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Mapping an index of extreme rainfall across the UK

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Abstract

Distance from the sea, proximity of mountains, continentality and elevation are all useful covariates to assist the mapping of extreme rainfalls. Regression models linking these and other variables calculated from a digital terrain model have been built for estimating the median annual maximum rainfall, RMED. This statistic, for rainfall durations between 1 hour and 8 days, is the index variable in the rainfall frequency analysis for the new UK Flood Estimation Handbook.

The interpolation of RMED between raingauge sites is most challenging in mountainous regions, which combine the greatest variation in rainfall with the sparsest network of gauges. Sophisticated variables have been developed to account for the influence of topography on extreme rainfall, the geographical orientation of the variables reflecting the prevailing direction of rain-bearing weather systems. The different processes of short and long-duration extreme rainfall are accounted for by separate regression models.

The technique of georegression combines estimates from regression models with a map of correction factors interpolated between raingauge locations using the geostatistical method of kriging, to produce final maps of RMED across the UK.

Introduction

CONTEXT: RMED AS AN INDEX OF EXTREME RAINFALL

A new study of flood estimation in the UK will result in the publication of the Flood Estimation Handbook (FEH) in early 1999 (Reed, 1994). One volume of the FEH is devoted to rainfall frequency studies. The FEH method of estimating design rainfalls comprises two stages: mapping an index rainfall and deriving rainfall growth curves. Growth curves, which relate rainfall of various return periods to the index rainfall, are derived by the FORGEX method which is described by Reed *et al.* (1998). The present paper describes the mapping of the index rainfall across the UK.

The FEH rainfall frequency analysis is based on annual maximum rainfalls, aggregated over durations from 1 hour to 8 days. The annual maximum series of a given duration from each raingauge is standardised by the index rainfall, which is taken to be the median of the series, RMED. The median is used in preference to the mean as it is a more robust statistic which is unaffected by the presence of unusually large or small values in the annual maximum series. In addition, the median value corresponds to a defined return period of two years on the annual maximum scale.

A required minimum record length of nine years ensures that RMED is reasonably estimated. The estimates will still be susceptible to climatic fluctuations, but the chosen minimum record length is a compromise between having too short and too few records. There are many new sub-daily rainfall records around ten years long, some of which are in remote areas and are thus particularly valuable in the mapping of RMED.

Maps of RMED for each rainfall duration on a one-kilometre grid were required, enabling the estimation of design rainfall for any location in the UK. These maps were obtained by interpolating values of RMED observed at the sites of raingauges.

BACKGROUND

There is a wide choice of interpolation techniques for mapping environmental variables. These range from simple methods such as interpolation of neighbouring data, through more complex methods like kriging, to methods which incorporate information from covariates, such as cokriging.

The method of kriging has seen many applications, firstly in the mining industry and in recent years increasingly in hydrology and meteorology. Kriging and variants of the method such as cokriging are based on the theory of geostatistics (Journel and Huijbregts, 1978). Geostatistics involves analysing the spatial structure of a variable by deriving a semivariogram, which describes how the variance between pairs of points changes with their separation.

A model is fitted to the experimental semivariogram, and this model is then used in the *ordinary kriging* process which assigns values to ungauged locations using a weighted linear combination of nearby sample values. Stewart *et al.* (1995) found that kriging was a good method for mapping RMED in the Severn catchment.

Ordinary kriging works well in lowland Britain, where there is a dense network of daily raingauges providing sample values of RMED (Fig. 1). However, RMED is less well sampled in mountainous areas. In addition, the network of recording raingauges (which provide values of RMED for durations 1 to 24 hours) is much sparser in all areas, as can be seen from Fig. 2. One avenue for improving the interpolation is to incorporate information from covariates (secondary variables) which are related to rainfall. Covariates such as elevation, distance from the coast or more subtle topographic variables can be derived from a digital terrain model (DTM) and evaluated at every 1-km grid node (Prudhomme and Reed, 1998).

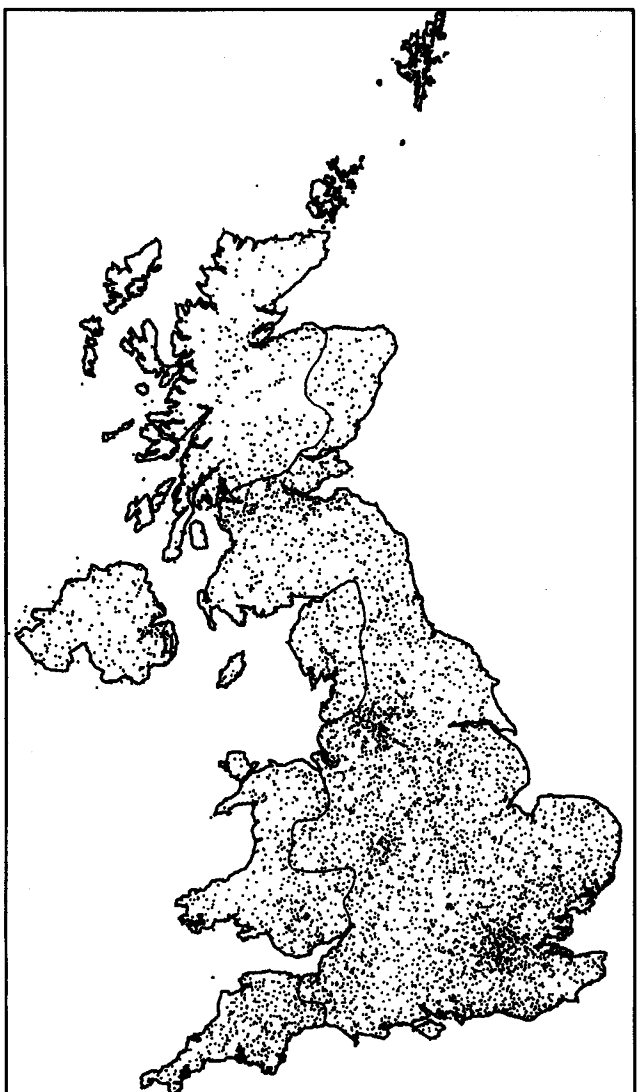

Fig. 1. *Daily raingauges in the UK and border areas of the Republic of Ireland providing values of RMED. The Celtic region is to the west of the boundary lines.*

