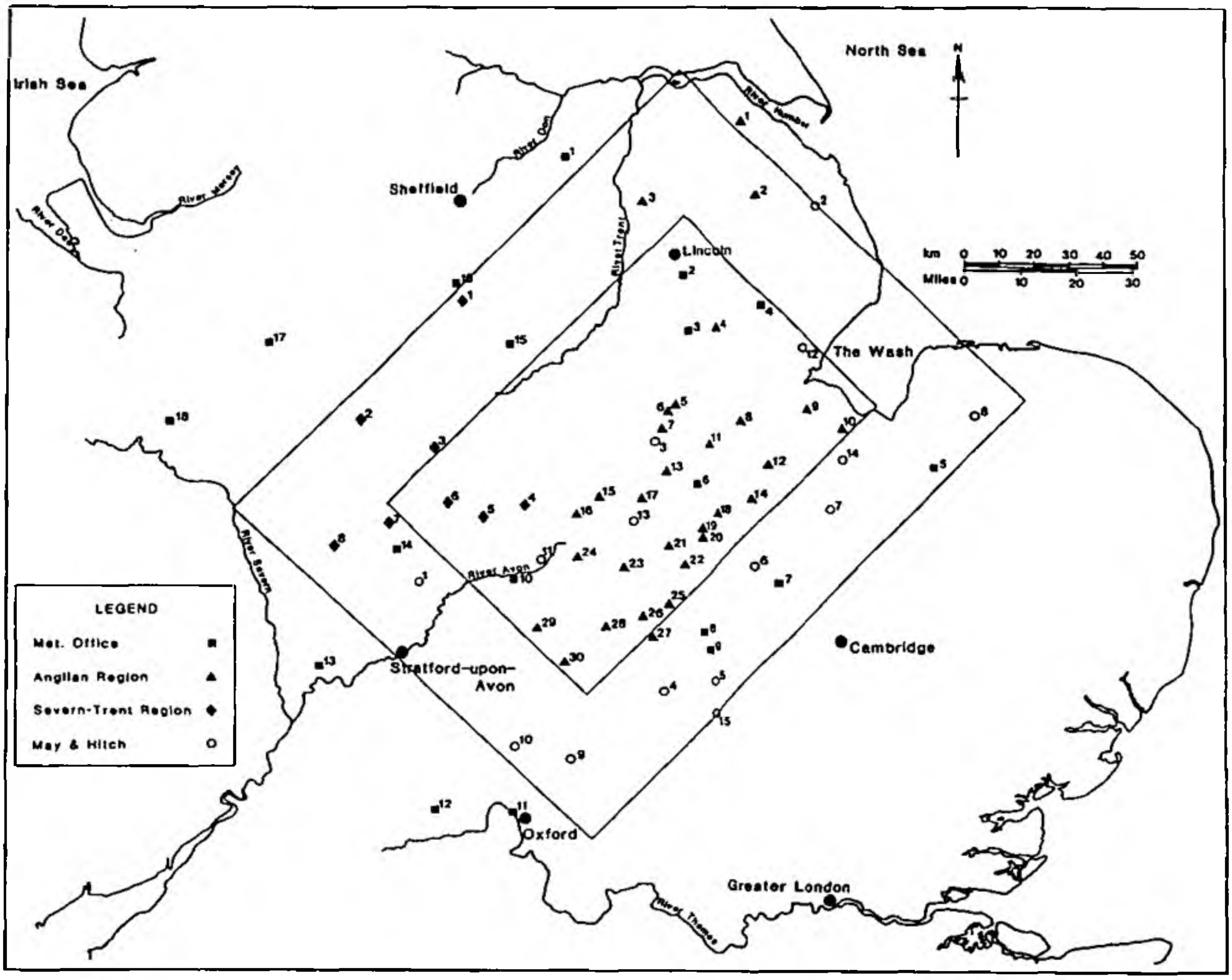

Figure 3.5 Map of pilot study region.

Table 3.6 Details of PEPR stations outside London

Name	Met Office number	Period of record
Abingdon	260990	1944-1975
Farnborough	271432	1941-1971
St Mawgan	383478	1956-1968
Rhoose	492325	1958-1975
Elmdon	97008	1949-1972
Shawbury	433710	1946-1975
Finningley	125843	1958-1973

3.4.2 Radar data

The Institute of Hydrology currently holds data from the Hameldon Hill and Chenies radars, which form part of the UK's C-band weather radar network. The Hameldon Hill radar is situated 20 km north of Manchester, with the data being provided by the Met. Office's PARAGON data processing system (May, 1988). This system produces calibrated rainfall totals which can subsequently be adjusted by recording raingauge data. The data are in the form of hourly rainfall totals for 400 five-km squares and cover 143 days on which rainfall was heavy and widespread in the region between 1981 and 1987.

The Chenies radar data was provided for use in the NRA-funded rainfall forecasting project in the Thames region. The radar is situated to the north-west of London. Data representing 5-minute rainfall intensities averaged over 2-km grid squares are available from October 1987 to the present. There are also data available on a 5-km grid at 15-minute intervals from January 1988 to the present.

3.4.3 FRONTIERS data

The FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite) system was devised to use radar and satellite imagery to produce very short-term (0-6 hours) rainfall forecasts.

As part of the aforementioned project for the NRA Thames Region, IH holds continuous records since October 1990 of two of the three data types produced, for a 5-km grid over the Greater London area. Accumulation forecasts (in mm) are made every half hour for each 15-minute interval in the next six hours. Instantaneous forecasts (in mm h^{-1}) are made every half hour for each hour in the next six hours and can be produced for the whole of England and Wales. Of more interest to this project are the actual rainfall accumulations for the same grid and these are held at 30-minute intervals (at 20 and 50 minutes past the hour) since July 1991.

Some accumulations are also held at IH for north-west England, but these only begin in April 1992.

3.4.4 Dee recording raingauge network

Data from a network of recording raingauges in the Upper Dee catchment in north Wales are held at IH. This dense raingauge network was installed in the early 1970s as part of the Dee Weather Radar Project (Central Water Planning Unit, 1977) in which point rainfall measurements were required to calibrate radar returns. The network was operational from September 1971 to March 1975 and consisted of 62 recording raingauges within a catchment area of approximately 1000 km^2. The data are in the form of 15-minute totals and have been quality controlled, although some missing values remain. The data are available for use in the current study, although the length of record would preclude an annual maximum analysis.

