Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management Research & Development Programme

Reservoir Safety – Long Return Period Rainfall

R&D Technical Report WS 194/2/39/TR
Volume 2: Appendices

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Statement of use
This document provides details of the analysis undertaken during project WS 194/2/39 entitled *Reservoir safety: long return period rainfall* funded by Defra. The report describes a new model of rainfall depth-duration-frequency applicable to the UK, which is proposed as a replacement to that published in the Flood Estimation Handbook (IH, 1999). The report is intended to inform Defra and Environment Agency staff, reservoir panel engineers, consultants, contractors and other agencies and organisations involved in hydrological frequency estimation about the new model. Further work to develop a software implementation of the new model is ongoing.

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Foreword

This report presents the results of a major project to develop a new statistical model of point rainfall depth-duration-frequency (DDF) for the UK. This is intended to replace both the Flood Estimation Handbook (FEH) model (Faulkner, 1999) and the present guidance given to Defra panel engineers (Defra, 2004) that the FEH rainfall estimates should not entirely replace the old Flood Studies Report (FSR) estimates of 1975.

Acknowledgements

Rainfall data have been supplied by the Environment Agency for England and Wales, by the Scottish Environment Protection Agency for Scotland, by the Met Office for locations throughout the United Kingdom, and by Met Éireann for locations in the Republic of Ireland near the border with Northern Ireland. The use of all these data is gratefully acknowledged.

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Besides those listed as authors, CEH staff who made substantial contributions to the project included Fai Fung and Sonja Folwell.

Contents

References appearing in the appendices are listed in the References Section (Section 11) of the main text.

Appendix A Sites with hourly rainfall maxima

This Appendix comprises figures and tables to illustrate the hourly rainfall maxima in the United Kingdom and the Republic of Ireland that have been used for the project.

Figure A.1 shows the locations of all the 969 gauge sites with at least 9 1-hour annual maxima. It also shows which one of Figures A.2 to A.21 covers a particular area of the country. The figures in this group show the magnitudes of the 1-hour annual maxima at each gauge in association with a list of the gauges, with details including the site's name, coordinates, Standard Average Annual Rainfall (SAAR) and the number of annual maxima at the site (nmax). The gauges are listed from west to east within each area. Coordinates for locations in Great Britain are given in the Great Britain National Grid system, and coordinates in Northern Ireland and the Republic of Ireland are in the Irish Grid system.

Tables A.1 to A.9 list all sites for which annual or seasonal rainfall maxima have been used. The series are included if there are at least nine annual or seasonal maxima of any hourly duration (1, 2, 4, 6, 12, 18 and 24 hours). In total 1030 sites are listed in alphabetical order, in separate tables for each region. These regions are based on the UK environment agencies' and the UK Met Office's divisions of the country. The tables show gauge number, gauge name, east and north coordinates, and range of the data series. Note that valid maxima may not be available for all years in the stated range, but the numbers of valid 1-hour maxima are shown on Figures A.2 to A.21.

Where available, the UK Met Office gauge number has been used. These range from 1 to 998999. Any gauges from the Environment Agency or the Scottish Environment Protection Agency that did not have a Met Office number were assigned a 7-digit number beginning with 9. In contrast to the Met Office numbers, these gauge numbers do not imply any particular location. Gauges in the Republic of Ireland have 7-digit numbers beginning with 8.

If gauges were located within 300 metres of each other, the maxima series were concatenated into a single long series. These sites are given 8-digit numbers beginning with 1. If a Met Office gauge is among the gauges that can be concatenated at a site, then the new gauge number for the concatenated series will incorporate the Met Office gauge number. For example, a gauge numbered 10005784 has a concatenated record (provided valid maxima are available at more than one of the gauges on the site). The last 7 digits of the number are for a Met Office gauge on the site, and reveal that the gauge is located in north-east England.

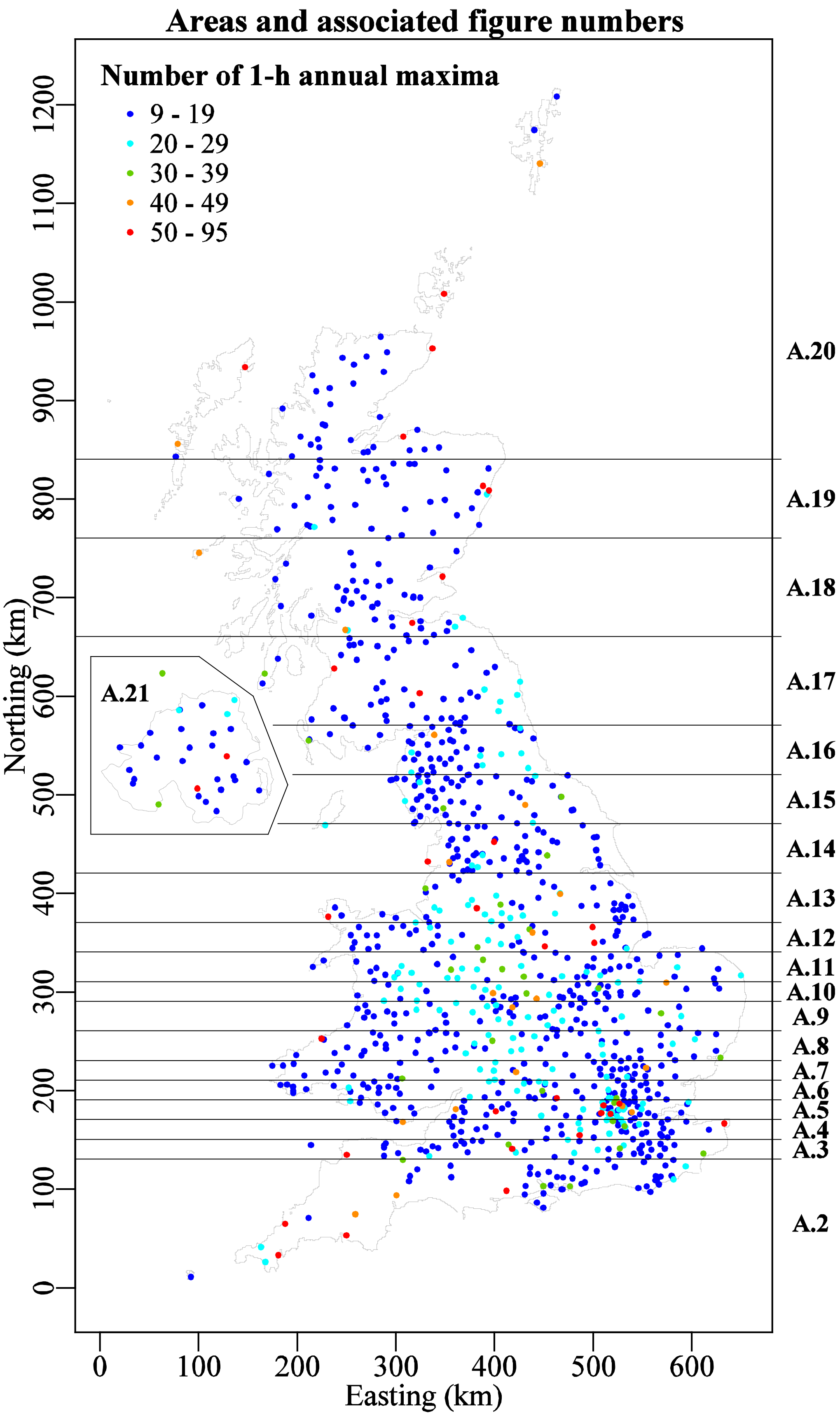


Figure A.1 Areas of the country associated with Figures A.2 to A.21.

GAUGE	E	N	SAAR	nmax
Scilly: St Marys Airport	917	105	825	13
Camborne	1627	407	1071	27
Culdrose	1671	256	1036	22
Falmouth	1802	325	1077	61
St Mawgan	1872	642	1004	55
Cardinham Bodmin	2110	703	1325	15
Plymouth: Mountbatten	2492	527	983	68
Princetown: Prison	2583	740	1927	45
Exeter	3001	933	764	44
Maundown	3065	1291	1100	30
Dunkeswell Aerodrome	3128	1075	1065	15
Hemyock (Tbr)	3138	1128	1002	11
Fulwood Wks Auto	3211	1197	860	10
Yeovilton	3550	1232	718	18
Sutton Bingham	3556	1116	839	9
Hurn	4116	978	790	51
Efford TBR	4301	940	753	15
Brockenhurst TBR	4310	1028	839	17
Testwood TBR	4354	1150	792	16
Romsey TBR	4357	1216	825	16
Calbourne TBR	4425	859	820	14
Portswood TBR	4434	1146	763	17
Calshot	4489	1025	737	32
Chale TBR	4490	806	854	12
Cowes TBR	4491	952	800	16
Bishops Waltham TBR	4545	1169	802	16
Peel Common TBR	4566	1034	711	15
Worlds End TBR	4629	1118	803	9
Portsea: Eastney P Sta	4675	992	724	17
Portsea: Eastney	4684	993	667	16
Cowplain: Greenfield C..	4691	1114	868	18
Thorney Island	4760	1022	689	33
Princes Marsh TBR	4772	1270	915	13
Walderton TBR	4786	1103	817	12
Chichester TBR	4878	1050	757	14
Tangmere	4911	1064	797	11
Midhurst TBR	4918	1211	863	13
Hardham PS 2 TBR	5033	1177	853	11
Horsham STW TBR	5149	1296	773	13
Cowfold TBR	5215	1220	787	11
Newhaven	5453	1007	709	9
Burnt Oak TBR	5509	1269	829	12
Deep Dean TBR	5537	1022	803	9
Cornish Farm Ww TBR	5575	968	782	12
Horseye TBR	5627	1083	743	9
Herstmonceux: West End	5630	1127	799	14
Herstmonceux	5645	1099	691	12
Pevensey Bay TBR	5661	1043	753	14
Hazards Green TBR	5681	1122	758	9
Robertsbridge TBR	5728	1235	857	9
Hastings Beauport Ww TBR	5790	1132	811	9
Hastings Newgate TBR	5806	1102	731	11
Sandhurst STW TBR	5808	1290	728	10
Hastings	5810	1094	728	22
Playden Scots Float	5933	1226	729	20