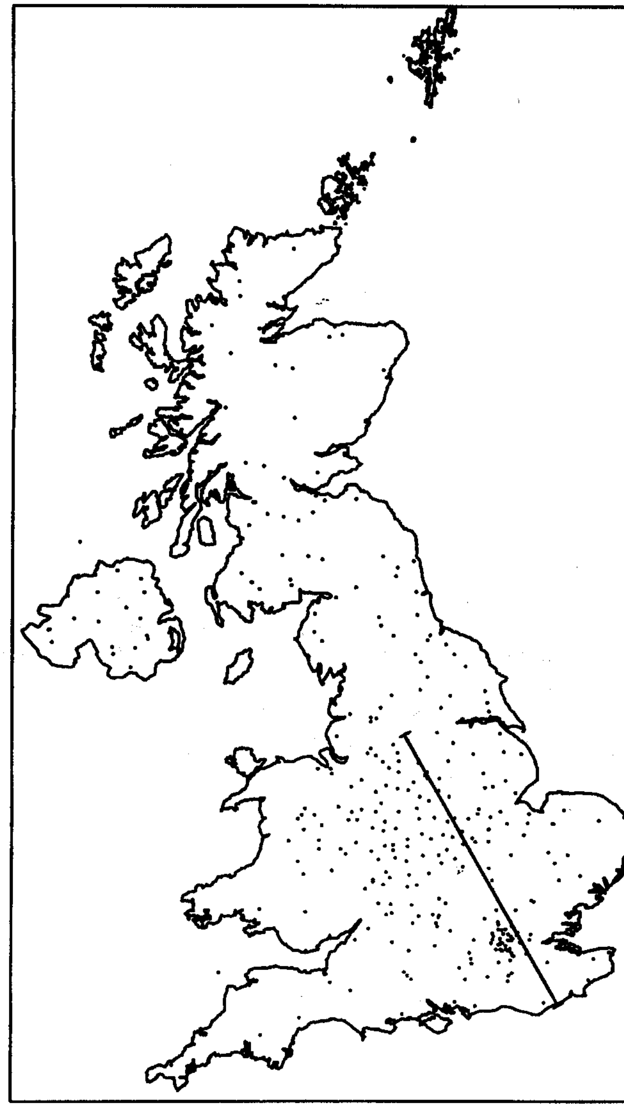

Fig. 2. *Recording raingauges in the UK providing values of RMED. The transect studied by May & Hitch (1989b) is marked.*

One way to incorporate covariates is via the method of cokriging. This involves the estimation of cross-variograms which describe the spatial relationships between the variable of interest and prospective covariates. Phillips *et al.* (1992) demonstrated the usefulness of cokriging for estimating average annual rainfall in mountainous terrain using altitude as the secondary variable. Stewart *et al.* (1995) tried cokriging for mapping RMED, also using altitude as the covariate. They found that cokriging offered no improvement over ordinary kriging, possibly because of the poor correlation between RMED and altitude in the Severn catchment.

Cokriging becomes difficult to apply when there is more than one covariate. A simpler alternative which makes use of any number of covariates is *georegression.* A regression model relating the primary variable with the covariates is used to estimate the primary variable at all sites. The estimates are improved by combining them with residuals, which are interpolated (by ordinary kriging) between gauge locations. The technique has also been termed elevation-detrended kriging (Phillips *et al.*, 1992).

STRUCTURE OF THE PAPER

Maps of RMED, for rainfall durations 1 hour to 8 days, were produced for the UK using georegression. The study is described in two stages: first the building of regression models relating rainfall to topography and second the production of maps. Sample results are then presented, and the implications for rainfall frequency estimation discussed.

DATA

The number of sufficiently long records from UK daily raingauges is just over 6000. Most records cover the period from the 1960s to the 1990s, but there are several longer records, some of which extend back to the mid-19th century.

A total of 375 gauges provide estimates of 1-hour RMED. Most series are short, covering 10–20 year periods from the 1960s to the 1990s. The longest records extend for 100 years. As is evident from Fig. 2, parts of the UK are very sparsely sampled by recording raingauges.

Relating rainfall to topography

REVIEW OF TOPOGRAPHIC EFFECTS ON PRECIPITATION

Relationships between precipitation and topography, especially elevation, have been studied for a long time. For example, Bleasdale and Chan (1972) reviewed research in Great Britain and Ireland from the late 19th century. One of the best known relationships is the orographic effect: rainfall increases with elevation. This simple relation has to be moderated by a secondary phenomenon, the rain-shadow effect (Flohn, 1969), and, in large upland areas such as the Cairngorm mountains, by rain-out of the low level moisture before it reaches the highest summits.

The orographic effect has been explained by a seeder-feeder process, whereby rain from a widespread 'seeder' cloud sweeps out droplets from low-level 'feeder' clouds which have developed over hills through the uplift of moist air (Bergeron, 1967). Rainfall can also be redistributed over hills in the absence of a feeder cloud, when the perturbed airflow modifies the trajectories of raindrops. Such redistribution of rainfall does not alter the total water flux to the land, but may appear to do so given the typical sparsity of raingauges in mountainous areas (Bradley *et al.*, 1997). The resulting rainfall pattern is likely to be related to topographic measures such as exposure and slope.

In addition to the above topographic effects on rainfall, 'other factors, such as the direction and the distance to moisture sources, as well as the synoptic climatology of a given region, considerably complicate and, hence, weaken precipitation-elevation relationships' (Konrad, 1996). Thus, orographic enhancement of rainfall is most noticeable in western parts of the UK, because they tend to be more mountainous and they are exposed to the prevailing westerly and south-westerly wind directions which bring rainfall from Atlantic depressions. Distance to the sea is more likely to be important for winter precipitation, when the sea is the main source of moisture. In the summer, evaporation from the warm land surface can exceed that from the sea.

TOPOGRAPHIC VARIABLES

This section introduces the topographic variables used in the georegression. These are based on an earlier study of extreme rainfall in Scotland (Prudhomme and Reed, 1998). The variables are derived from a 1-km DTM, provided by the UK Met. Office, and calculated for eight cardinal directions (N, NE, E, SE, S, SW, W, NW) and, for some variables, in two additional directions which represent the prevailing winds (WSW, ENE).