3.5 Summary of data holdings

This project is concerned with the analysis of rainfall frequency for durations ranging from one hour to eight days. The UK is in the fortunate position of having extensive, computerized records of daily rainfall data of good quality which are held by the Met. Office. These data are also held on computer at IH and all records of daily gauges in England, Wales and southern Scotland are being made available to the project.

In the case of sub-daily durations, the availability of rainfall data is less clear. To conduct a formal frequency analysis using annual maxima, reliable rainfall records of at least ten years in length are desirable. Ideally, these records should be stored on computer as continuous hourly totals (or tip times in the case of logging gauges). The available data which fulfil these criteria amount to about 1100 station years from 78 gauges held by the Met. Office (Figure 3.1) and about 560 station years from 40 gauges held by the NRA (Figure 3.4). The PEPR data set held at IH would increase the record lengths to a limited extent, but would not improve the coverage of Wales and northern England.

If an annual maximum approach is taken to the analysis, the sub-daily data can be substantially augmented by the May & Hitch computerized database of 1-hour maxima (Figure 3.2), as well as the tabulated annual maxima for longer durations which are available in manuscript form for up to 94 gauges (Figure 3.3). A summary of the total station years available is given in Table 3.7 and the locations of the raingauges are shown in Figure 3.6.

Table 3.7 Summary of station years available to an annual maximum analysis

Data source	No. of gauges	No. of station years
Computerized hourly data (Met. Office)	78	1100
Computerized hourly data (NRA)	40	560
May & Hitch	185	3785
Tabulated annual maxima for a number of durations	94	4100

It can be seen from Figure 3.6 that this combination of data sets for a range of durations substantially improves the coverage of England and Wales. However, a number of problem areas still exist, notably south-west England and parts of Wales and north-west England.

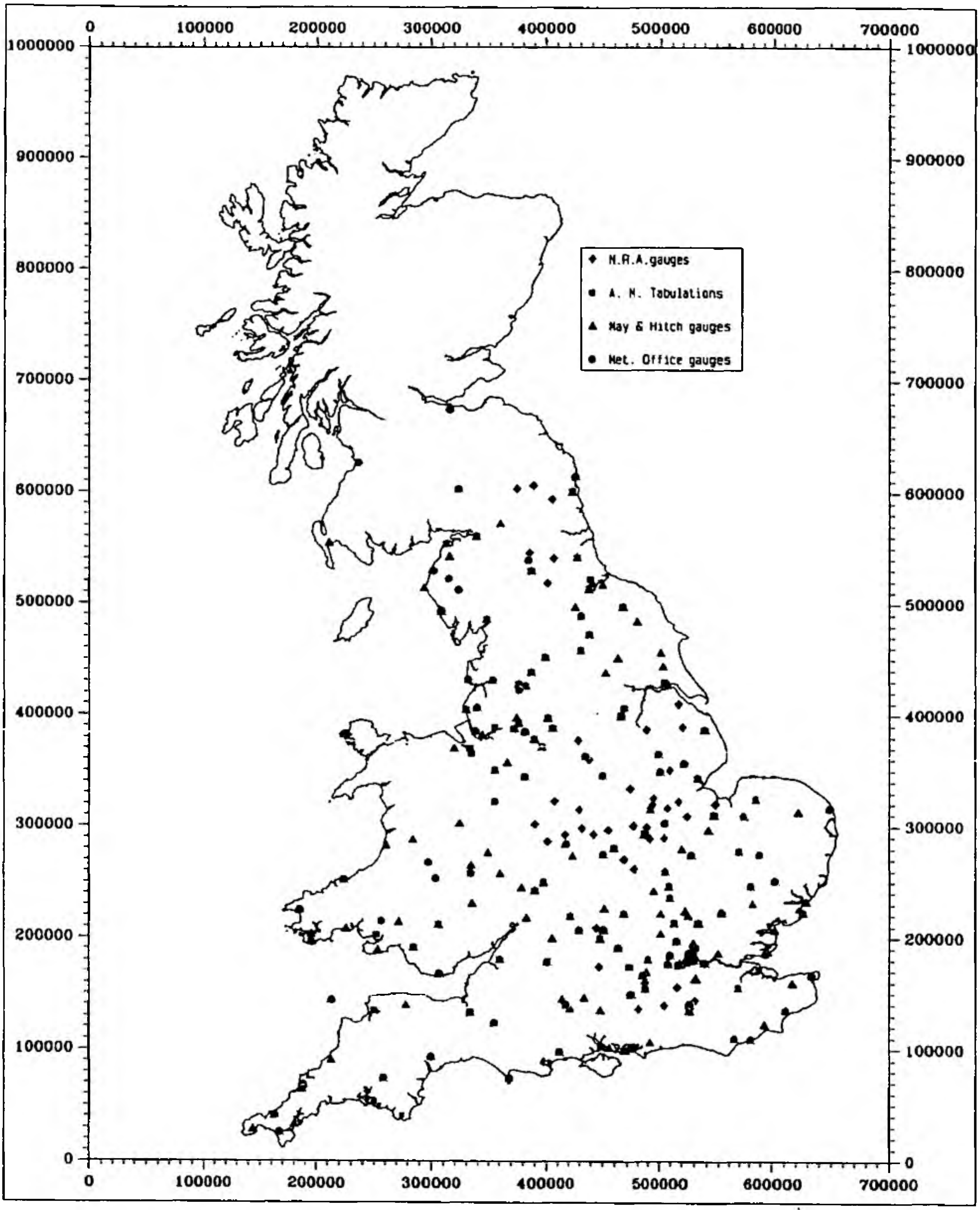

Figure 3.6 Map of gauges with sub-daily data in England and Wales.

Some digitization of recording raingauge charts and computerization of tabulated hourly data would provide a valuable addition to the data available in these regions. Also, owing to the phased nature of the project, some recording raingauge records which are currently too short to be of interest will, in time, become utilizable. This further source of information is likely to become important as more regions adopt the RAINARK system for the storage of rainfall data.

An alternative to the analysis of annual maxima would be the adoption of a POT approach, which has the advantage that shorter records such as those available for the Upper Dee catchment could be utilized. However, such an approach would need to be integrated with the annual maximum analysis of the daily rainfall data and would inevitably be more complex and time-consuming than the annual maximum option. Furthermore, recent developments of analytical techniques using annual maxima show considerable potential for exploiting and integrating daily and hourly extremes. This is discussed further in Chapter 5.