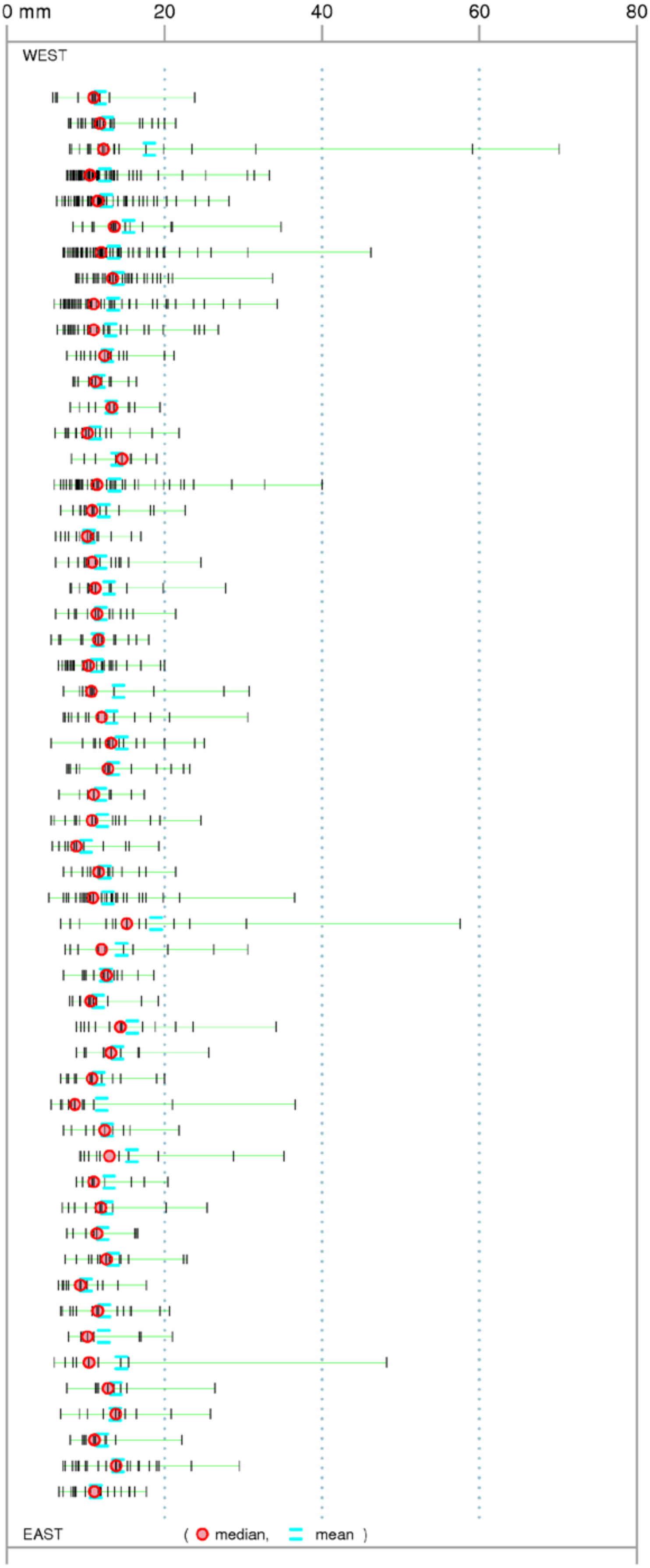


Figure A.2 1 hour annual maxima for GB raingauges between 0 N and 1299 N

GAUGE	E	N	SAAR	nmax
Lundy: Stoneycroft	2133	1443	924	10
Chivenor	2496	1344	856	51
Liscombe	2874	1332	1377	12
West Dunkery	2874	1417	1613	10
Wilmersham Farm	2874	1437	1390	9
Porlock	2892	1460	1113	9
Treborough Auto	3016	1361	1076	9
Brymore School Log	3244	1394	751	10
Rivers House	3301	1377	768	10
Northmoor P Sta	3332	1330	675	27
Gold Corner Logger	3367	1430	700	14
Shapwick Heath	3423	1411	717	9
Darshills Wks Logger	3600	1440	987	10
Stoke Bottom P S Aut	3657	1481	1121	10
Downhead Resr Auto	3686	1457	1149	11
North Brewham	3721	1370	878	10
Frome STW	3773	1487	881	9
Upton Scudamore P.S.	3863	1483	839	10
Larkhill	4137	1447	741	31
Boscombe Down	4173	1403	705	70
Porton	4210	1366	734	26
Middle Wallop	4302	1390	754	13
Andover TBR	4368	1467	747	15
Bishops Sutton TBR	4605	1320	827	16
Odiham	4737	1494	724	27
Bordon	4804	1362	815	24
Farnham R30	4856	1481	708	13
Cranleigh S Wks	5041	1393	765	24
Ockley TBR	5151	1401	807	14
Broadfield	5263	1345	861	19
Gatwick	5265	1407	754	38
Burstow S Wks	5305	1437	741	24
Weir Wood Res TBR	5407	1354	832	12
Cowden STW TBR	5466	1403	765	11
Hartfield STW TBR	5482	1361	795	10
Bough Beech Res TBR	5490	1437	753	13
Redgate Mill TBR	5552	1320	868	10
Leigh TBR	5563	1464	735	9
Tunbridge Wells TBR	5585	1395	814	12
Bewl Bridge Res TBR	5674	1334	822	11
Paddock Wood STW TBR	5678	1453	678	13
Horsmonden STW TBR	5721	1406	717	13
Headcorn STW TBR	5818	1443	659	13
Lympne Airport	6112	1355	709	34

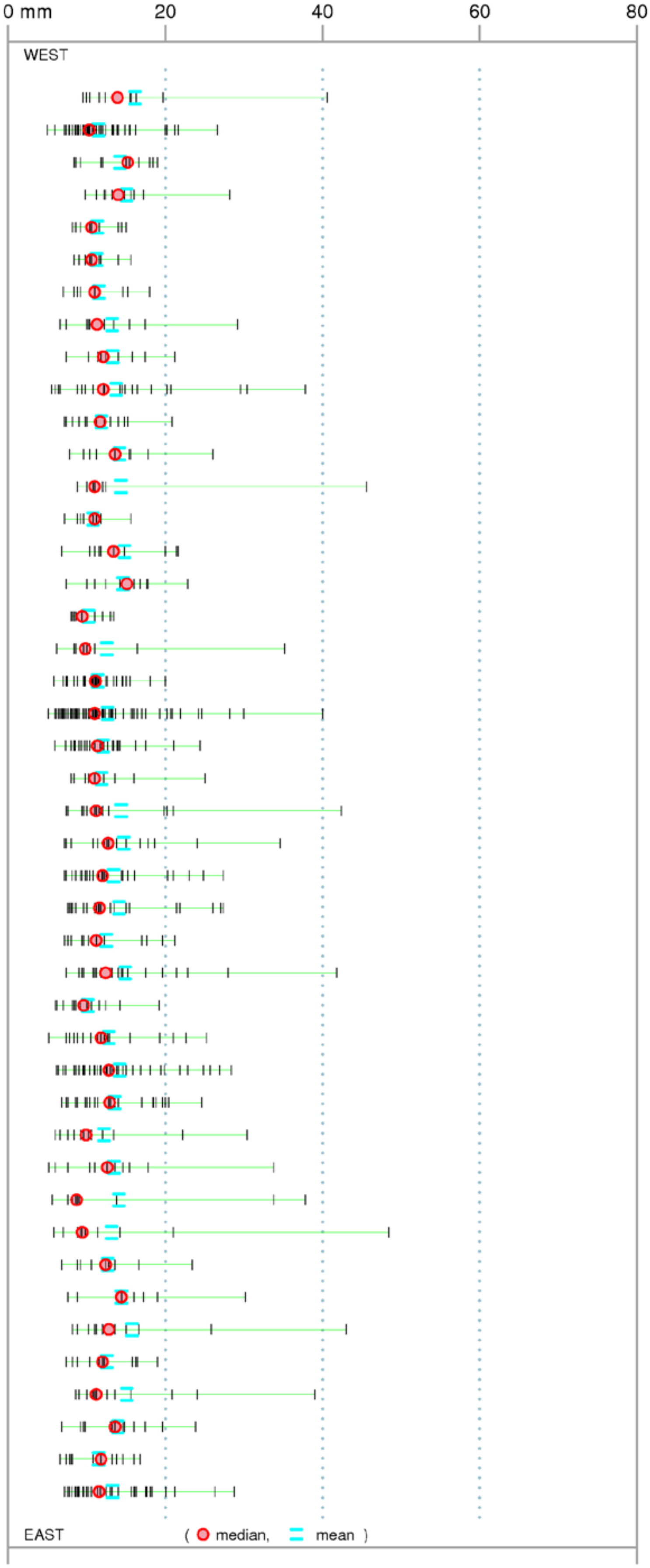


Figure A.3 1 hour annual maxima for GB raingauges between 1300 N and 1499 N

GAUGE	E	N	SAAR	nmax
St Athan	2999	1684	1096	9
Rhoose	3066	1677	930	44
Barrow Gurney Auto	3537	1679	934	11
Chew Magna PS Auto	3565	1631	889	11
East Harptree Auto	3579	1536	1182	11
Paulton STW Auto	3655	1575	866	11
Keynsham STW	3663	1687	771	10
Bradford On Avon STW	3815	1603	784	11
Bowerhill STW	3903	1623	691	10
Easterton	4026	1545	771	11
Marlborough: Salisbury..	4184	1686	785	19
Overton TBR	4519	1507	751	15
Kingsclere R05	4531	1609	773	15
Mortimer Lc	4668	1642	683	15
Basingstoke R27	4676	1552	695	15
Bracknell: Beaufort Park	4846	1664	656	29
South Farnborough	4857	1541	671	83
Camberley S Wks	4862	1598	656	24
Guildford R28	5002	1518	656	14
Chertsey R08	5016	1674	622	15
Hampton W Wks	5131	1695	594	21
Leatherhead: Elmer Wks	5159	1557	699	21
Hogsmill Valley S Wks	5194	1683	596	35
Raynes Park P Sta	5237	1695	603	13
Cheam PS	5247	1641	657	19
Morden Hall	5261	1685	613	15
Chipstead: How Green R..	5283	1581	789	19
Beddington: New S Wks	5299	1661	617	21
Croydon Airport	5312	1633	689	33
Purley: Oaks Depot	5321	1623	691	21
Kenley Airfield	5331	1578	769	14
Kelsey Park	5374	1692	643	16
Limpsfield&Oxted TBR	5398	1501	736	12
Keston	5422	1636	769	14
Orpington P Sta	5459	1652	700	24
Sundridge PS	5489	1556	771	15
Sevenoaks PS TBR	5532	1571	738	12
Eynsford P.S.	5535	1655	668	15
West Malling	5677	1553	669	17
Cuxton PS TBR	5689	1669	672	11
Wateringbury STW TBR	5693	1532	651	13
Ham Hill STW TBR	5707	1610	637	11
Coxheath STW TBR	5750	1521	675	10
Hockers Lane PS TBR	5790	1574	693	9
Hollingbourne TBR	5939	1679	790	10
Canterbury S Wks	6169	1597	622	12
Manston	6324	1661	569	55