Elevation is the topographic variable most often used in rainfall studies. ELEV is defined as the elevation in m of the DTM grid point nearest to the gauge. Hereafter, this position is referred to as the gauge grid point, ggp. The difference between the 'true' elevation (altitude of the gauge stored in the rainfall database) and ELEV can sometimes be up to 100 m, due to the particularly steep slopes encountered in Scotland and the relatively coarse grid interval of the DTM used. However, the error is not considered too significant, and in any case ELEV is not used in the final regression models.

Average elevation is an alternative elevation suggested by Konrad (1996). Two average elevations are calculated: (i) ELEV4, arithmetic mean elevation of the typically 25 DTM-grid-points in a 4×4 km square centred on ggp; (ii) ELEV10, arithmetic mean elevation of the typically 121 DTM-grid-points in a 10×10 km square centred on ggp.

Geographical position is represented by EASTING and NORTHING (in km units) of ggp on the national grid reference system.

The slope variable was considered at several distances and in several directions. SLOPEi is the *mean slope* between ggp and a point i km away in each of the eight cardinal directions. In this study, SLOPE2, SLOPE5 and SLOPE10 are calculated.

Two *average* mean slopes are evaluated in each of the cardinal directions:

$$ASLOPE = \frac{SLOPE2 + SLOPE5 + SLOPE10}{3};$$

$$WSLOPE = \frac{2xSLOPE2 + 5xSLOPE5 + 10xSLOPE10}{17};$$

the latter being a weighted mean slope.

Other topographic variables mentioned in the literature, such as *exposure* (Basist *et al.*, 1994, Konrad, 1996), 'bumpiness' of the terrain or *bump* (Leblois and Desurosne, 1994), and distance to a barrier (Schermerhorn, 1967) were derived from the DTM and used in single regressions in the Highlands of Scotland. Prudhomme and Reed (1998) found that they explain very little of the variation of 1-day RMED in Scotland. One of the weaknesses of these variables is that they are defined in a straight line and therefore their value is dependent on the DTM-grid points found in that particular linear direction, which might express the presence of a small feature (for example a hill or a narrow sea loch). In order to reduce this bias, these variables are calculated and averaged over a 90° sector centred on each of the cardinal directions, **d**, where **d** is N, NE, E, etc.

Figure 3 illustrates the definition of the following three variables. The plan view shows the 90° sector centred on the direction **d** and one of eleven secondary directions radiating at angle α from the ggp. The variables are averaged over these eleven directions, each value being weighted by cos α to give more weight to directions close to **d**. The longitudinal section shows the gauge and the horizon in one direction.

Distance from sea (SEA) is the weighted average of the 11 distances (in km) from the sea averaged across a 90° sector centred on the direction of interest **d**.

Obstruction (OBST) is the averaged version of *exposure*. It represents the average angle subtended by the highest topographic barrier in a sector centred on **d**. It is calculated by taking the weighted average of the eleven tangents of the angles subtended by the horizon, $(\Delta h/\Delta x)$, with units m/km. The smallest value OBST can take is zero, for a totally exposed site.

BAR is the weighted average of the eleven distances (in km) to the horizon, Δx.

SHIELD represents a roughness index for a sector centred on **d**. It is the sum of the 'ups and downs' in elevation, each elevation difference being divided by its distance from the gauge, so that roughness closer to the gauge is given more weight. It is the modified version of *bump*.

In general, the new averaged variables perform better than their unidirectional equivalent in Scotland (Prudhomme and Reed, 1998), and were the only ones considered for the UK-wide regression analysis of RMED.

BUILDING A MODEL FOR LONG-DURATION RMED: 1 TO 8 DAYS

Single-variable regressions between RMED and the various topographic variables were used to explore the relationships between RMED for long duration rainfall (1 to

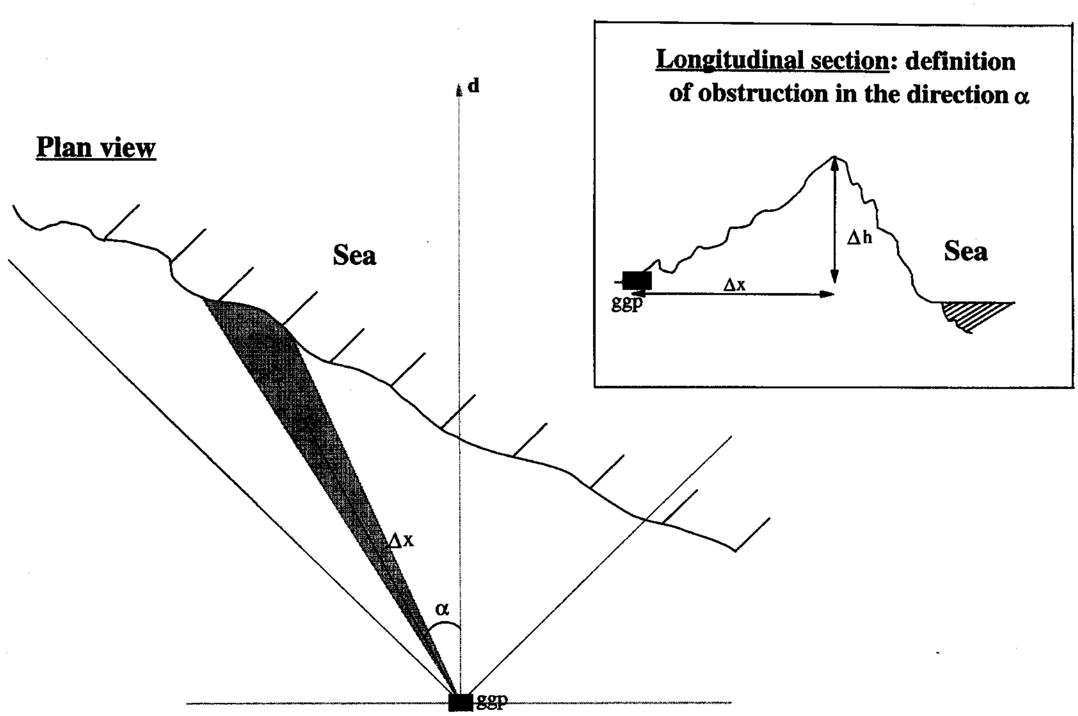

Fig. 3. *Definition of the topographic variables SEA, BAR and OBST.*

Table 1. Coefficients of the variables in regression models for 1000/(D-day RMED) in Great Britain.