3.6 Comparison with data used in FSR II

In the case of daily raingauge data, it is clear that the total number of station years available to the current project is greater than that used in the analysis which underpinned the Flood Studies Report. A total of about 117 000 station years of daily data are now available in England and Wales, in comparison to the 96 000 station years from sites throughout the UK which were used in the FSR II analysis. An important advantage of the present situation is that all the data are stored on computer as continuous daily rainfall totals, allowing flexibility in the abstraction of extreme values as well as providing the necessary date information.

The quantity of recording raingauge data which were available to the FSR analysis is not very clear, but a maximum of about 2300 station years were probably used at each sub-daily duration for the whole of the UK, much effort being put into the analysis of the 1-hour and 60-minute durations. Most of the data analysed were in the from of annual maxima. In comparison, a total of 3785 station years of 1-hour annual maxima in England, Wales and southern Scotland are available to the current study from the May & Hitch database. A further 4100 station years of annual maxima at various durations greater than one hour are available from tabulations, and 1660 station years of continuous, computerized records are also available. The existence of the continuous data will provide a means of validating the results of the analyses of pre-existing annual maxima.

4. APPRAISAL OF SAMPLE SUB-DAILY RAINFALL DATA

4.1 Introduction

Samples from each source of computerized data identified in the previous chapter were obtained for appraisal. A computerized record of hourly rainfall depths for a single gauge was provided by the Met. Office, together with the complete data set of 1-hour annual maxima compiled by May & Hitch (1989b). In addition, a number of short examples of sub-daily records in a variety of computerized formats were provided by Anglian and Severn-Trent Regions of the NRA.

4.2 Recording raingauge data

4.2.1 Data from the Met. Office

Hourly data for a single gauge situated in the pilot region of the East Midlands were transferred from the Met. Office to the IBM mainframe computer at IH for appraisal. Gauge number 179624 situated at Wyton, Cambridgeshire was chosen on the basis of its relatively long record (January 1974 to December 1990). In order to assess the quality of the data, the hourly totals were built up into daily totals running for 24 hours from 0900 GMT. These totals were then compared with the daily rainfall depths recorded at the Met. Office daily gauge numbered 179624. The days on which the difference was greater than 5% were investigated and the number of missing values was also examined. Summary statistics are given in Table 4.1.

Table 4.1 shows that between 1974 and 1987 the number of missing hourly values varies from about 10 to 12%. The year 1980 has a much smaller proportion of missing data than any other, but the reasons for this are not clear. Between 1974 and 1987, the differences in accumulated 24-hour totals and daily totals are less than 5% for about half the time. Most of the differences were found to occur as a result of missing values causing 24-hour totals to be less than daily totals. From Table 4.1, it can be seen that the nature of the data changes from 1988 onwards. This can be explained by the installation of a solid-state event recorder on the site in 1987 causing an improvement in the quality of the data, demonstrated by the increase in the level of correspondence between hourly accumulated values and daily totals. Also there are no missing data from 1988 onwards.

In general, the number of missing data was found to be large enough to cause uncertainty in the extraction of the extremes of any duration up to 24 hours, particularly if a peaks over threshold approach is adopted. Therefore it would appear preferable to retain an annual maximum approach, using a system of checking short-duration maxima against their corresponding daily totals. Since the hourly gauges are relatively widely spaced, it would probably not be useful to use nearest neighbours to estimate missing values. Moreover, the total number of missing hours in 78 separate gauge records would be so great as to make such an exercise far from trivial.

Table 4.1 Appraisal of the Wyton hourly rainfall data

Year	Number of days with missing data	Missing hours (%)	Days with sum = total (to within 5%)	Days with sum ≠ total (to within 5%)
1974	249	11.9	172	193
1975	231	9.8	205	160
1976	221	10.2	210	156
1977	259	12.6	163	202
1978	231	12.8	176	189
1979	233	11.3	173	192
1980	80	4.1	236	130
1981	243	10.5	170	195
1982	234	10.8	206	159
1983	210	10.0	206	159
1984	214	10.7	187	179
1985	231	11.6	184	181
1986	221	10.6	185	180
1987	243	12.0	175	190
1988	0	0.0	255	111
1989	0	0.0	280	85
1990	0	0.0	277	88

4.2.2 Data from the NRA

Most regions of the NRA now use, or intend to use, the RAINARK system (Hydro-Logic Ltd) to store current and historic rainfall data on microcomputers. To facilitate the transfer of regional archives, it was thought to be appropriate to adopt the same system at IH. Therefore a licence to operate RAINARK version 1.3 for the duration of the first phase of the project has been agreed with Hydro-Logic Ltd, and it is envisaged that the system will be used to hold all the recording raingauge data deriving from the NRA which will be analysed during the course of the project. It may also be found to be appropriate to store the sub-daily data originating from the Met. Office in the same way, but as yet the procedure for importing the Met. Office's hourly data into RAINARK has not been tested.

Problems were encountered in transferring archived data in RAINARK format from NRA regions to the IH system because the regions did not hold the new version of the software. It will not be possible to appraise the sub-daily data held by the NRA until RAINARK version 1.3 has been installed and fully tested.

A number of sample records of recording raingauge data were received from Anglian and Severn-Trent Regions of the NRA in a variety of formats including tabular and spreadsheet output. The quality of the data was good, but the stations had been chosen subjectively making it difficult to draw more general conclusions about the characteristics of the NRA's holding of sub-daily data.

4.3 May & Hitch data

The complete database of 1-hour and 60-minute annual maxima compiled by May & Hitch (1989b) was received from the Met. Office and stored on the IBM mainframe computer at IH. The data consisted of annual maxima for 285 gauges in the UK. Fifty-one of the gauges were found to have very short records and it is thought that these were not included in the analysis of 234 gauges presented by May & Hitch (1989b). A further 49 gauges were situated in Scotland and Northern Ireland and are therefore beyond the scope of the current study. Of the remainder, five did not have information about the month of occurrence of the annual maxima, leaving a total of 180 gauges with data of greatest relevance to the project.