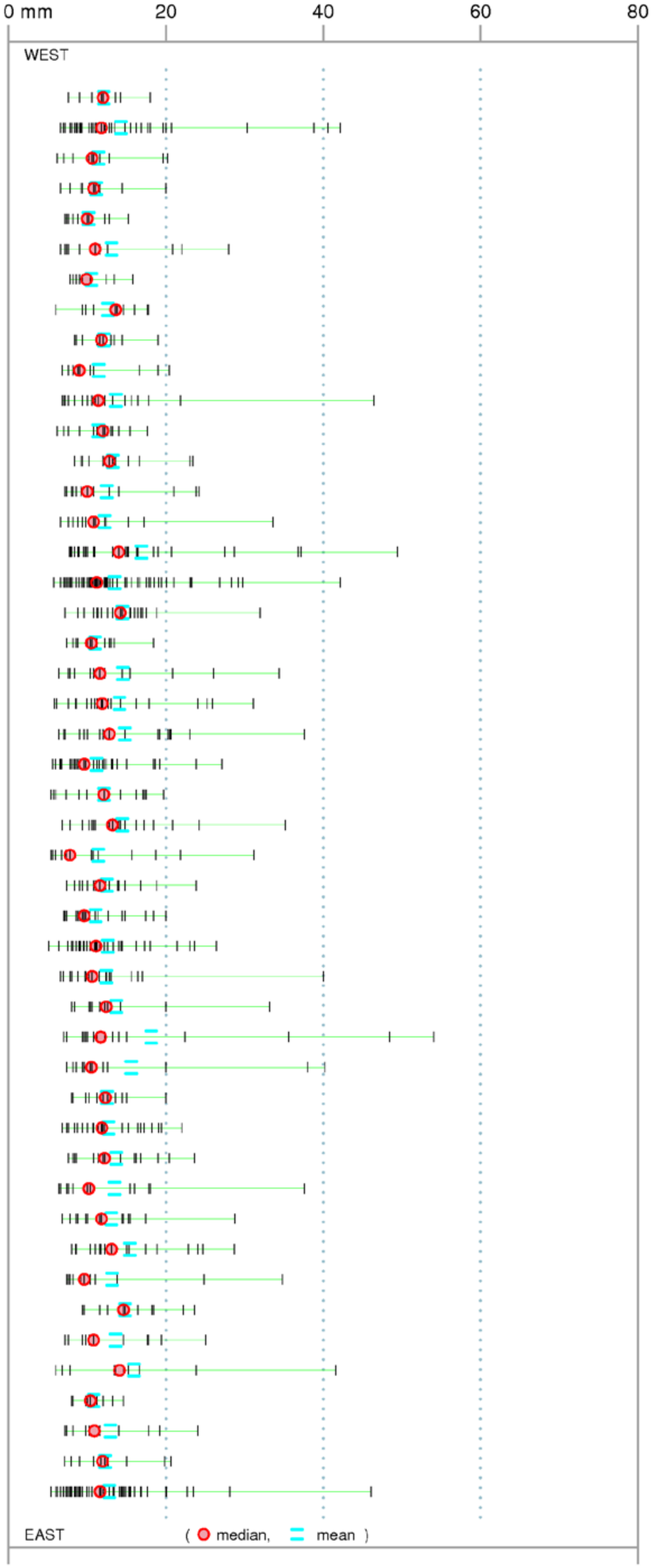


Figure A.4 1 hour annual maxima for GB raingauges between 1500 N and 1699 N

GAUGE	E	N	SAAR	nmax
Penmaen	2531	1888	1199	25
Mumbles Head	2627	1871	976	14
Margam Park	2809	1854	1137	13
Schwyll P.S.	2885	1769	1038	13
Pencoed	2967	1819	1307	10
Rhiwbina Resr Logger	3149	1824	1281	9
Cardiff Weather Centre	3182	1761	891	11
Bristol Weather Centre	3584	1728	831	12
Filton	3601	1805	782	49
F. Cotterell Mill Ln	3666	1822	777	10
Cromhall Sw Auto	3685	1893	789	11
Parkfield STW	3689	1777	781	12
Hardenhuish Reserv'r	3912	1750	765	10
Gt Somerford STW	3965	1832	743	10
Lyneham	4006	1783	707	54
Wootten Bassett STW	4072	1813	683	11
Swindon R25	4132	1855	695	16
Ogbourne Works Lc	4191	1763	744	10
Chieveley S Wks	4468	1739	718	23
Cleeve R19	4601	1818	664	18
Caversham R10	4720	1740	620	17
Bracknell R06	4858	1718	644	18
Maidenhead S Wks	4893	1804	639	28
Perry Oaks	5060	1759	621	12
Heathrow	5077	1767	597	57
Ruislip: Manor Farm Bo..	5090	1876	658	21
Wood End Nurseries	5094	1813	620	26
Northolt	5099	1845	616	60
Pinner Cemetery	5130	1893	666	13
Ealing/Greenford Cmt	5141	1815	624	16
Isleworth: Mogden S Wks	5154	1753	598	23
Ealing: Castlebar	5170	1819	647	12
Kew	5171	1757	591	95
Kingston: Canbury Gard..	5179	1700	601	28
Kew (Rbg)	5187	1774	606	22
Kew S Wks	5197	1767	592	15
Brent Resr	5208	1870	648	39
Putney Heath Resr	5234	1737	615	23
Holland Park	5246	1795	609	14
Kensington Palace	5259	1801	631	25
Hampstead	5262	1863	683	71
Mitcham: London Road C..	5278	1701	607	21
Camden Square No 2	5291	1838	634	40
St James Park	5298	1801	612	27
Hornsey	5308	1894	658	11
London Weather Centre	5311	1820	532	24
Hackney: Clapton Pond	5349	1860	610	16
Walthamstow: Lowhall F..	5363	1881	607	9
Deptford PS	5377	1771	578	16
Greenwich	5387	1776	585	42
Grove Park	5415	1715	651	13
Wanstead P.S.–Redbr.	5415	1882	589	13
Gascoigne Road	5447	1830	546	15
Danson Park	5468	1754	598	15
Cross Ness S Wks	5486	1805	529	25
Dagenham: Central Park..	5499	1863	554	23
Dartford STW TBR	5553	1766	552	13
Northfleet STW TBR	5619	1735	567	11
Whitewall Creek TBR	5751	1702	589	9
Grain Eacompound TBR	5888	1770	524	10
Shoeburyness	5948	1857	503	10
Shoeburyness: Landwick	5961	1878	507	28

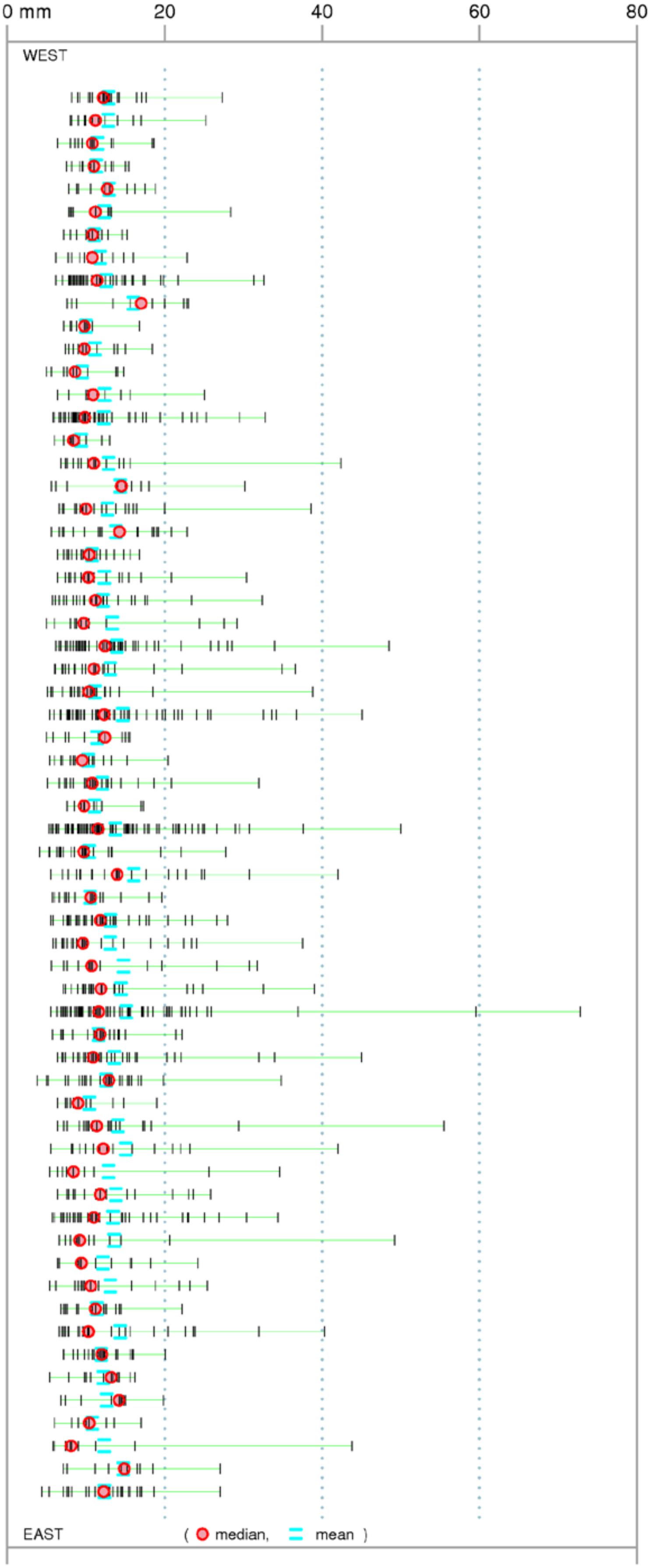


Figure A.5 1 hour annual maxima for GB raingauges between 1700 N and 1899 N

GAUGE	E	N	SAAR	nmax
Dale	1823	2051	829	11
Milford Haven Conserv.Bd	1891	2055	1014	11
Pembroke Dock Met Office	1952	2033	1035	9
Orielton	1953	1991	1084	11
St Twynnells	1955	1969	1009	10
St Florence	2085	2009	1145	10
Pembrey Sands	2365	2044	1093	13
Llanelli Filters	2516	2024	1301	21
Penclacwydd	2532	1985	1142	10
Victoria Park	2642	1922	1179	12
Upper Lliw	2662	2058	1688	11
Trebanos	2712	2023	1412	10
Ystradgynlais	2774	2087	1819	9
Fforch Dwm	2820	1972	1919	11
Resolven	2824	2026	1632	12
Llyn Fawr Logger	2919	2035	2522	15
Aberdare Filters Logger	2998	2021	1752	14
Nant−Yr−Ysfa Logger	3034	1963	1948	14
Estarvarney Farm Logge..	3353	2032	1056	10
Kingswood S Wks	3743	1929	773	26
Tetbury STW	3894	1927	804	10
Miserden	3937	2087	941	22
Shorncote R09	4034	1971	773	14
Colnpen Lc	4070	2080	800	9
Lechlade: St Johns Lock	4222	1990	642	20
Brize Norton	4292	2067	637	20
Stanford R02	4343	1929	580	13
Witney STW Lc	4348	2084	643	12
Wantage Lc	4403	1915	619	10
Eynsham Lock	4445	2087	631	20
Abingdon	4479	1991	595	33
Abingdon S Wks No 2	4493	1952	580	19
Osney Lock	4504	2058	633	19
Oxford	4509	2072	632	21
Wheatley R22	4608	2052	637	12
Benson R12	4613	1913	594	14
Benson	4625	1917	605	55
High Wycombe Hqstc	4826	1988	771	11
High Wycombe Auto	4884	1920	714	10
Bovingdon	5007	2038	771	13
Radlett: Blackbird S Wks	5148	2002	676	20
Stanmore: Uxbridge Road	5155	1921	678	27
Aldenham School No 2	5157	1973	682	13
Edgware: Chandos Park	5189	1911	686	28
Boreham Wood	5213	1967	663	9
Mill Hill Cemetery	5231	1917	688	32
Mill Green	5245	2098	607	15
Southgate	5299	1952	657	14
Hadley Road	5303	1980	653	16
Darnicle Hill	5309	2048	675	15
Epping Forest	5412	1981	673	15
Ray Park Nur.	5417	1923	603	11
Thornwood	5476	2048	603	16
Moreton	5533	2068	616	14
Stanford Rivers	5546	1999	621	14
Nag's Head Lane	5565	1914	594	16
Hutton S Wks	5651	1957	576	11
Writtle	5678	2067	569	13
Basildon Nevendon S Wks	5738	1906	536	13