Duration (days)	Constant	$OBST_{SW}$	ELEV10	SEA_{WSW}	R^2 (%)
1	26.39	–0.070	–0.028	0.053	53
2	20.22	–0.063	–0.023	0.041	58
4	14.86	–0.050	–0.019	0.038	61
8	10.35	–0.038	–0.014	0.032	62

8 days) and topography. For each rainfall duration, a model for RMED was then built using multiple regression analysis. The maximum number of explanatory variables to be included in each model was limited to four.

In addition to the proportion of variance explained by the model, the following criteria were considered when selecting variables for inclusion in the model. Explanatory variables should not be highly correlated with each other, and, where possible, models should respect physical explanations for variations in rainfall. For example, most of the long-duration rainfall extremes in the UK are associated with the prevailing westerly and south-westerly winds. Accordingly the explanatory variables oriented W–E or SW–NE are more likely to be physically meaningful than those oriented N–S or NW–SE.

It was decided to focus the regression analysis on the mountainous regions of the UK. Topography and relief are expected to be more clearly correlated here than in regions with less varied relief. The priority in model-building was to fit the data well in these sparsely-gauged mountain regions. Elsewhere, it was expected that the good density of sample values would enable the interpolated residuals to account for any variations in the fit of the model.

After several alternative groups of gauges were tried, the model was fitted to data from the 1589 raingauges in a 'Celtic' region comprising the Scottish Highlands, north-west England, Wales (minus the Severn catchment) and south-west England. The boundary of the region is marked on Fig. 1. A separate regression model was fitted in Northern Ireland.

Least-squares regression relies on an assumption of constant variance, i.e., no relationship between the squared residuals and the predicted variable. Several transformations of the primary variable, RMED, were tried in order to increase compliance with the assumption. The final model was framed in terms of the most effective transformed variable, which was 1000/RMED.

The model-building technique was a stepwise multiple regression: variables were added to the model one at a time. The preferred model for 1000/(1-day RMED) is:

$$1000/RMED = 26.39 - 0.070\ OBST_W - 0.028\ ELEV10 + 0.053\ SEA_{WSW}. \quad (1)$$

where RMED is in mm, ELEV10 in m and SEA_{WSW} in km.

This model explains 53% of the variance in the Celtic region, and 57% of the variance in the whole of Great Britain. The model makes physical sense: the rainfall increases with average elevation and with the obstruction to the west, which reflects orographic enhancement of rainfall moving from the west. RMED decreases with distance from the sea in the west-southwest direction, in accordance with the prevailing wind direction.

For rainfall durations longer than one day, models were fitted to the same trio of topographic variables, since broadly similar processes govern extreme rainfall for durations between 1 and 8 days. The coefficients of the equations for 1, 2, 4 and 8-day rainfall are given in Table 1. The coefficients vary smoothly with rainfall duration. For longer durations, somewhat more of the variance is explained by the model. This is probably because the topographic effects represented by the model are more influential on longer-duration rainfall extremes. Another possible reason is that the measurement of rainfall at 0900 often separates a heavy rainfall event into two parts, so 1-day annual maxima are less likely to capture true rainfall processes.

The regression models for long-duration RMED perform fairly well everywhere, with more of the variance explained in the whole of Britain than in the fitting region. This is because the Celtic region is deliberately chosen to include the largest variations in topography and rainfall. The formulation of the model in terms of 1000/RMED was found to cause some problems in combining modelled RMED with residuals for long-duration rainfall in a few high-altitude areas. These were overcome by using the estimates of 1-day RMED (which do not suffer from the problem) as a base to estimate RMED for longer durations in the problem areas.

A similar methodology was applied for Northern Ireland, where records are available from 269 raingauges with at least ten annual maxima, including 27 in border areas of the Republic of Ireland. The stepwise regression for 1000/(1-day RMED) resulted in the following model:

$$1000/RMED = 19.08 - 0.097\ OBST_{SW} - 0.048\ ELEV10 + 0.056\ SEA_{SW} + 0.047\ SEA_E. \quad (2)$$

Table 2. Coefficients of the variables in regression models for 1000/(D-day RMED) in Northern Ireland

Duration (days)	Constant	$OBST_{SW}$	ELEV10	SEA_{SW}	SEA_E	R^2 (%)
1	19.08	–0.097	–0.048	0.056	0.047	64
2	16.26	–0.084	–0.037	0.036	0.033	67
4	14.46	–0.073	–0.033	0.024	0.015	71
8	11.08	–0.054	–0.023	0.017	0.004	68

This model explains 64% of the variance of 1-day RMED. The same topographic variables were used in modelling 2, 4 and 8-day RMED, and the coefficients are given in Table 2. The differences between the variables in Eqns. 1 and 2 reflect the different topographic features of Northern Ireland. While more locally appropriate regression models could be fitted to other regions of the UK, these would raise the problem of discontinuities at regional boundaries.

BUILDING A MODEL FOR SHORT-DURATION RMED: 1 TO 12 HOURS

Short-duration rainfall extremes are more difficult to model, mainly because of a lack of data. The number of sites offering sub-daily data for Northern Ireland is not sufficient to fit a separate regression model, so data from the whole of the UK are considered simultaneously.

Maps of RMED are required for rainfall durations of 1, 2, 6 and 12 hours. There are fewer data for longer durations, because not all annual maxima are extracted from computerised continuous records; some are obtained from manuscript tables which were compiled from chart records in the 1970s, often only for hourly extremes.

RMED is particularly difficult to model for the shortest rainfall duration, 1 hour, owing to large variations in the sample values over short distances, particularly in eastern England. It was thought that data connected with thunderstorm activity might help explain these variations, and so lightning strike data were included in the analysis. The data were recorded using the Arrival Time Difference system in which several sensors detect the electromagnetic impulses associated with lightning strikes. The lightning strike data were aggregated within 10 × 10 km blocks over the years 1988 to 1996. The median strike density (MEDLIGHT) for the period 1988–1996 was calculated and included as a possible explanatory variable within the regression analysis.