The annual maxima were found to be in a form that would be likely to present few problems in an extreme value analysis and thus represent a useful addition to the continuous data from recording raingauges. The fact that information about the date of occurrence of individual annual maxima was restricted to the month only was considered to be a slight disadvantage of the data set. Previous research at IH (for example, Reed & Stewart, 1989) has used more precise date information to identify dependent annual maxima at neighbouring stations. However, date is not the only criterion that can be applied in studies of dependence, and the drawback was considered to be a minor one.

5. OPTIONS FOR FUTURE WORK

5.1 Introduction

The current study of rainfall frequency has a number of specific applications in flood design, each of which is associated with its own ranges of event duration and return period. At the lower end of the temporal scale, techniques of urban drainage design require rainfall frequency estimates of durations as short as a few minutes and up to several hours. The return periods relevant to storm sewer design are typically between about 0.5 and 10 years (Natural Environment Research Council, 1975). The critical durations relevant to river engineering problems are generally in the range 1 hour to 8 days with associated return periods of between 50 and 100 years. Finally, reservoir safety standards are based on return periods of up to 10 000 years.

To support the full spectrum of applications in flood design, reliable methods of rainfall frequency estimation therefore need to be developed for durations from a few minutes up to several days. Data measured at a temporal resolution of less than one hour are not widely available, although the development of the UK's weather radar network promises to improve the situation. However, hourly rainfall depths for stations throughout the UK are now routinely transferred to computer by the Met. Office and most regions of the NRA are in the process of implementing archive systems for rainfall data.

5.2 Problems with current methods

It is now nearly 20 years since the FSR was published and a number of the problems inherent in the rainfall synthesis presented in Volume II have already been discussed in Chapter 2. A major criticism of FSR II is that it does not adequately represent observed regional variations in rainfall frequency at both long and short durations. Recent advances in statistical techniques have allowed the FORGE methodology to be developed and applied to 1 and 2-day durations in south-west England (Reed & Stewart, 1989), while at the 1-hour duration May & Hitch (1989b) have improved the basis of the map of M5 rainfall, particularly in south-east England. However, there remains a general requirement to re-evaluate the FSR method in all regions of the UK and for the full range of design storm durations.

5.3 Data available

The extent of data available to the study of rainfall frequency in England and Wales has been discussed in Chapter 3. Daily data of good quality are widely available and record lengths are sufficient to allow detailed frequency analyses to be undertaken. For the study of short durations, hourly data are required and archives of computerized hourly totals are generally of limited length. If the analysis of hourly depths were to be restricted to continuous data currently held on computer, the total number of station years would represent only about 70% of the number analysed for FSR II. However, the computerized data can be augmented by pre-existing annual maxima of a number of durations in computerized or tabulated form. The existence of the annual maximum data is likely to make large-scale digitization of recording raingauge charts unnecessary to the project, although digitization of individual records of good quality would help to improve the representation of particular regions such as Wales. In this way, the project would aim to utilize some continuous hourly records from every region of England and Wales.

5.4 Cost-benefit considerations

5.4.1 Context

This report details the survey of scope carried out in Phase 1a of the project, and thus represents only a part of the Phase 1 feasibility study. A preliminary review of the likely costs and benefits of the proposed research is now presented, although it should be made clear that such considerations are difficult to assess such a short way into the project. It is envisaged that a fuller cost-benefit analysis will form part of the outcome of Phase 1b, when the pilot region study has been completed; this will require as many data sets as possible to be made available within the pilot region.

5.4.2 Options

A number of options for proceeding with the analysis of rainfall frequency in Phase 2 of the project for durations ranging from one hour to eight days are presented. An indication of the data requirements for each option is given in Table 5.1.

1. Use only daily data.

2. Use daily data plus annual maxima for short durations (May & Hitch and tabulations).

3. Use daily data; for short durations use only Met. Office-held computerized data plus annual maxima (May & Hitch and tabulations).

4. Use daily data; for short durations use Met. Office and NRA-held computerized data plus annual maxima (May & Hitch and tabulations).

5. Use daily data; for short durations use all hourly records of at least ten years in length from the Met. Office and NRA; digitize/computerize all NRA-held records considered to be of use in poorly gauged areas; use all May & Hitch annual maxima; computerize all suitable annual maxima from Met. Office tabulations and extend with further manual extractions.

5.4.3 Costs

The above options appear in ascending order of cost. Since the daily raingauge totals are already held at IH, the costs of using the daily data are limited to data processing. In addition, IH holds the May & Hitch data set, and thus any further costs would be associated with annual updating and would be minimal. The costs associated with transferring computerized hourly data from the Met. Office to IH are currently £9.07 + VAT per station year at 1992/93 prices. The transfer of computerized sub-daily data from the NRA to IH would involve some staff and administration costs. The cost of digitizing recording raingauge charts would be of the order of £80 per station year. It is envisaged that this would only be necessary in areas where data are particularly scarce. An alternative to digitization may be manual extraction of annual maxima with dates and times from charts or tabulations, although this might not be practical for durations of longer than one hour. Such data would need to be computerized and the associated costs would be about £0.25 per station year per duration.

Table 5.1 Data sets required in further research

Data set	1	2	3	4	5
Daily data	✓	✓	✓	✓	✓
May & Hitch data		✓	✓	✓	✓
Annual maximum tabulations		✓	✓	✓	✓
Computerized hourly data (Met. Office)			✓	✓	✓
Computerized hourly data (NRA)				✓	✓
Further annual maximum abstractions					✓
Digitization of further daily and sub-daily data					✓

5.4.4 Methods

At IH, recent research has been carried out to quantify the extent of both spatial and temporal dependence in rainfall extremes. By estimating an equivalent number of independent station years, and also the associated number of independent site-duration years, this work will allow the "worth" of additional data sets to be determined. This will form a vital part of the pilot study of the East Midlands, and it is hoped that data will be made available from as many sources as possible. It is on this foundation that the production phase (Phase 2) of the project will be based, and as a result the associated data requirements for the national study will become clearer.

The methodological implications of the various options for proceeding with Phase 2 of the project are now discussed. Option 1 would use only daily data and would thus represent an extension of the current guidelines developed in a previous study for South West Water (Stewart & Reed, 1989) to the whole of England and Wales. The basis of the method is the use of extensive daily rainfall data to derive rainfall frequency estimates for durations from one to several days through application of the FORGE technique. In the absence of records of sub-daily rainfall, the method assumes that the FSR model of rainfall frequency is adequate at the 1-hour duration. For durations between one hour and one day, a correction to the FSR frequency estimates is made based on the difference between the FSR and FORGE estimates at the 1-day duration. The application of correction factors amounts to a "bridge" between the FORGE and FSR methods. It is likely that further methodological developments could be made based on the results of recent research carried out at IH into corrections for temporal discretization (Coyle et al., 1991; Dwyer & Reed, 1993).