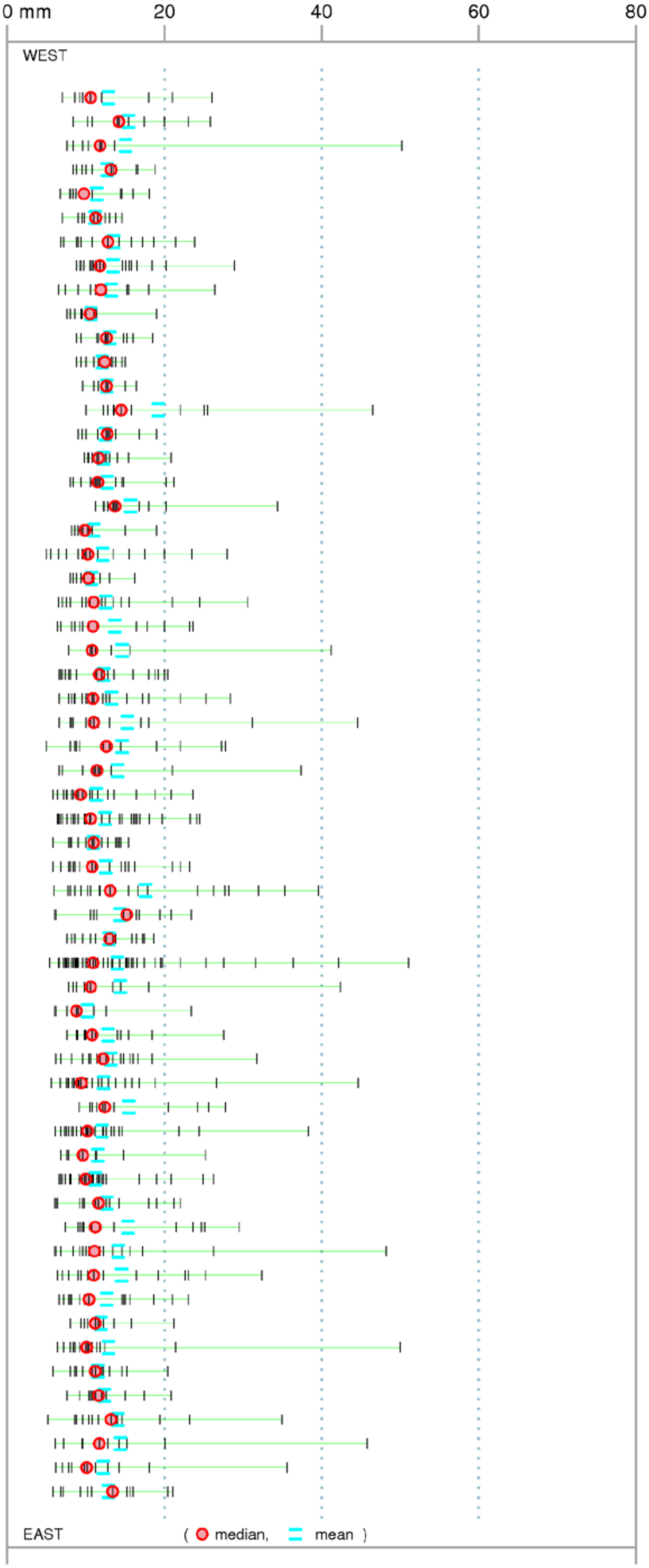


Figure A.6 1 hour annual maxima for GB raingauges between 1900 N and 2099 N

GAUGE	E	N	SAAR	nmax
St Davids	1742	2245	983	10
Brawdy	1851	2248	1097	19
Wolfscastle	1958	2266	1278	11
Canaston Bridge	2065	2148	1236	13
St Clears	2282	2178	1322	12
Johnstown	2402	2191	1287	11
Rhydargaeau	2446	2260	1649	13
Gorslas Resr	2563	2147	1609	16
Ystradfellte Telem.	2940	2144	1917	12
Llwynon Logger	3011	2112	1713	14
Brecon Wtw Logger	3037	2276	1148	12
Pontsticill Upper Wtw ..	3058	2118	1717	35
Cross Ash Logger	3406	2198	854	12
Longford W.Recl.Wks Au..	3847	2209	633	25
Dowdeswell	3987	2196	780	23
Rapsgate Resr	3996	2104	841	20
Langley	4002	2281	769	21
Bourton–On–The–Water S..	4182	2203	734	17
Little Rissington	4212	2181	706	44
Chipping Norton R13	4294	2268	703	15
Worsham R29	4301	2105	669	17
Upper Heyford Met Office	4513	2263	676	16
Bicester S Wks	4581	2212	621	20
Aylesbury STW Auto	4791	2148	628	9
Toddington Wbs (T)	5002	2284	643	13
Runley Wood PS	5064	2217	667	16
Markyate S.W.– Auto	5071	2155	682	15
Lilley Manor	5112	2278	607	14
Rothamsted	5132	2133	689	26
Wheathampstead Sw	5181	2142	635	13
Whitwell STW	5194	2209	620	15
Bragbury Park	5273	2213	630	14
Weston STW	5276	2296	601	14
Dane End Sw	5334	2219	624	15
Hertford S Wks	5338	2134	635	20
Warebroadmeads	5353	2140	623	10
Rye Meads	5394	2105	583	13
Widford STW	5417	2164	608	14
Braughing Friars	5420	2245	644	15
Stansted Mountfitchet:..	5504	2243	651	18
Hatfield Heath	5524	2141	610	14
Stansted	5531	2226	622	40
Takeley	5548	2210	602	14
Andrewsfield	5687	2248	628	9
Witham S Wks	5827	2139	556	19

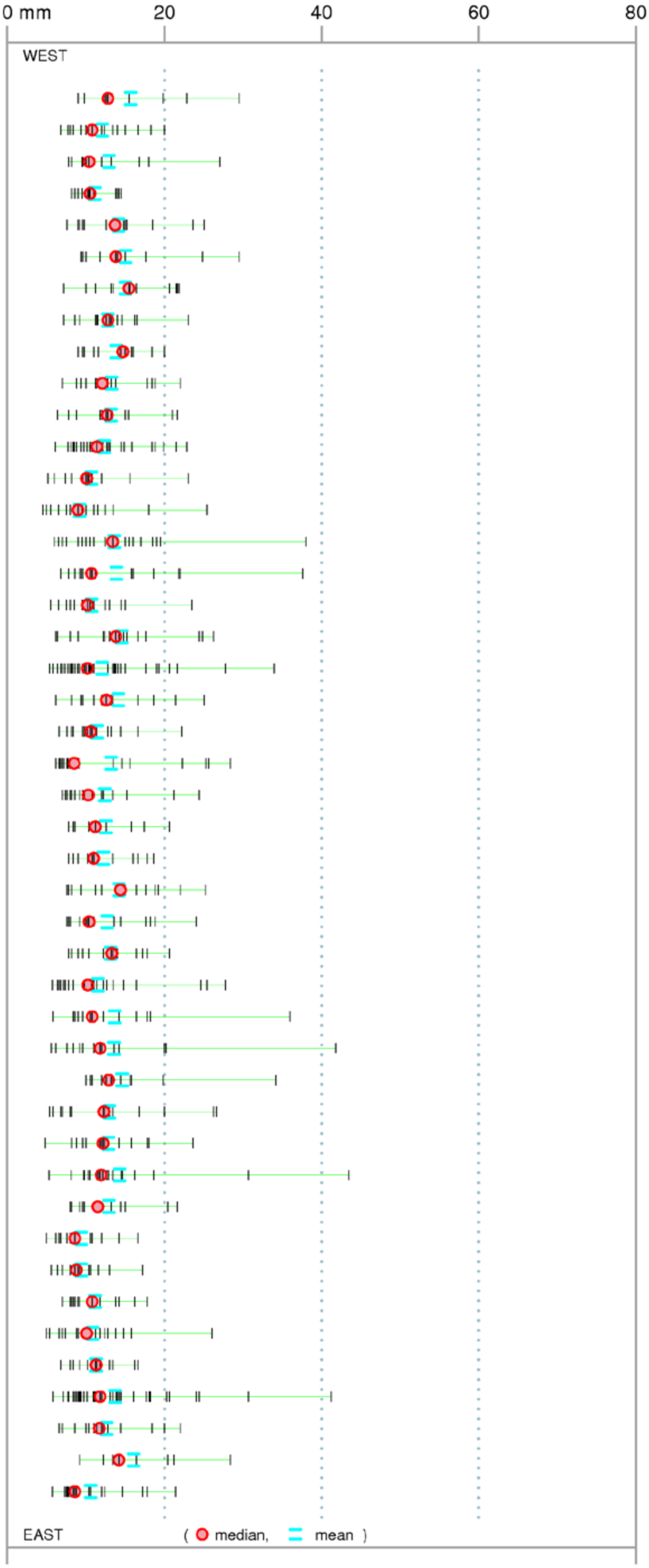


Figure A.7 1 hour annual maxima for GB raingauges between 2100 N and 2299 N

GAUGE	E	N	SAAR	nmax
Llanychaer	1985	2355	1272	12
Aberporth	2241	2521	851	57
Aberporth STW	2266	2513	848	9
Saron	2374	2376	1410	12
Highmead	2501	2433	1332	11
Tonn	2646	2352	1285	11
Caio	2674	2396	1433	11
Nantymaen	2761	2584	1781	13
Ystradffin	2787	2471	1608	12
Llanerch–Yrfa Logger	2835	2555	1918	12
Abernant Telem	2892	2460	1538	13
Sennybridge No 2	2894	2418	1502	11
Builth Wells: Cefndyrys	3038	2530	1013	10
Tregoyd Logger	3195	2378	886	9
Newchurch Logger	3217	2508	1029	12
Titley Mill Telem	3328	2584	831	10
Lyonshall	3335	2577	811	15
Lower Maes–Coed	3348	2308	951	19
Broomy Hill Logger	3496	2395	647	11
Leominster Logger	3503	2580	628	13
Yarkhill Logger	3596	2431	641	12
Bredenbury Telemetry	3609	2565	768	12
Ledbury W Wks	3702	2371	678	23
Malvern Met Office	3787	2447	702	9
Great Malvern	3791	2470	711	20
Defford Met Office	3899	2422	613	9
Crowle W.Recl.Wks Auto..	3934	2558	626	24
Pershore	3973	2500	573	32
Chipping Campden: W Wks	4164	2393	712	24
Milcote W Wks	4182	2528	586	21
Shipston On Stour: W Wks	4268	2411	600	25
Wellesbourne	4271	2565	605	15
Knightcote Farm	4398	2545	627	26
Grimsbury R31	4458	2418	638	14
Byfield STW Auto	4523	2525	658	9
Litchborough S Wks	4624	2551	668	16
Foxcote (T)	4713	2358	642	12
Yardley Hastings (T)	4867	2574	618	11
Birchmoor Wsw (T)	4943	2348	647	14
Cardington	5081	2463	538	26
Bedford STW (T)	5085	2496	549	14
Silsoe	5091	2358	546	21
Letchworth STW (T)	5207	2344	568	13
Potton STW (T)	5222	2485	545	13
Bourn STW (T)	5337	2579	553	13
Chipping	5357	2323	608	15
Elmdon STW (T)	5470	2403	602	13
Clavering STW	5476	2318	605	14
Haverhill S Wks	5681	2449	581	13
Kirtling Green	5681	2559	607	9
Poolstreet	5771	2364	568	9
Cavendish	5801	2469	562	25
Halstead(Logger)	5825	2302	561	11
Langham W Wks Auto	6017	2340	563	13
Wattisham	6025	2514	568	25
Stowmarket (Logger	6058	2580	581	10
Levington (Logger)	6241	2399	550	10
Charsfield (Logger)	6243	2566	573	11
Felixstowe	6286	2328	541	37