Two other covariates were added to the candidates for model-building for short-duration RMED. The first was the interpolated 1-day RMED (RMEDDY) at the site of the short-duration RMED sample. The second new variable was an index of 'continentality', which was taken as being the distance from Lille in north-west France, DLILLE. The index broadly represents a continentality effect noted in an earlier analysis of extreme rainfall (NERC, 1975). DLILLE is small in south-east England where thunderstorms are more frequent and severe.

The relationships between short-duration RMED and the topographic and lightning variables were first explored by single-variable regressions. Selected results are shown in Table 3. The two most influential variables on 1-hour RMED are DLILLE (the distance from Lille) and NORTH (the latitude of the site). For longer durations, as convective rainfall becomes less important and frontal rainfall more so, RMEDDY has a rapidly increasing influence. Note that over 70% of the variation in 12-hour RMED is explained by the interpolated 1-day RMED.

The lightning strike variable, MEDLIGHT, explains little of the variance of RMED for any duration. The relationship between lightning strike rate and extreme rainfall is not simple. In a convective storm lightning strikes do not necessarily occur at the same time as heavy rainfall, and therefore, if the storm is moving, may occur in a dif-

Table 3. Percentage of variance in short-duration RMED explained by selected covariates

Variable	R^2 (%) for: 1-hour RMED	2-hour RMED	6-hour RMED	12-hour RMED
DLILLE	14.4	1.9	3.2	5.3
NORTH	13.9	3.1	1.2	2.3
RMEDDY	5.1	21.6	62.9	70.3
MEDLIGHT	5.6	0.4	3.9	6.5
$OBST_{NW}$	2.3	0.2	10.2	14.7
BAR_{SE}	3.2	2.7	0.4	1.4

Table 4. Coefficients of the variables in regression models for short-duration RMED.

Duration (hours)	Constant	$OBST_{NW}$	BAR_{SE}	DLILLE	RMEDDY	R^2 (%)
1	8.46	–0.030	0.012	–0.00036	0.102	32
2	8.97	–0.030	0.012	–0.00036	0.210	45
6	6.28	–0.030	0.012	–0.00036	0.564	70
12	3.51	–0.030	0.012	–0.00036	0.826	78

ferent location. Also locations prone to lightning strikes are not necessarily prone to heavy rainfall.

A multiple regression analysis, coupled with the choice of physically realistic variables, produced the models for short-duration RMED (mm) specified in Table 4. The presence of the topographic variables $OBST_{NW}$ and BAR_{SE} supports a finding of May and Hitch (1989b). They mapped 1-hour rainfall with a return period of 5 years in the UK and looked at the results along a swath running approximately southeast-northwest through London and into the English Midlands (shown on Fig. 2). The largest 1-hour rainfall totals appear to be co-located with south-east facing ground slopes. May and Hitch (1989b) suggested that this was an effect of heavy rainfall produced by orographic uplifting associated with summer thunderstorms which develop over France, cross the English Channel and travel into the English Midlands. The models for RMED in Table 4, with a positive coefficient for BAR_{SE} and a negative coefficient for $OBST_{NW}$, support this interpretation, producing larger values for extreme rainfall on south-east facing slopes.

The coefficients of the topographic variables and the index of continentality, DLILLE, were found to vary only slightly with duration. A single coefficient was therefore adopted for each variable, and the difference between durations is accounted for by a change in the constant and, most significantly, in the coefficient of RMEDDY. The percentage of variance explained increases dramatically with duration, from 32% for 1-hour rainfall to 78% for 12-hour rainfall, partly because of the increasing relevance of RMEDDY for longer durations

Mapping RMED by georegression

DESCRIPTION OF GEOREGRESSION

The method of georegression is a relatively simple way of incorporating information from covariates when interpolating a variable. Once a regression model is found, the steps involved in georegression are as follows:

(i) The model is used to estimate RMED at every 1-km grid point;
(ii) The differences between observed and estimated RMED (i.e. the residuals) are calculated at all raingauge sites;
(iii) The residuals are interpolated, by ordinary kriging, to give a map of correction factors;
(iv) The maps of regression estimates and correction factors are combined to give a final estimate of RMED on a 1-km grid.

Thus, any local variations in the performance of the regression model are explicitly accounted for.

REGRESSION MODEL RESULTS

The models specified in Tables 1 and 3 were used to estimate RMED for various rainfall durations at every 1-km grid point over the UK. Figure 4 is an example of the results, a map of estimated 1-day RMED. The map is very detailed, following the relief closely. The largest area where the modelled RMED is high is the Grampian mountains in eastern Scotland, where the high altitude and steep slopes give rise to estimates of RMED which are significantly higher than gauged estimates.

MAPPING THE RESIDUALS

The residuals for long-duration RMED are defined as $1000/RMED_{modelled}-1000/RMED_{observed}$. The experimental semivariograms derived from the residuals for each rainfall duration were represented by semivariogram models which were isotropic, i.e. the same in all directions.

Guided by the semivariogram models, the residuals were interpolated using ordinary kriging. An example of the results is shown in Fig. 5, a map of the interpolated residuals of 1000/(1-day RMED). The pattern of residuals is similar for longer durations (2 to 8 days). Residuals of 1000/RMED are generally positive in the eastern part of Britain, particularly Lincolnshire and Yorkshire, where the value of SEA_{WSW} is large but RMED is not substantially smaller than elsewhere in lowland England. Residuals are most negative over the Grampian mountains in Scotland, where the model does not account for the rain-shadow effect, by which rainfall over the Grampians is lower than in areas of similar elevation further west in Scotland.