The greatest drawback of confining the data analysis to daily totals is the necessity of relying on the FSR model for short durations. May & Hitch (1989b) identify a lack of detail in the map of 1-hour M5 rainfall reproduced in FSR II and suggest that the techniques that were used oversmoothed the original values. Also the heavy reliance of the FSR method on M5 rainfall does not correspond with the simpler concept of standardizing by the mean of annual maxima adopted in the FORGE technique. Since hourly data do exist, it would appear that options 2 to 5 offer the prospect of a better scientific solution, even if the analysis serves merely to confirm the basis of the FSR method.

Option 2 would utilize only pre-existing annual maximum information and thus the analysis would be limited by the paucity of date information and the lack of well defined criteria for the extraction of maxima. Use of the longest computerized records of sub-daily rainfall depths held by the NRA would allow a more detailed analysis of some regions, but data are seriously lacking in others which tend to correspond with those lacking in annual maximum data. Therefore a more extensive analysis would be possible using the computerized data from the Met. Office (option 3), preferably in combination with data from the NRA (option 4). Option 5 would utilize all the sources of data which have already been mentioned, and in addition would involve some digitization and/or computerization of data currently held by the NRA and the Met. Office in chart or tabulated form.

5.4.5 Benefits

The net benefits of the project can be considered in terms of the expected increase in the accuracy of the final rainfall frequency estimates. The frequency estimates are, in turn, related to the issue of design safety and, at the other extreme, that of possible overdesign. A necessary outcome of the project will be an increase in the confidence with which rainfall frequency estimates can be applied in hydrological design.

The accuracy of the resultant rainfall frequency estimates is largely dependent on the amount of data of good quality available to the project. Recent methodological developments will undoubtedly be of assistance in generalizing the results of the study, but the final conclusions can only be as reliable as the data used in the analysis. The availability of daily data is not a problem, but in the case of data from recording raingauges the situation is more complex. It is likely that the pre-existing annual maximum data will form a good basis for the analysis of short durations, but the reliability of the solution for the whole of England and Wales can only be demonstrated by reference to continuous data for a range of durations from every region. Therefore it is recommended that as much short-duration information from as many sources as possible is utilized in the final analysis.

The statistical accuracy of various networks of raingauges has been used by O'Connell et al. (1977) as the major cost-benefit criterion in a network rationalization exercise. With respect to the present study, it will not be possible to define similar criteria until further phases of the project have been completed. However, work by Schaefer (1990) has illustrated the importance of short-duration rainfall data to frequency studies in terms of the amount of information they represent relative to data of longer duration. Because rainfall events of short duration tend to be limited in areal extent, spatial dependence is less important in, for example, hourly rainfalls than in daily rainfalls. Schaefer's findings indicate that the ratio of equivalent independent record length to actual station years is 79% in the case of 2-hourly rainfalls as opposed to 47% for the 24-hour duration. These results serve to emphasize the value of short-duration rainfall data, the use of which would also help to justify the recent investment in data collection, quality control and data archiving made by the NRA.

6. SUMMARY AND CONCLUSIONS

In the UK, current practice in rainfall frequency estimation still relies largely on the method presented in the Flood Studies Report (FSR) which was published in 1975. Recent research using the extensive records of daily raingauges collected by the Met. Office has revealed shortcomings in the FSR's rainfall synthesis and, as a result, the Focused Rainfall Growth Estimation (FORGE) technique (Reed & Stewart, 1989) has been implemented in south-west England for 1 and 2-day durations. The main advantage of the FORGE methodology is its recognition of the spatial dependence inherent in rainfall extremes. In contrast, in recent years relatively little research has been undertaken into the frequency of short-duration rainfalls, largely due to the problem of gaining access to long, reliable records of hourly data in computer-compatible form. Nevertheless, May & Hitch (1989b) have highlighted lack of detail as a problem in the current implementation of the FSR model for the 1-hour duration. These factors point to the need to develop improved methods of rainfall frequency estimation for the full range of durations required for flood hazard assessment in the UK.

A review of the extent of the rainfall data which would be available to later phases of the project has confirmed that computerized daily rainfall totals can be easily accessed for England, Wales and southern Scotland. In the case of sub-daily durations, information from a number of sources would be available to the project. The longest records of sub-daily data amount to about 1100 station years from 78 gauges held by the Met. Office and about 560 station years from 40 gauges held by the NRA. In addition, over 3500 annual maximum 1-hour values computerized by May & Hitch (1989b) are now held at IH, and up to 4100 annual maxima of durations between two and 24 hours are available in manuscript form. Some further raingauge data of high temporal resolution could also be incorporated into the final analysis.

An appraisal of samples of sub-daily rainfall data from a number of sources suggests that the analysis of continuous hourly records will provide a vital means of checking analyses of pre-existing annual maxima, especially where date information is lacking. The reconciliation of daily and hourly totals at the same site is likely to be time-consuming, but will be necessary to ensure consistent results.

A number of options for proceeding with the analysis have been presented based on different data inputs. Recent methodological developments in the analysis of annual maxima offer a means of building on the FORGE technique to allow consistent rainfall growth estimates to be derived for durations ranging from one hour to eight days. Greater consistency in rainfall frequency estimation will yield greater consistency in the design of flood alleviation works. The new techniques have the added advantage of being able to determine the relative value of the various sources of data. Thus, if as many different sources of data as possible are made available to the pilot study in Phase 1b, the application of these techniques will allow the most cost-effective exploitation of the available data throughout England and Wales during Phase 2.

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APPENDIX A : NATIONAL RIVERS AUTHORITY RESEARCH AND DEVELOPMENT PROGRAMME PROJECT INVESTMENT APPRAISAL

1. R & D Commission C : Flood Defence

Topic C1 : Engineering Hydrology and Hydraulics

Project Title : Rainfall Frequency Studies

Project No. : C01(91)01

Classification of R & D : Applied research with specific aims

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Project Manager: Dr Duncan Reed

4. Contract Details

Start Date: March 1992
End Date: February 1996
Contract Type: Single Source Contract

5. Objectives

Overall project objective

To review current methods used for rainfall frequency analysis, and develop new procedures where the current methods give unsatisfactory results.