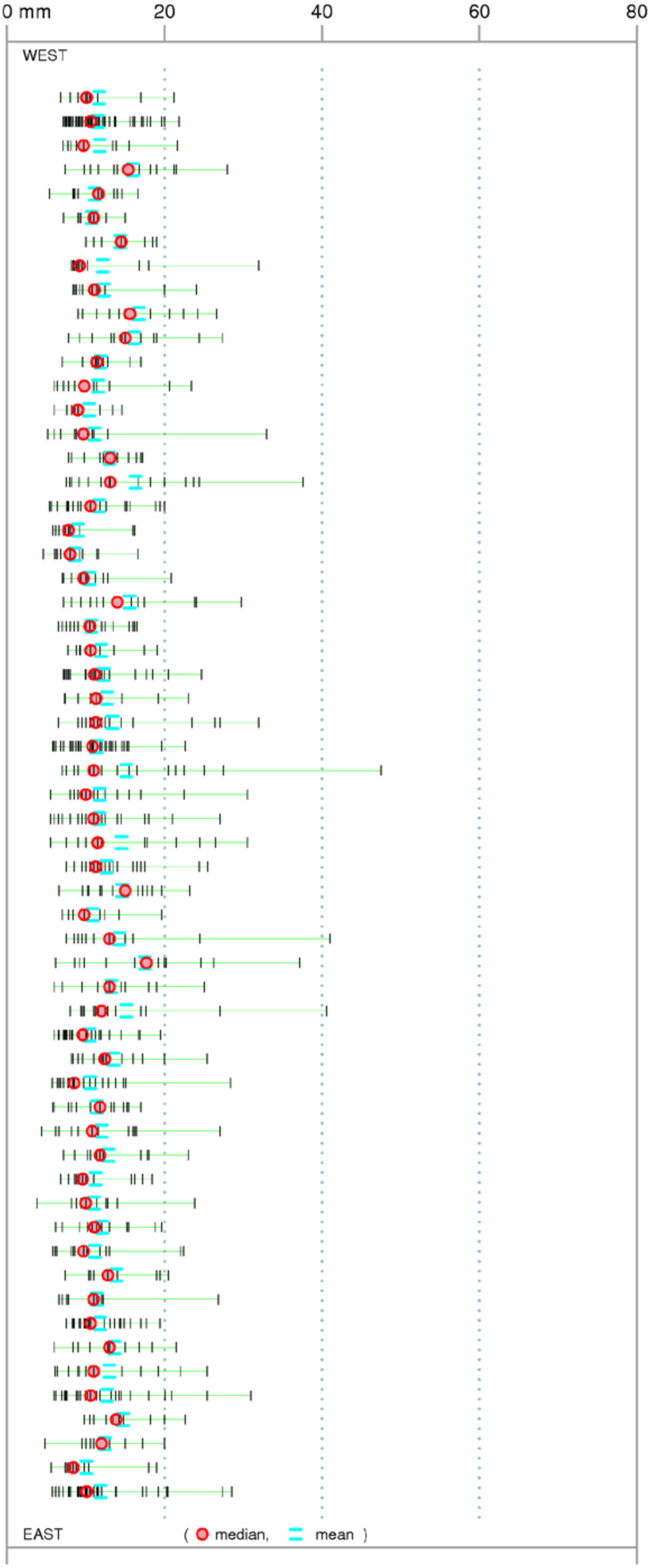


Figure A.8 1 hour annual maxima for GB raingauges between 2300 N and 2599 N

GAUGE	E	N	SAAR	nmax
Morfa Fawr	2501	2658	972	10
Frongoch	2605	2825	968	15
Trawsgoed	2674	2736	1174	15
Bontgoch Log	2683	2861	1379	10
Cwm Rheidol	2708	2792	1297	9
Pwllpeiran	2772	2749	1752	14
Llangurig Logger	2907	2797	1574	11
Nantgwyn	2979	2768	1323	16
Rhayader S Wks	2979	2674	1155	18
Llanbadarn Logger	3098	2778	1138	13
Bettws–Y–Crwyn	3203	2814	1075	22
Bishops Castle	3338	2873	813	14
Shobdon Airfield	3396	2609	783	13
Craven Arms S Wks	3437	2811	756	25
Oakly Park	3491	2762	730	11
Brimfield	3503	2682	727	10
Ditton Priors No.2 Aut..	3604	2882	840	25
Trimpley W Wks	3772	2789	679	20
Hartlebury Auto.Sta.	3846	2698	632	19
Lye W Wks	3919	2849	678	21
Frankley	4007	2801	807	19
Warley Park	4010	2861	785	20
Lye Bridge W Wks	4032	2717	729	24
Winterbourne Uni.Birmi..	4052	2841	785	15
Solihull: Tudor Grange..	4147	2789	726	18
Henley–In–Arden	4154	2679	681	24
Elmdon	4176	2839	699	45
Norton Green S Wks	4185	2749	704	9
Coleshill	4211	2870	763	9
Finham W Wks	4334	2740	658	21
Church Lawford	4456	2736	678	16
Rugby	4507	2749	637	16
Braunston	4533	2658	645	23
Daventry: Borough Hill..	4584	2619	683	9
Stanford Resr	4596	2804	651	28
Dodford (T)	4627	2607	635	11
Husbands Bosworth(L)	4645	2847	680	9
Ravensthorpe (T)	4681	2703	655	20
Stimpson Ave (L)	4768	2616	607	11
Dingley Resr	4774	2867	689	17
Hannington Res (L)	4826	2712	642	11
Barford Bridge (T)	4861	2831	622	14
Corby S Wks No 2	4906	2889	605	14
Wellingborough Ps(L)	4908	2674	582	13
Yelden STW (T)	5014	2674	617	13
Oundle S Wks	5038	2897	588	18
Great Gidding	5120	2824	566	9
Brampton Office (T)	5210	2710	543	10
Wyton	5284	2745	539	28
Ely Office	5552	2807	562	14
Mildenhall	5683	2778	523	34
Brooms Barn	5752	2656	584	11
Mundford Road (T)	5865	2845	608	12
Rushbrooke Wsw (T)	5873	2624	591	12
Honington	5888	2750	573	29

Figure A.9 1 hour annual maxima for GB raingauges between 2600 N and 2899 N

GAUGE	E	N	SAAR	nmax
Aberdyfi Log	2605	2960	1007	10
Dolydd	2873	2905	1876	25
Llanbrynmair Log	2919	3068	1629	9
Caersws	3040	2925	914	16
Cefn Coch P.Sta. Auto...	3042	3026	1233	22
Sarn S.Wks Auto.Sta.	3206	2906	867	23
Welshpool S Wks	3233	3073	779	24
Rorrington	3304	3005	757	18
Cosford W Wks No 3	3782	3047	679	21
The Bratch W Wks	3868	2937	662	18
Barnhurst W Wks	3901	3017	673	25
Willenhall S Wks No 2	3979	2983	690	40
Roway Lane	3986	2902	737	12
Walsall Wood	4038	3042	695	24
Kingstanding: Perry Ba..	4084	2952	692	9
Minworth S Wks	4164	2922	644	17
Lea Marston	4208	2937	647	11
Atherstone S. Wks. Aut..	4318	2980	639	36
Hinckley S Wks	4420	2927	637	40
Narborough S Wks	4549	2966	619	25
Fleckney	4657	2945	636	19
Kibworth STW (L)	4691	2936	625	16
Tugby (L)	4760	3005	664	12
Hallaton S.Wks Auto.Sta.	4795	2959	624	14
Braunston (T)	4838	3065	666	15
Caldecott P Sta	4865	2932	585	14
Empingham P.Sta. Auto...	4946	3081	619	14
Kingscliffe (T)	5013	2975	570	12
Wittering	5043	3026	582	27
Wittering	5048	3032	582	36
Stamford (T)	5069	3065	572	12
Castor: Splash Lane	5124	2982	527	16
Etton (L)	5143	3051	557	11
Chesterton Res. (L)	5148	2946	550	9
Crowland S Wks	5246	3091	545	21
Whittlesey: Dog-In-A-D..	5272	2993	516	12
Wittlesey (L)	5274	2962	540	12
March	5420	2967	563	10
March STW (T)	5441	2991	549	10
Marham	5737	3090	610	45
Carbrooke Wsw (T)	5940	3026	650	10
Norwich Weather Centre	6233	3082	611	9
Framingham (Logger)	6272	3030	596	12