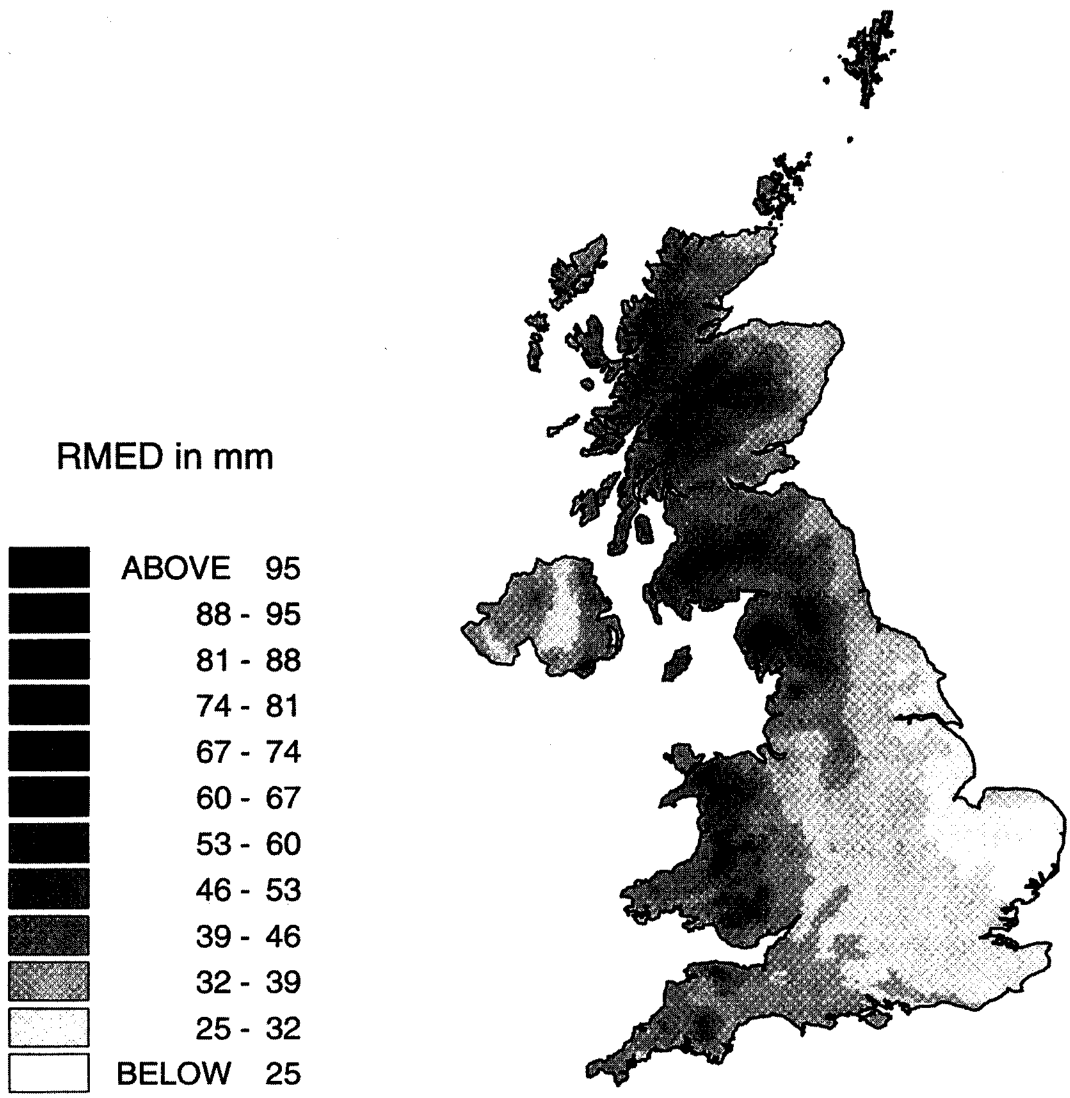

Fig. 4. *1-day RMED estimated by the regression model.*

Results and discussion

MAPS OF RMED OVER THE UK

Figure 6 is the final map of median annual maximum 1-day rainfall (RMED) over the UK, a combination of the regression model and the map of correction factors. The maps for 2 to 8-day rainfall have a similar structure. The largest values of RMED for long-duration rainfall are found in mountainous regions, and especially in the western parts of the mountains. The south coast is generally wetter than more inland areas, and the smallest values can be found at the east coast, and especially in East Anglia.

Figure 7 is the final map of RMED for 1-hour rainfall. The largest values are again in the western uplands, but there are also areas in eastern and southern England with increased RMED, thought to reflect convective storm activity. The smallest values are in eastern Scotland. There is no particular sign that RMED is higher in urban areas, despite evidence that urban heat island effects influence the initiation and development of convective storms (Thielen and Gadian, 1997).

CONSEQUENCES FOR ESTIMATING DESIGN RAINFALLS

To recap, estimates of design rainfall given by the Flood Estimation Handbook are a combination of the index rainfall, RMED, and a growth factor. The nationwide variation in growth factors is smaller than the variation in RMED. For example, the growth factor for 1-hour rainfall with a return period of 100 years varies over the UK