Specific Objectives

1) To review the current status of both practice and research in methods of rainfall frequency estimation for flood studies, including a literature review.

2) To develop, where appropriate, new methods of determining rainfall frequency in England and Wales.

3) To produce documents and software to allow the procedures to be widely implemented for engineering design and post event analysis, with clarity and ease.

6. Background

Procedures for estimating rainfall frequency were set down in Volume II of the UK Flood Studies Report (1975), based on research at the Met. Office. Widespread use of the procedures has identified discrepancies in some regions. Institute of Hydrology research on spatial risk confirmed that the procedures are over-generalized (Dales & Reed, 1989). New advice is available for South West England (Reed & Stewart, 1989), for areal reduction factors (Stewart, 1991), and for estimation of maximum hourly rainfall depths (May & Hitch, 1989). However, there is a need to examine rainfall frequency estimation more comprehensively.

The analysis of rainfall frequency is fundamental to river engineering design. The project is applicable to every region in the NRA. Other applications lie in reservoir, balancing pond, storm sewer, and building design, and in assessing the rarity of specific damaging events (e.g. for insurance purposes).

Context

This project has direct relevance to the Topic Investment Appraisal in providing the practising engineer with improved techniques for studying fluvial flood defence problems. Rainfall frequency analysis is fundamental to river engineering design, and the indications that current practices are inadequate must be investigated.

Institute of Hydrology have a unique position in the UK as having carried out the previous work related to the Flood Studies Report, and subsequent Supplementary Reports (FSSRs). They have undertaken the above-mentioned specific developmental work under negotiated contracts with DoE (Water Directorate), MAFF and the former Regional Water Authorities. It is therefore appropriate that this work is negotiated as a Sole Source Contract.

Justification for Sole Source Award

a. The Institute of Hydrology have unique knowledge and experience in rainfall frequency analysis. It can be noted that IoH have carried out similar work for DoE Water Directorate in their Reservoir Safety Research area under Single Source tender. The methodology for the proposal now contains unique aspects involving data held by IoH in their work on the Flood Studies Report (and subsequent issued) so involvement with other contractors is not feasible.

b. Work needs to proceed on the basis of a Memorandum of Understanding between Met. Office, IoH and NRA as the existing intellectual property rights of IoH are clearly recognised by those closely involved in project development. This is again proof of IoH's unique attributes for this work.

c. The current project will extend the work done in SW by IoH in 1989 to the whole of England and Wales, and to include shorter rainfall durations. The 1989 project was successful and its nature was such that it could not have been done by others.

7. Strategy

Phasing

To take into account technical and contractual considerations, the project will comprise 3 phases: Phase 1 (Feasibility Study), Phase 2 (Production), and Phase 3 (Implementation). The Feasibility Study will be subdivided into Phase 1a (Scoping Survey) and Phase 1b (Pilot Region Study). The later phases of the project will be evaluated after Phase 1a, and proceeding to Phase 1b is dependent on the outcome of Phase 1a. Co-operation in the provision of data and revision of the rainfall frequency procedures for England and Wales is subject to a Memorandum of Understanding between National Rivers Authority, Institute of Hydrology and Meteorological Office.

During Phase 1 all parties will review costs and benefits, and a detailed programme and costing of Phase 2 will be determined.

PHASE 1a Scoping Survey

The current status of both practice (including the revised procedures for SW region) and research in methods of rainfall frequency estimation will be reviewed. This will include a literature review, and the objectives of the project confirmed to be complementary to other research programmes. Local problems and methods of rainfall frequency estimation will be discussed with NRA engineers and hydrologists. Sample hourly rainfall data will be obtained from NRA and Met. Office sources, and their format and quality appraised. Sample annual maximum hourly rainfall data (May & Hitch) will also be obtained from the Met. Office and appraised. The availability and costs of long-term hourly rainfall records in computer compatible form will be confirmed in detail for the pilot region and in outline for the rest of England and Wales (and the Scottish Borders). Other possible sources of sub-daily rainfall data will be reviewed. A cost benefit appraisal will be made on the available sub-daily rainfall data to allow a decision to be made about proceeding to the next phases.

PHASE 1b Pilot Region Study

Long-term hourly rainfall data will be obtained from those sources identified in Phase 1a as being relevant to rainfall frequency estimation on the Pilot region. Using the hourly rainfall records in the pilot study area and long-term daily rainfall records, a method will be developed for rainfall frequency estimation for durations between one hour and eight days, and return periods between 0.5 and 200 years. The method will be a two-step procedure: extraction of index variables from maps (e.g. mean annual maximum 1-hour and 1-day rainfall depths) and application of dimensionless growth curves. A mapping method based on cokriging (a geostatistical technique) will be explored for the index variables, with the aim of using digital terrain (i.e. altitude) data to improve interpolation between gauged values; this will be undertaken using a subsidiary test area (the Severn basin) for which digital terrain data are already available. Individual growth curves will be defined for focal points distributed throughout the pilot study area, following the principle of the FORGE method (Reed & Stewart, 1989).

During Phase 1 a parallel investigation will be undertaken by Met. Office and IoH to estimate their future usage and interest in Phase 3 output. This will be included in a review of Phase 2 costs by all parties.

The outcome of Phase 1 will be a research report and detailed programme and costings of Phase 2 work, including reference to future markets and use of the output from Phase 2.

PHASE 2 Production

Phases 2 and 3 are dependent on the outcome of Phase 1 and the details will be firmed up as a result of Phase 1. The method of rainfall frequency estimation developed in Phase 1 will be extended to higher return periods and applied throughout England and Wales. Examples will be given of typical differences in rainfall and flood estimates wrought by the new procedure. A broad guide to the confidence to be attached to the estimates will be provided by temporary exclusion of selected records from parts of the analysis. The outcome of Phase 2 will be a progress report, algorithms (coded in FORTRAN) and maps for the frequency calculations, comprehensive documentation, and details of the potential implementation.

PHASE 3 Implementation

Phase 3 will see the adaptation of the algorithms and maps into finished forms. It is necessary to have a method of rainfall frequency estimation that is easy to apply and comprehensively documented.