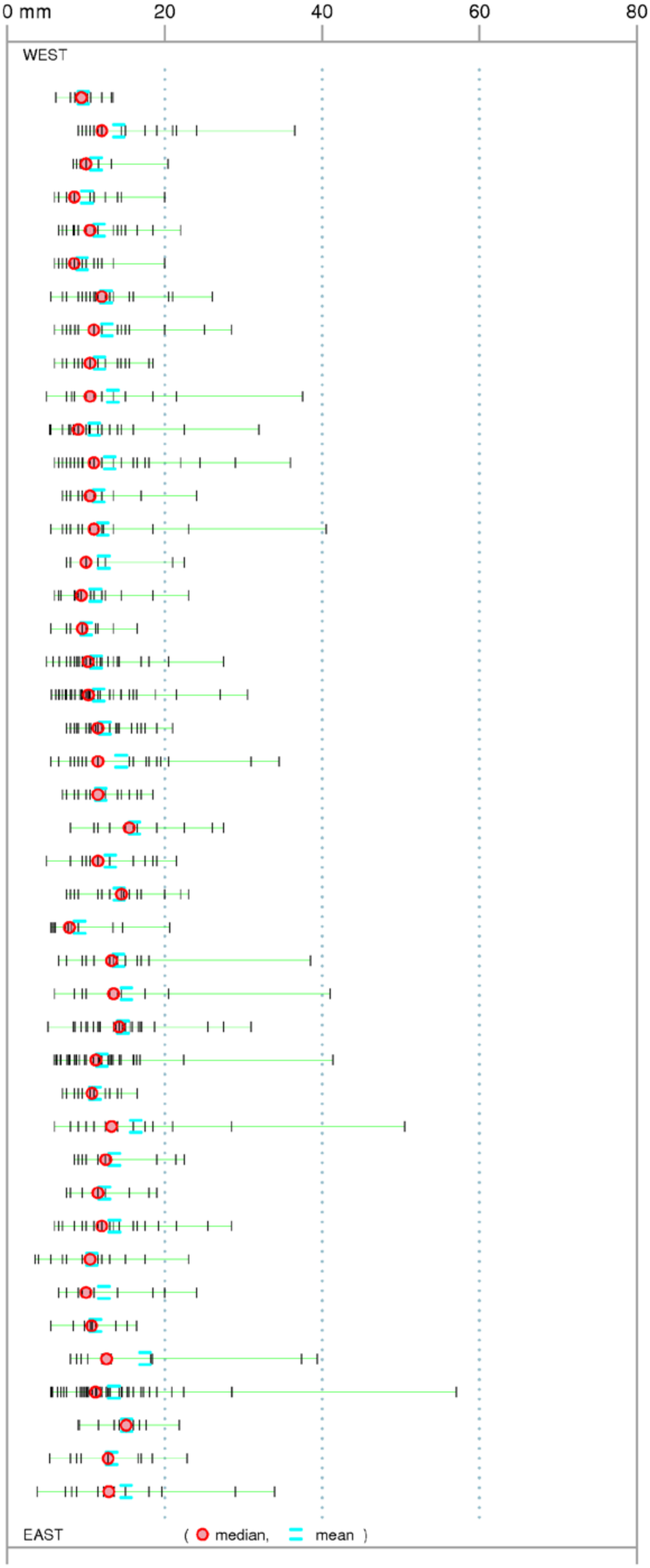


Figure A.10 1 hour annual maxima for GB raingauges between 2900 N and 3099 N

GAUGE	E	N	SAAR	nmax
Aberdaron	2153	3248	825	13
Botwnnog Log	2262	3313	1027	10
Rhiwgoch Log	2592	3304	1165	10
Cynnwch Log	2735	3203	1654	10
Aberllefni Cymau Log	2776	3106	2277	10
Rhydymain Log	2797	3238	1965	10
Llanymawddwy Log	2888	3170	2082	9
Pen−Y−Coed Auto.Sta.	2978	3144	1680	22
Lake Vyrnwy No 2	3012	3187	1564	11
Lake Vyrnwy	3017	3188	1640	20
Llangynog W Wks	3053	3259	1323	22
Llanfyllin W Wks	3154	3188	979	23
Bagley	3413	3277	712	19
Shrewsbury: Monkmoor S..	3517	3136	613	20
Shawbury	3553	3221	653	31
Prees	3573	3351	711	12
Rushmoor S Wks	3617	3135	637	20
Ercall	3665	3233	668	20
Hollies P Sta	3816	3224	703	23
Stone No 2	3878	3321	735	37
Rodbaston	3920	3116	680	19
Blithfield Resr	4071	3226	705	30
Claymills W Wks	4265	3259	642	22
Overseal S Wks	4291	3149	631	31
Kirk Langley	4293	3392	737	13
Spondon	4395	3345	646	16
Mount St Bernard Abbey	4459	3158	758	19
Wanlip	4597	3114	633	19
Colwick	4613	3393	601	19
Brooksby Hall No 2	4679	3154	598	22
Langar	4733	3339	575	15
Whissendine	4834	3146	629	19
Cottesmore	4909	3153	629	18
South Witham (L)	4929	3198	641	20
Ridds Farm (L)	4938	3255	638	12
Corby Glen S.T.W.(L)	4992	3246	618	13
Ropsley S.T.W (L)	5001	3336	624	14
Manthorpe S Wks	5067	3164	608	23
Bourne S.T.W (L)	5109	3202	569	13
Guthram Gowt	5171	3225	578	17
Donington Bridge (T)	5174	3356	560	12
Spalding S.T.W. (L)	5262	3251	563	13
Holbeach S.T.W. (L)	5358	3258	574	15
Holbeach No 2	5440	3328	582	16
Wisbech P Sta	5465	3102	583	24
Sutton Bridge	5476	3201	587	12
Heacham	5668	3364	612	10
Castle Acre	5820	3150	678	9
West Raynham	5847	3245	727	21
North Creake(Logger)	5854	3371	685	9
Horsham St Faith: Met ..	6220	3131	615	10
Coltishall	6262	3229	623	16
Hemsby	6493	3162	596	21

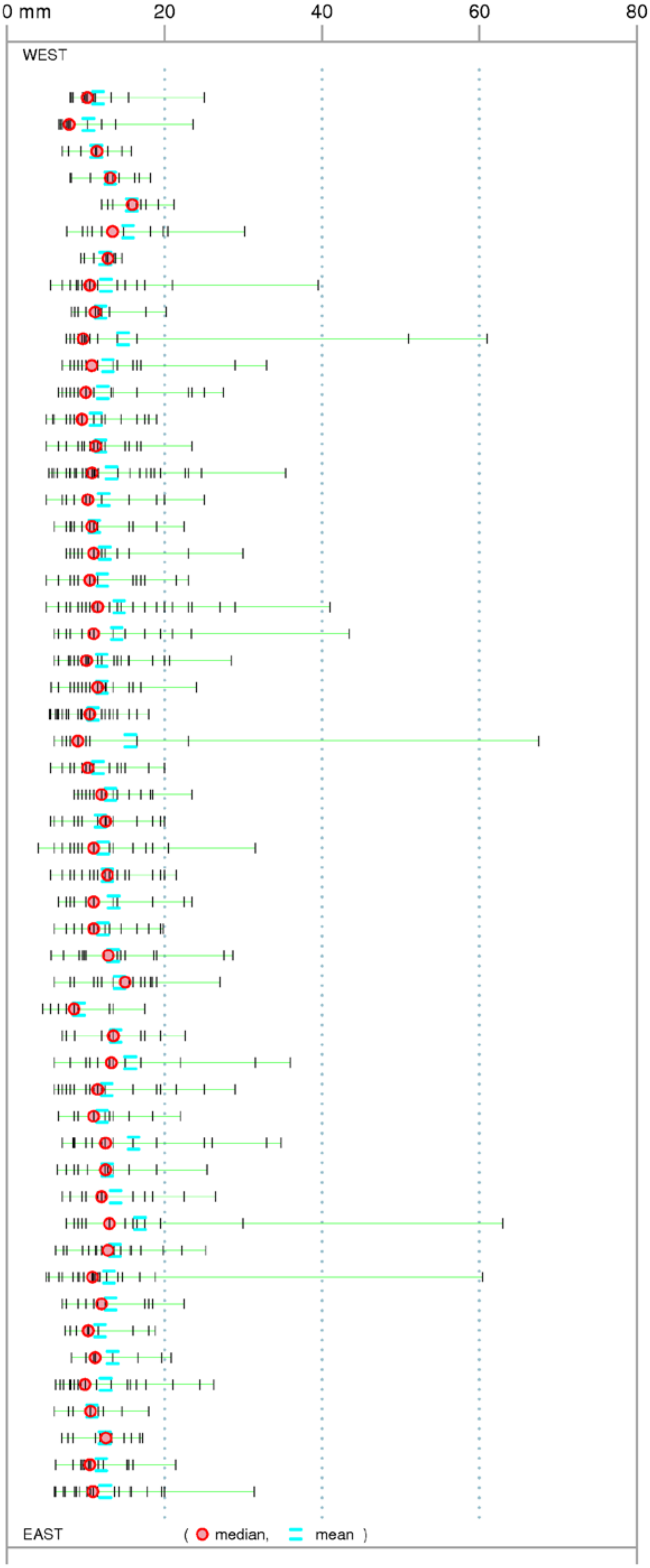


Figure A.11 1 hour annual maxima for GB raingauges between 3100 N and 3399 N

GAUGE	E	N	SAAR	nmax
Betws Garmon Log	2537	3572	1801	9
Cwmystradllyn Log	2556	3441	2017	10
Hafod Wydr Log	2575	3498	2486	9
Bethesda Log	2619	3654	1836	10
Capel Curig No 3	2701	3570	2402	12
Minafon Logger	2716	3432	1989	10
Betws–Y–Coed Log	2802	3570	1451	10
Ysbyty Ifan Log	2810	3455	2211	10
Plas Pigot Log	2951	3646	1027	9
Denbigh STW Log	3070	3664	742	9
Brynhyfryd Log	3133	3584	756	10
Moel–Y–Crio	3193	3698	896	23
Loggerheads Log	3200	3621	908	10
Cefn Mawr Log	3274	3422	868	10
Hawarden Airport	3341	3646	722	21
Five Fords	3361	3480	729	10
Churton Log	3418	3564	681	10
Chester Log	3419	3666	688	10
Cholmondeley	3552	3505	735	24
Worleston S Wks	3665	3574	692	15
Keele	3820	3447	795	39
Stanley Resr	3929	3519	936	20
Cauldon Low	4058	3480	943	20
Hollinsclough Auto Sta.	4066	3665	1265	18
Ashbourne: St Oswald's..	4173	3465	847	11
Derwent Divn.	4228	3553	997	23
Carsington Dam	4242	3503	887	18
Meynell Langley	4284	3402	758	10
Ashover No 2	4349	3629	858	33
Wingerworth No 2	4378	3665	790	18
Ogston Resr	4380	3598	791	40
Nottingham Watnall	4503	3456	707	59
Sutton–In–Ashfield S Wks	4510	3595	723	19
Waddington	4988	3653	601	55
Cranwell	5005	3493	586	78
Ruskington (L)	5091	3505	590	14
Coningsby	5224	3567	568	12
Fulsby (T)	5241	3611	594	10
Boston Grand Slce(T)	5324	3445	575	11
Boston: Church Road P ..	5335	3435	576	21
Wainfleet No 2	5522	3570	637	10
Burgh Sluice (T)	5552	3586	593	13
Weybourne	6099	3437	596	16