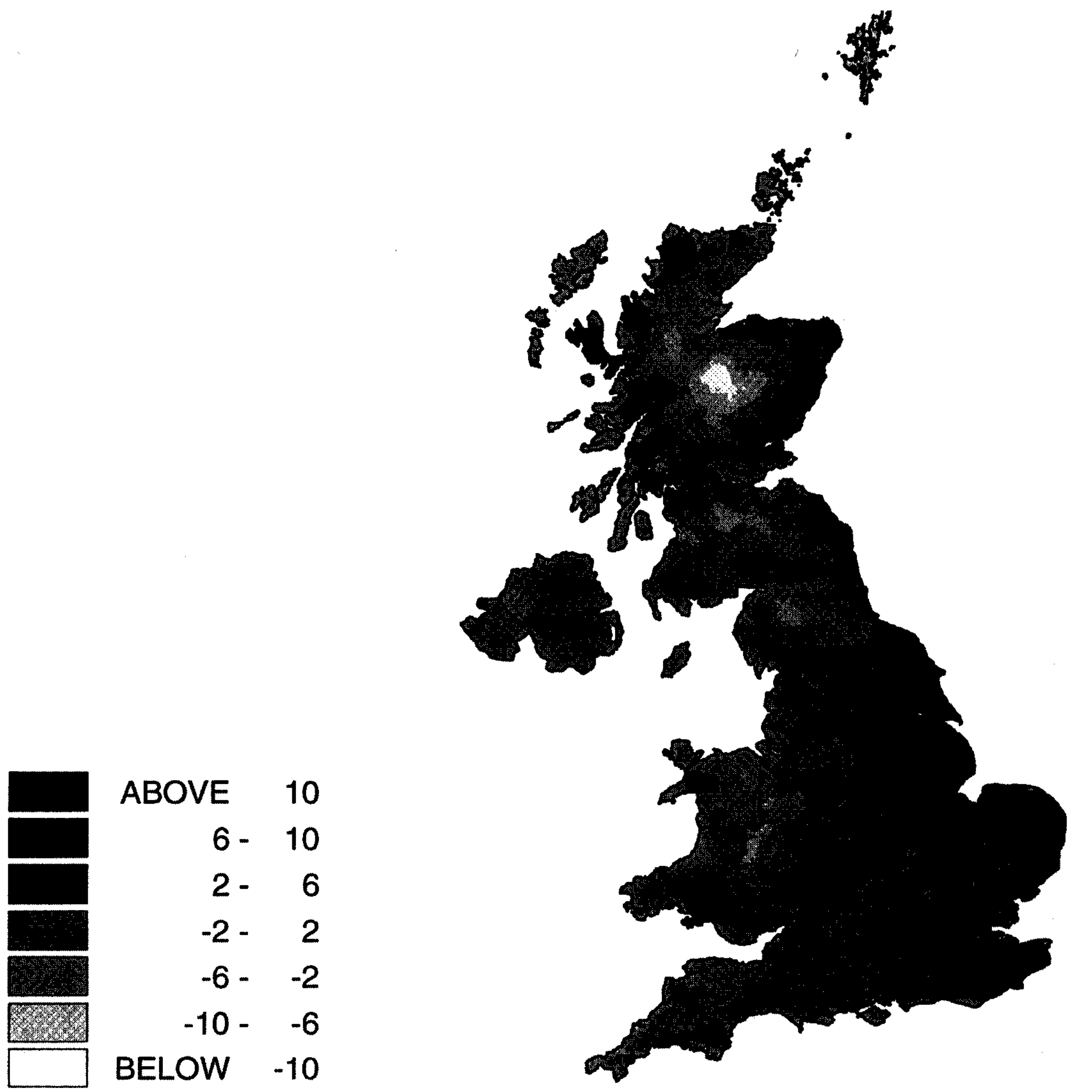

Fig. 5. *Map of residuals of 1000/(1-day RMED) interpolated by kriging.*

from 2.7 to 4.2, whereas the 1-hour RMED varies from 7 to 17 mm (Fig. 7). Thus the maps of RMED have a large influence on the final estimates of design rainfall, even for long return periods.

For example, the map of 1-hour RMED (Fig. 7) indicates that in parts of the East Midlands and south-east England, estimates of 1-hour rainfall are rather larger than elsewhere in lowland England. Estimated design floods for small catchments or quickly-responding urban catchments could be larger in these areas than elsewhere.

COMPARISON OF GEOREGRESSION WITH ORDINARY KRIGING

The results show that the method of georegression is effective in incorporating the effects of topography into a map of extreme rainfall. A more formal assessment of the effectiveness of georegression makes use of a cross-validation technique. This can compare the performance of georegression with that of ordinary kriging (using no topographic data). The accuracy and bias of the final estimates of RMED are compared at the sites of a set of validation gauges which are not used at all in the kriging or georegression.

The results of such a cross-validation exercise (Faulkner and Prudhomme, 1997) indicate that the estimation of RMED by georegression is less biased than when using ordinary kriging. Overall, the estimation is also more accurate using georegression, which explains more of the variance of RMED. This nationwide comparison of the two methods understates the more substantial increase in performance of georegression over ordinary kriging in