Updates are envisaged to a number of recognized computer packages, including micro-FSR (Institute of Hydrology) ITED (Met. Office), RAINARK (HydroLogic Ltd) and WIS (ICL and Institute of Hydrology). There may be separate agreements between relevant parties for some of these updates, with NRA only being involved in funding for the implementations which it requires.

Other outputs of Phase 3 will be a final project report, which will be an appropriate NRA R&D document, and a Flood Studies Supplementary Report.

Monitoring

Project monitoring by project leader in liaison with regional contacts.

Report/progress meeting after Phase 1a reviewed by Project and Topic Leader.

Decision on Phase 1b.

PROVISIONAL STAGES FOR LATER PHASES
Report/progress meetings at 6 monthly intervals thereafter.

Dissemination
Phase 1a - Restricted, to NRA regions. This may be changed at a later date.
Phases 1b, 2 and 3 - To be determined later.

Customer Acceptance Level
R & D Commissioner for Flood Defence

8. Targets and Timescales

	Month
Report on Phase 1a	6
Decision of Phase 1b	8
PROVISIONAL	
Phase 1b inception meeting	10
Progress report/meeting	16
Report on Phase 1b	21
Review and planning meeting	23
Phase 2 scheduled for:	24-38
Phase 3 scheduled for:	41-48

9. Outputs

Project report, including literature review (Phase 1a)	15 copies
Half yearly progress reports	1 copy each
Phase 2 report/algorithms/maps	15 copies
Draft final report	15 copies
Final R&D Note/software/user guide	50 copies

10. Costs

PHASE 1a
(Note these costs are firm)

Item	External
Staff (112 man days)	23275
Travel & Subsistence	500
Capital	0
Computing	500
Data (Met Office)	200
Reports	300
Total	24775

PHASE 1b
(Note costs based on 1991/92 rates for work in 1991/92, and 1992/93 rates thereafter. Costs in 1993/94 will therefore be subject to re-valuation. The costs for Phase 1b may change as a result of the conclusions of Phase 1a.)

Item	External
Staff (396 man days)	72496
Travel & Subsistence	550
Capital	5000
Computing	2600
Data (Met Office)	2700
Reports	300
Total	83646

PHASES 2 & 3
Costings for Phases 2 & 3 is highly dependent on the findings of Phase 1, but has been estimated to be in the region of £200K to £300K. During Phase 1 other major beneficiaries will be identified so that Phases 2 & 3 can be equitably funded if the work is substantial. So the cost to NRA is also dependent on this study.

R & D Budget Provision

Phase 1 costs have been negotiated with IH and represent best achievable value for money. The rates are those appropriate to non-commercial contracts, and are those used for commissioned work for government departments. Phase 2 will be negotiated on basis of Phase 1 and the Memorandum of Understanding.

	1991/92	1992/93	1993/94
PHASE 1a	10854	13931	
PHASE 1b (provisional)		48018	35628

11. Benefits

The projects will provide rainfall frequency techniques for the practising engineer for use in river engineering design. These procedures will be easy to use and supersede the current methods which are not universally satisfactory at present. The NRA has responsibility for control and regulation of all works which affect main river and discretionary powers to carry out flood defence capital and maintenance works on main rivers. The rainfall frequency analysis is fundamental to river engineering design and improved techniques of flood estimation will provide more accurate estimates of design flows. In some cases the research may reinforce confidence in existing methods, and in others will produce new guidelines. In some cases the new guidelines may result in a reduction in capital expenditure but in others it may result in an increase in capital expenditure. More accurate design estimates will ensure more effective spending of public money, and the expenditure on flood defence capital projects by NRA which would be influenced by the findings is considerable.

If the project is not undertaken, then the existing methods will continue to be used and there is a danger that a) unduly conservative design assumptions are made increasing the cost of flood defence works, or b) through lack of hydrological knowledge unsafe design assumptions are made and flood defence works may fail more regularly than expected.

12. Assumptions and Risks

The success of the project is strongly dependent on the experience, knowledge and ability of the contractor. The overall risks are minimal.

13. Overall Appraisal

The project is an essential part of the overall Topic programme, and will provide substantial benefit to the practising engineer through the NRA. The risks, which are minimal, are limited to the adequacy of the contractor.

APPENDIX B : MEMORANDUM OF UNDERSTANDING

1. Introduction

This Memorandum of Understanding sets out to define the responsibilities of the principal parties involved in the project "Rainfall Frequency Studies: England and Wales". These are the National Rivers Authority (NRA), the Institute of Hydrology (IH), and the Meteorological Office (Met. Office). The Project is defined in Para. 3 and, more fully, as part of the Project Investment Appraisal prepared by the NRA. The Memorandum of Understanding acknowledges the close links between the three parties and identifies their respective contributions to rainfall frequency estimation in the UK. It also acknowledges that the NRA contributes generally to the work of the Met. Office provision of rainfall data from NRA-operated sites.

The Memorandum of Understanding is separate from, but complementary to, the Phase 1 contract between the NRA and IH.

It is agreed that no party to this agreement will seek to profit unduly from the inputs (as listed in Section 4) of any other party.

It is agreed that the Memorandum of Understanding may be altered during the course of the project by agreement of all three parties.

2. Background

Procedures for rainfall frequency estimation were set down in Volume II of the UK Flood Studies Report (Natural Environment Research Council, 1975), based on research at the Met. Office. Subsequent to particular studies in South West England, IH was asked by the NRA to investigate the feasibility of reworking rainfall frequency estimation procedures for England and Wales. The Project requires sub-daily rainfall data held by the Met. Office as custodians of the national rainfall archive.

3. Objectives

i) Review the current status of research in methods of rainfall frequency estimation for flood studies;

ii) Where appropriate, develop new methods of determining rainfall frequency in England and Wales;

iii) Produce documents, algorithms and software to allow the procedures to be implemented with clarity and ease, to the satisfaction of all parties.