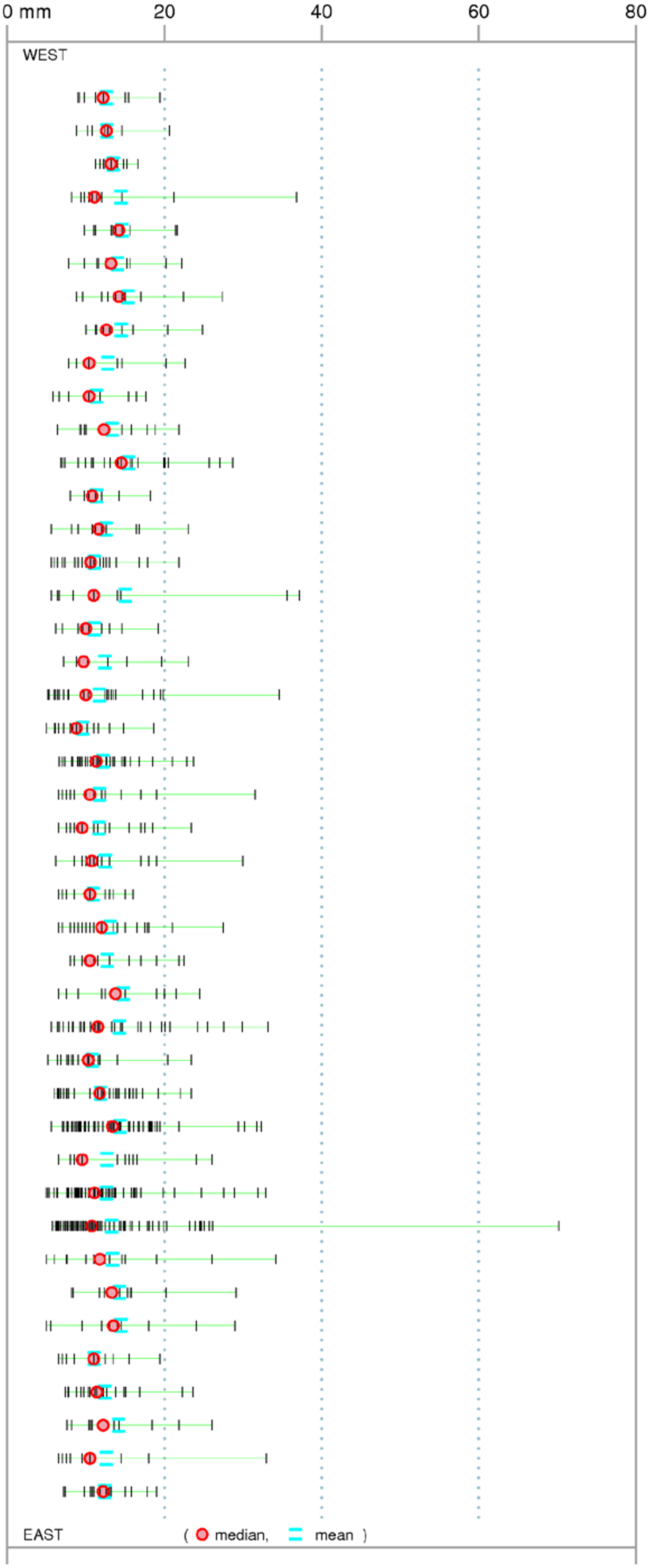


Figure A.12 1 hour annual maxima for GB raingauges between 3400 N and 3699 N

GAUGE	E	N	SAAR	nmax
Valley	2309	3758	844	77
Llyn Alaw Log	2376	3852	1076	10
Cefni Log	2444	3771	1053	10
Colwyn Bay Log	2858	3784	736	10
Rhyl No 2	2994	3747	791	15
Formby Hightown Log	3295	4045	814	34
Crosby	3299	4006	839	10
Ness Log	3302	3754	705	10
Sealand Met Office	3332	3701	689	16
Aigburth (Rtc)	3384	3852	804	22
Aughton	3394	4063	854	16
Speke	3437	3820	783	23
Common Bank Log	3568	4176	977	14
Lower Rivington	3631	4126	1168	9
Dunham Massey Log	3726	3875	813	29
Sale C'ton Ln Log	3764	3927	840	25
Ringway	3814	3844	808	62
Prestbury S.Wks Tel	3897	3782	859	25
Trentabank Resr	3962	3712	1099	25
Arnfield Reservoir Log	4012	3972	1112	25
Ringstone Logger	4050	4178	1318	16
Kinder Filters Tel	4054	3880	1175	30
Chapel Res	4068	3794	1203	20
Tideswell	4154	3745	1062	23
Derwent Res	4174	3899	1256	16
Redmires Logger	4268	3857	1066	18
Barbrook	4281	3770	992	23
Rotherham: British Steel	4440	3950	634	9
South Elmsall S Wks	4484	4107	618	19
Sandall Logger	4600	4062	546	15
Worksopmanton	4608	3791	622	21
Finningley	4658	3995	576	20
Finningley	4659	3989	576	43
Upton:S.Wks Auto.Sta.	4877	3868	590	18
Cadney (T)	4996	4053	620	13
Toft Newton (T)	5033	3873	607	10
Keelby (L)	5169	4098	647	19
Benniworth (T)	5203	3826	655	12
Ludford (L)	5208	3893	691	18
Baumber (T)	5222	3740	620	13
Stenigot (T)	5259	3829	682	12
Horncastle (T)	5261	3702	628	13
Welton Le Wold (T)	5282	3878	702	10
Belchford (T)	5296	3754	680	11
Raithby (T)	5319	3859	690	11
Tathwell (T)	5323	3830	704	10
Covenham (T)	5351	3967	610	9
Manby	5393	3867	622	19
Ulceby Cross (T)	5405	3730	707	10

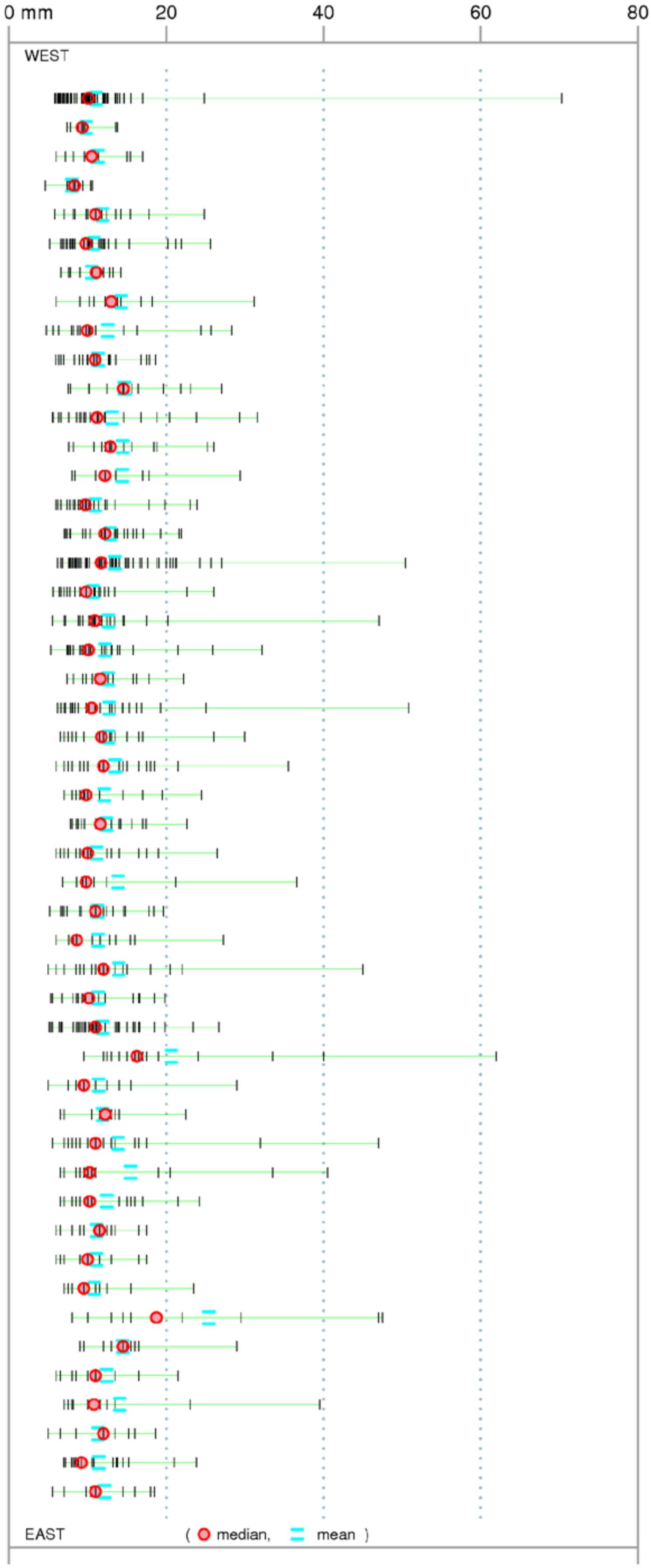


Figure A.13 1 hour annual maxima for GB raingauges between 3700 N and 4199 N

GAUGE	E	N	SAAR	nmax
Ronaldsway	2279	4687	862	23
Blackpool: Squires Gate	3317	4316	853	50
Barnacre Reservoir	3528	4481	1253	9
Preston Moor Park	3537	4311	1004	45
Preston Borough Town H..	3541	4295	1024	10
Abbeystead Tel Log	3556	4539	1339	11
Abbeystead Gdns Log	3567	4547	1373	14
Haighton Reservoir Log	3574	4352	1124	15
Chipping Log	3614	4441	1430	14
Longridge Spade Log	3620	4372	1195	15
Wennington Clint Log	3627	4698	1097	14
Darwen Sunnyhurst	3679	4221	1387	11
Croasdale House Log	3704	4550	1634	11
Stocks Reservoir Tel Log	3717	4548	1506	10
Pickup Bank Log	3721	4237	1394	13
Clapham Turnerford Log	3722	4661	1329	13
Great Harwood Log	3722	4327	1219	15
Accrington: Oak Hill P..	3764	4277	1099	20
Holden Wood Resr No 2	3767	4226	1449	14
Churn Clough Reservoir..	3785	4382	1252	15
Buttock Log	3807	4401	1548	15
Stainforth Log	3822	4675	1106	15
Greenfold Resr No 1	3823	4261	1356	20
Colne Swinden Log	3871	4394	1173	14
Nelson (Lancs)	3872	4384	1171	23
Malham Tarn Logger	3894	4671	1492	18
Gorple Logger	3945	4312	1472	13
Skipton Town Hall	3991	4518	929	54
Embsay Logger	4001	4544	1023	17
Bingley No 2	4089	4350	1011	11
Heckmondwike Logger	4220	4225	710	14
Otley S.Wks Logger	4223	4462	775	18
Farnley Hall Logger	4246	4324	748	17
Headingley Logger	4273	4374	724	17
Leeds Weather Centre	4290	4339	635	11
Harrogate	4304	4578	730	18
Eccup Logger	4309	4422	800	18
Knostrop Logger	4323	4315	656	16
Wakefield Logger	4346	4204	633	15
Lower Dunsforth Logg	4435	4643	629	19
Bramham Logger	4441	4412	658	18
Wheldale Logger	4444	4265	612	11
Linton On Ouse	4491	4613	601	14
Church Fenton	4528	4380	608	34
Acomb Landing Logger	4582	4527	596	16
York: Heslington	4631	4512	598	13
High Mowthorpe Loggr	4888	4685	740	19
Driffield	5004	4565	656	11
Leconfield	5025	4432	638	15
Leconfield	5026	4438	638	9
Driffield Logger	5030	4569	628	12
Cottingham P Sta	5048	4342	667	19
Hull: Ringrose Street	5067	4281	644	11