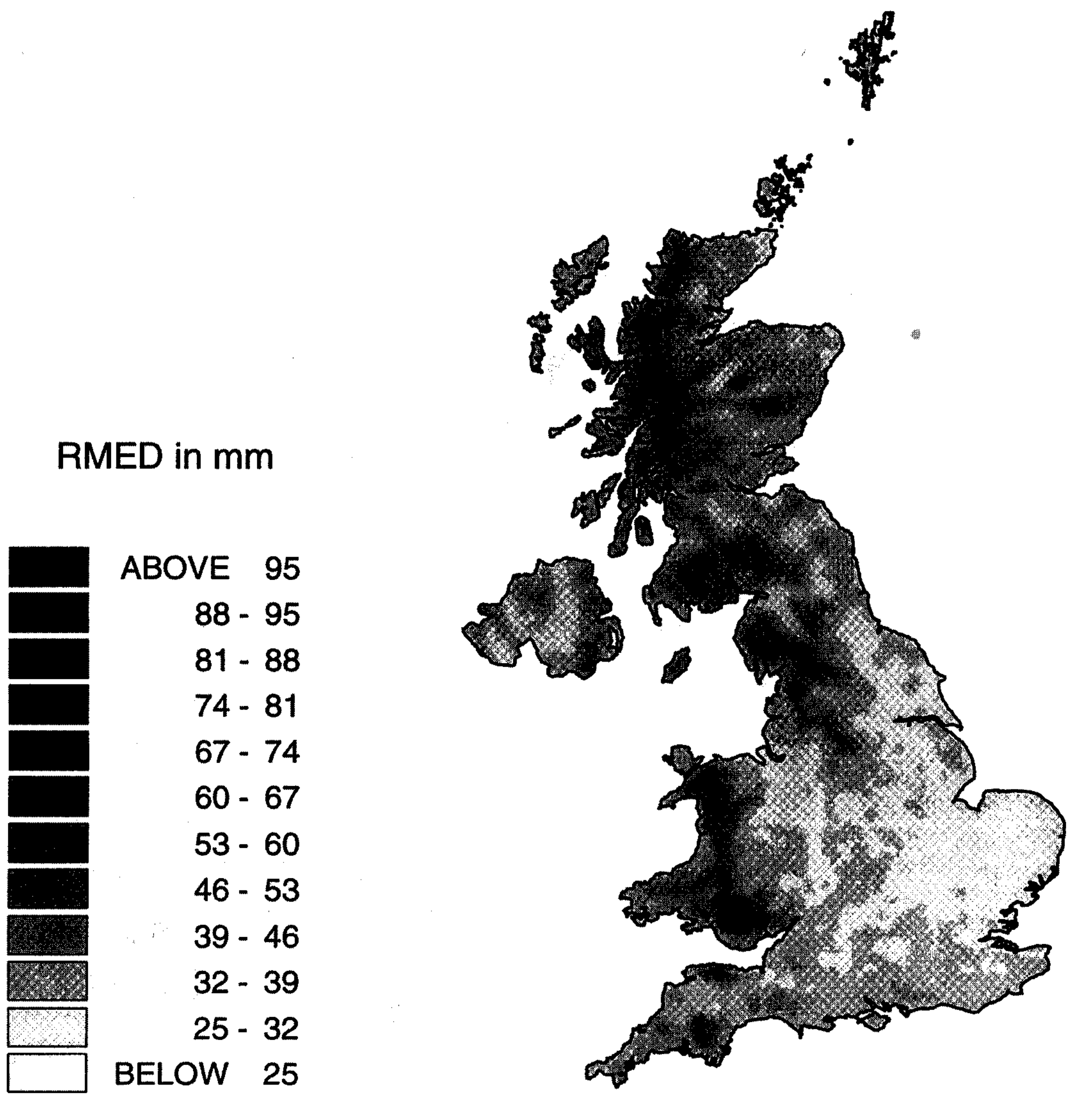

Fig. 6. *Final combined map of 1-day RMED.*

sparsely-gauged areas where the regression model plays a large part in providing the final estimate of RMED.

COMMENT ON CLIMATIC FLUCTUATIONS

The analysis ignores any climatic fluctuations which may cause estimates of RMED to be affected by the period of record. Periodic variations in extreme hourly rainfalls with periods of 7, 11, 20 and 50 years have been described by May & Hitch (1989a).

The required minimum record length of 9 years should help to smooth out short-period variations. Further smoothing is provided by the use of kriging as an interpolation technique, which combines data from several nearby sites. Because there are relatively few rainfall records longer than 30 years (particularly for sub-daily durations), it would be difficult to account for any long-period variations without using data from further afield than is desirable. No evidence was found that record length is linked to over or under-estimation by the regression models.

Concluding remarks

Georegression is an effective technique for improving the interpolation of rainfall extremes, particularly in mountainous and sparsely-gauged areas. The use of intricate topographic variables aids the regression analysis, which is rather more successful for long-duration rainfall. Rainfall extremes aggregated over shorter durations (e.g. 1 hour) are less closely related to topography, nor can they be readily modelled with lightning strike data.

The resulting maps of median annual maximum rainfall (RMED) on a 1-km grid play a key role in the design rainfall estimates provided within the Flood Estimation Handbook.

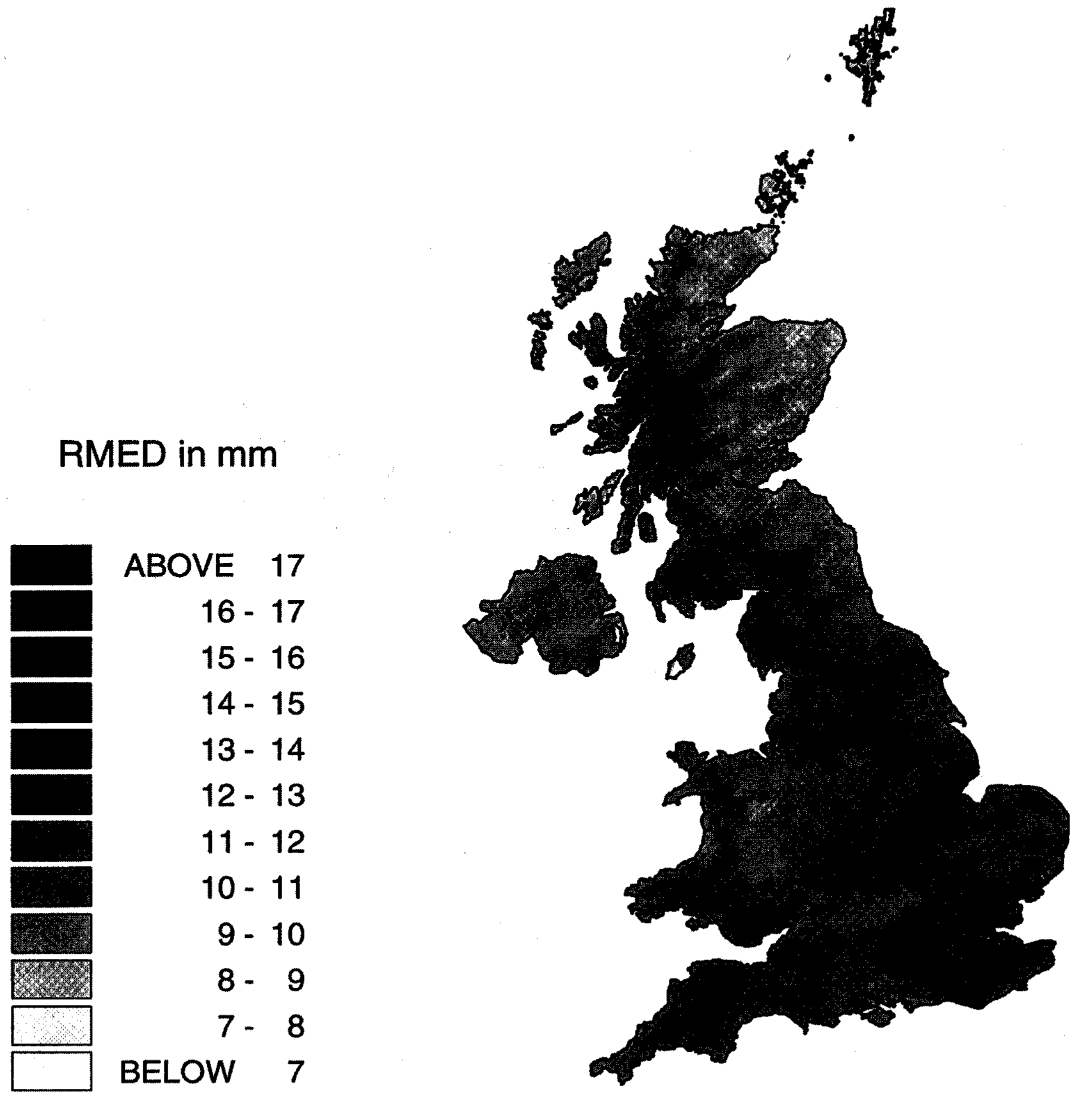

Fig. 7. *Final combined map of 1-hour RMED.*

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