4. Project

The terms and scope of the project agreed between the NRA and IH are attached as Annex to this Memorandum of Understanding. The project will be in three main phases.

a) Phase 1 will be a feasibility study comprising a "scoping survey" (in which requirements, methods and data are appraised) and a pilot study in an agreed region. If Phase 1a (scoping survey) is successful then Phase 1b (a pilot study) will be undertaken. The outcome of Phase 1a will be a Project Report. The outcome of Phase 1b will be a Project Report which will include a detailed proposal for Phase 2. The proposal will take account of the market study undertaken by the Met. Office and IH, identifying the potential beneficiaries of Phases 2 and 3.

b) If the feasibility study (Phase 1a and 1b) is successful, Phase 2 will extend the study to the whole of England and Wales. It will develop a series of algorithms and related documentation.

c) Phase 3 will see the conversion or adaptation of the algorithms derived in Phase 2 into agreed forms suitable to each party.

5. Inputs

a) Inputs from the Met. Office

i) The Met. Office will supply IH with sample hourly raingauge data for the scoping survey (Phase 1a). If the Project moves on to Phase 1b the Met. Office will supply hourly raingauge data for an agreed pilot region (probably East Midlands). If the Project moves on to Phase 2, the Met. Office will supply further hourly rainfall data for gauges throughout England and Wales (and in the Scottish borders). These data, taken from the national rainfall archive, will include some stations operated by the NRA, and stations for which data is collated by NRA.

ii) The Met. Office will supply IH with such hourly statistical data (May and Hitch, 1989) as are available: for sample gauges in Phase 1a, for gauges in the pilot region if Phase 1b proceeds and, if the Project proceeds to Phase 2, for gauges throughout England and Wales (and in the Scottish borders).

iii) Met. Office charges for the supply of these data will be confined to staff, computing and administration. No charge will be made in respect of costs accrued in observing, processing, quality control and analysis of the data, or in instrument inspection or database maintenance.

b) Input from NRA

i) The NRA will supply IH with hourly data for sample gauges in Phase 1a. Subject to the evaluation of Phase 1a, the NRA will supply additional raingauges in the agreed pilot region for Phase 1b and throughout England and Wales for Phase 2.

ii) The NRA will fund Phase 1a work at IH, and also Phase 1b should it proceed. It will also give strong support to Phases 2 and 3 if feasibility is proved in Phase 1.

c) Input from IH

i) IH will contribute expertise in rainfall frequency analysis derived in projects funded by DOE (from 1985), South West Water (1988), MAFF (1989) and NERC (1990).

ii) IH shall carry out its study for the NRA as described under "objectives" above and subject to the NRA/IH contractual agreement for "Rainfall Frequency Studies: England and Wales".

6. Outputs

a) Derived statistical data and algorithms

IH will provide copies of derived statistical data sets and algorithms (and with any subsequent amendments thereto) in agreed forms compatible with NRA and Met. Office requirements. These derived statistical data will comprise three main types of information:

i) rainfall statistics - deriving reasonably directly from the basic data,

ii) rainfall maps - coming from a fairly advanced analysis using digital terrain data,

iii) rainfall growth curves - deriving from an advanced analysis of extreme values.

b) Software implementations

Various implementations of the derived statistical data and algorithms for rainfall frequency estimation at any site in England and Wales are anticipated with existing packages such as Micro-FSR and RAINARK (both of which are heavily used by the NRA, either directly or by delegation), and within the successor to the Met. Office's ITED rainfall frequency estimation program. The form of implementation will reflect the characteristics of the particular package, and may be carried out (or contracted out) by any of the parties to the Memorandum of Understanding, subject to agreement. IH will supply copies of the derived statistical data and algorithms in computer-compatible form to assist in any approved implementation.

c) If all parties are in agreement that the revised methods supersede previous FSR methods for rainfall frequency estimation, IH will produce a Flood Studies Supplementary Report.

7. Rights and Restrictions

a) The restriction imposed on IH concerning use of pre-1961 daily rainfall data for some 400 long-term stations (held at IH under a previous project) will be lifted. This relaxation applies only to the "Rainfall Frequency Studies: England and Wales" project, and any other use must (as at present) be with the prior approval of the Met. Office.

b) IH will use the statistical data supplied by the Met. Office (Para. 4aii) and the basic hourly rainfall data supplied by the Met. Office (Para. 4ai) and NRA (Para. 4bi) only in the specified project. Any further use of these data by IH or their contractors or any transfer outside IH, would require further agreement with the supplier (i.e. Met. Office or NRA); the Met. Office or NRA reserve the right to refuse a request, to apply commercial charging rates, or to enter a further special agreement.

c) The NRA and its delegated representatives (as agreed by the other two parties) will be free to use the derived statistical data and algorithms (Para. 5a) in any application or further research.

d) IH will be free to use the derived statistical data and algorithms in any application or further research, and to supply (but not sell) these to any bona fide researcher.

e) The intellectual property rights for the outputs of the research will be shared according to the relative value of the inputs to this, and related earlier projects. Subject to the feasibility study not demonstrating undue profit, the suppliers of data (Met. Office and NRA) shall be granted sole rights to sell a general rainfall frequency estimation service based on the derived statistical data and algorithms. Software implementations in commercial packages such as Micro-FSR, RAINARK and WIS will be consistent with their general roles and will not seek to displace the successor to the Met. Office's ITED package.

   This paragraph will be subject to review following Phase 1 in the light of more detailed economic data.

f) The parties will openly advertise this study and their collaborative activities and responsibilities. Any publication package or sale arising out of the project will acknowledge the three principal parties, and may quote the Memorandum of Understanding.

APPENDIX C : CORRECTING FOR THE EFFECTS OF TEMPORAL DISCRETIZATION

Maximum rainfalls can be abstracted from recording raingauge records for a range of durations and data intervals. It is important to realize that a maximum rainfall of 60-minute duration is not identical to that of 1-hour duration, since the former is allowed to start at any time, while the latter is constrained to start on GMT clock hours. As a result, maximum rainfalls of 60-minute duration are larger on average than maximum rainfalls of 1-hour duration. In FSR II, correction factors are presented which can be used to convert from M5 values for durations measured in days or hours to the corresponding M5 values for durations measured in hours or minutes, respectively. Some of the FSR correction factors are tabulated below.

Table C1 Correction factors to give M5 equivalents for clock hours or rainfall days (from FSR II)

1 hour to 60 mins	2 hours to 120 mins	6 hours to 360 mins	1 day to 24 hours	2 days to 48 hours
1.15	1.06	1.015	1.11	1.06

Research into the effects of temporal discretization on environmental extremes is continuing at the Institute of Hydrology and some results are presented by Coyle et al. (1991) and Dwyer & Reed (1993).