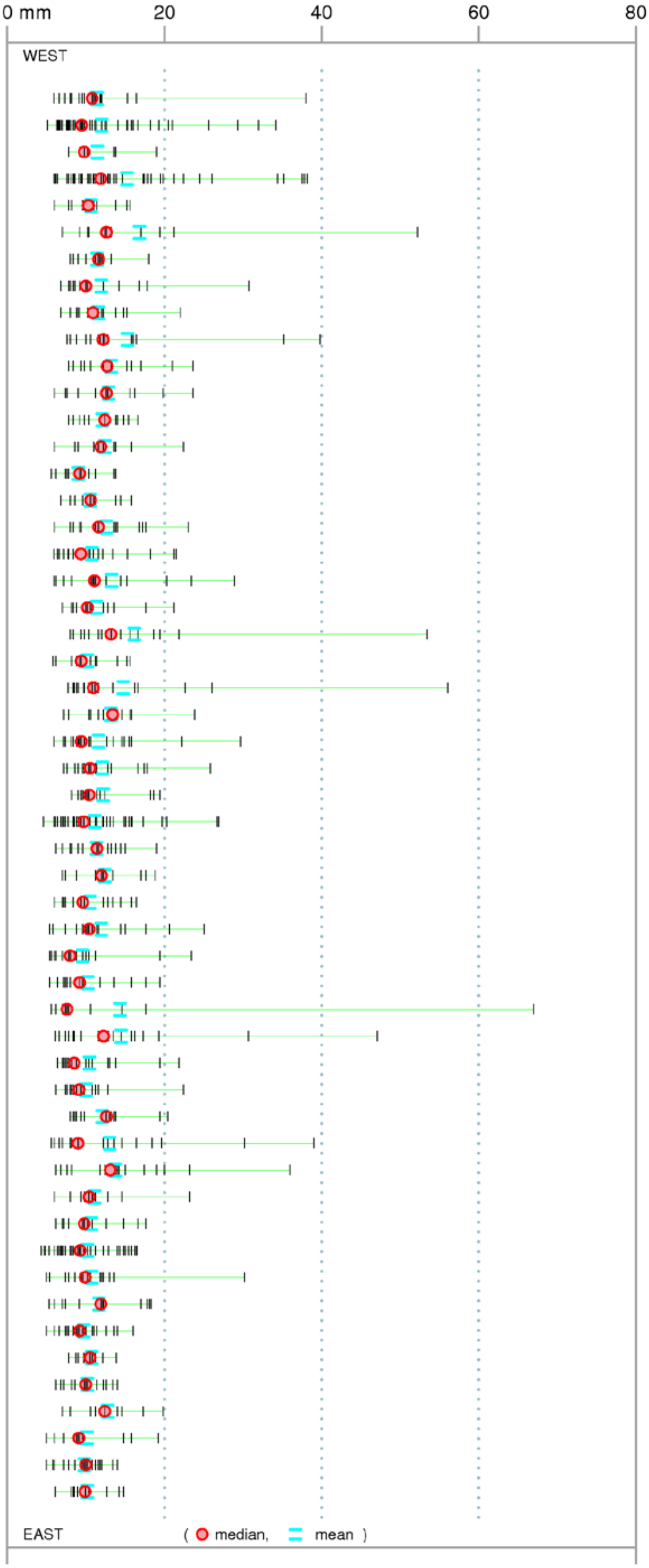


Figure A.14 1 hour annual maxima for GB raingauges between 4200 N and 4699 N

GAUGE	E	N	SAAR	nmax
St Bees Head	2941	5143	950	11
St Bees Head No 2	2955	5148	1031	15
Summergrove Tel	2999	5160	1229	11
Ennerdale Twks Tel	3084	5154	1795	9
Eskmeals	3085	4931	1057	22
Lanthwaite Log	3166	4851	1375	14
Walney Island	3179	4706	992	15
Wastwater Hotel Log	3187	5087	2466	10
Palace Nook Tel	3191	4718	949	15
Ulpha Duddon Tel Log	3209	4947	2035	11
High Snab Farm Log	3222	5190	2257	14
Honister Pass	3225	5135	3510	12
Seathwaite	3235	5121	3156	22
Ulverston P.F. Log	3241	4778	1159	11
Seathwaite Log	3249	4984	2466	11
St Johns Beck Tel	3313	5195	2049	10
Oxen Park Log	3317	4873	1394	12
Thirlmere Nook Log	3319	5129	2521	13
Elterwater Tel Log	3329	5039	2392	9
Brathay Hall Tel	3366	5032	1973	15
Liverpool N. STW Log	3394	4963	846	14
High Newton Reservoir ..	3399	4838	1339	13
Kentmere H'bank Tel	3466	5054	2094	10
Levens: Bridge End	3474	4858	1263	33
Beetham Hall Log	3499	4790	1189	12
Burnbanks Tel Log	3507	5159	1703	11
Pedder Potts No 2 Log	3535	4705	1053	11
Fisher Tarn Reservoir ..	3549	4927	1448	13
Shap	3557	5120	1689	13
Orton S'ford Log	3626	5083	1469	14
Scalebeck Tel Log	3673	5144	958	10
Sedbergh F'field Log	3677	4918	1459	14
Brackenber Log	3722	5195	862	14
Warcop Range	3734	5198	862	15
Far Gearstones	3783	4801	1681	11
Tow Hill Logger	3830	4867	1678	17
Barras Tel Log	3845	5121	945	10
Lartington Filters	4011	5183	842	19
Scar House Logger	4066	4766	1387	16
Richmond Logger	4172	5016	783	16
Lumley Moor Logger	4224	4706	929	14
Catterick Met Office	4249	4970	651	13
Leeming	4305	4891	613	44
Darlington Lingfiel	4322	5146	610	13
Middleton St George	4376	5132	578	12
Dishforth Airfield	4384	4712	624	28
Topcliffe	4399	4789	596	9
Hartburn Grange	4407	5185	555	27
Easby	4584	5087	813	16
Church Houses Logger	4668	4974	954	16
Farndale Vicarage	4673	4975	890	37
Loftus	4736	5192	596	10
Keld Head Logger	4777	4839	683	18
Pickering	4795	4842	731	18

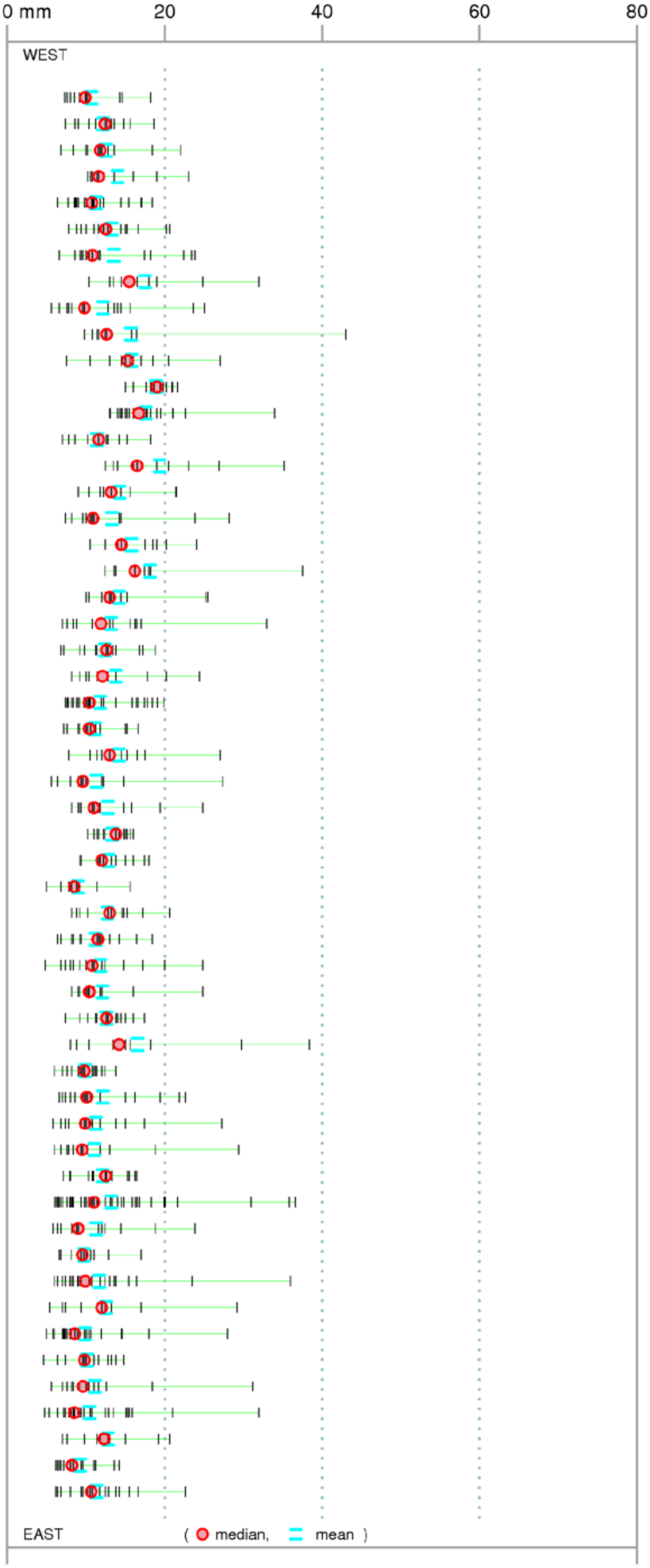


Figure A.15 1 hour annual maxima for GB raingauges between 4700 N and 5199 N

GAUGE	E	N	SAAR	nmax
West Freugh	2109	5546	989	30
West Freugh	2117	5555	989	16
Kirkcowan TBR	2326	5611	1309	16
Loch Fleet Craigwhinnie	2557	5698	2082	10
Dundrennan	2710	5472	1108	15
Dalbeattie Wwtw TBR	2833	5600	1215	9
Dearham Log	3081	5365	917	12
Silloth	3125	5537	882	12
Kinmount House TBR	3136	5693	979	14
Cornhow S Wks	3150	5222	1503	25
Aspatria	3154	5423	1001	21
Abbeytown K'side Log	3158	5514	847	11
Sunderland S Wks	3179	5351	1023	14
Quarry Hill F. Log	3219	5412	1054	12
Keswick	3254	5249	1471	14
Drumbergh Log	3259	5602	854	11
Thursby Wwtw Log	3317	5504	798	12
Calebreck Hall Log	3345	5361	1256	12
Mungrisedale Log	3360	5278	1717	12
C.A.D.Longtown Log	3363	5682	888	12
Groove Beck	3375	5223	1966	11
Carlisle	3383	5603	835	46
Skelton Tel	3436	5361	959	11
Cumwhinton Log	3462	5528	822	12
Newton Rigg Log	3493	5310	912	13
Walton H.F. Log	3530	5653	901	12
Castle Carrock Tel	3546	5551	938	11
Nunwick Hall Log	3554	5360	808	12
Damas Ghyll Log	3575	5537	1227	11
Haresceugh Ctle Log	3610	5428	960	12
Kirkbythore Log	3644	5267	716	12
Haltwhistle	3680	5640	998	14
Alston S Wks	3714	5473	1221	19
Cow Green No 1 Auto	3817	5291	1493	10
Burnhope Resr	3850	5391	1258	23
Allenheads Allen Lo	3858	5455	1191	13
Forest-In-Teesdale	3872	5295	1250	20
Tunstall Resr Auto	4064	5407	898	22
N/Hall Farne School	4204	5672	631	13
Jesmond Dene	4253	5672	675	21
Newcastle Weather Centre	4258	5648	634	15
Durham	4267	5415	650	21
Harpington Hill Farm	4336	5266	632	20
Sunderland University	4389	5567	601	14

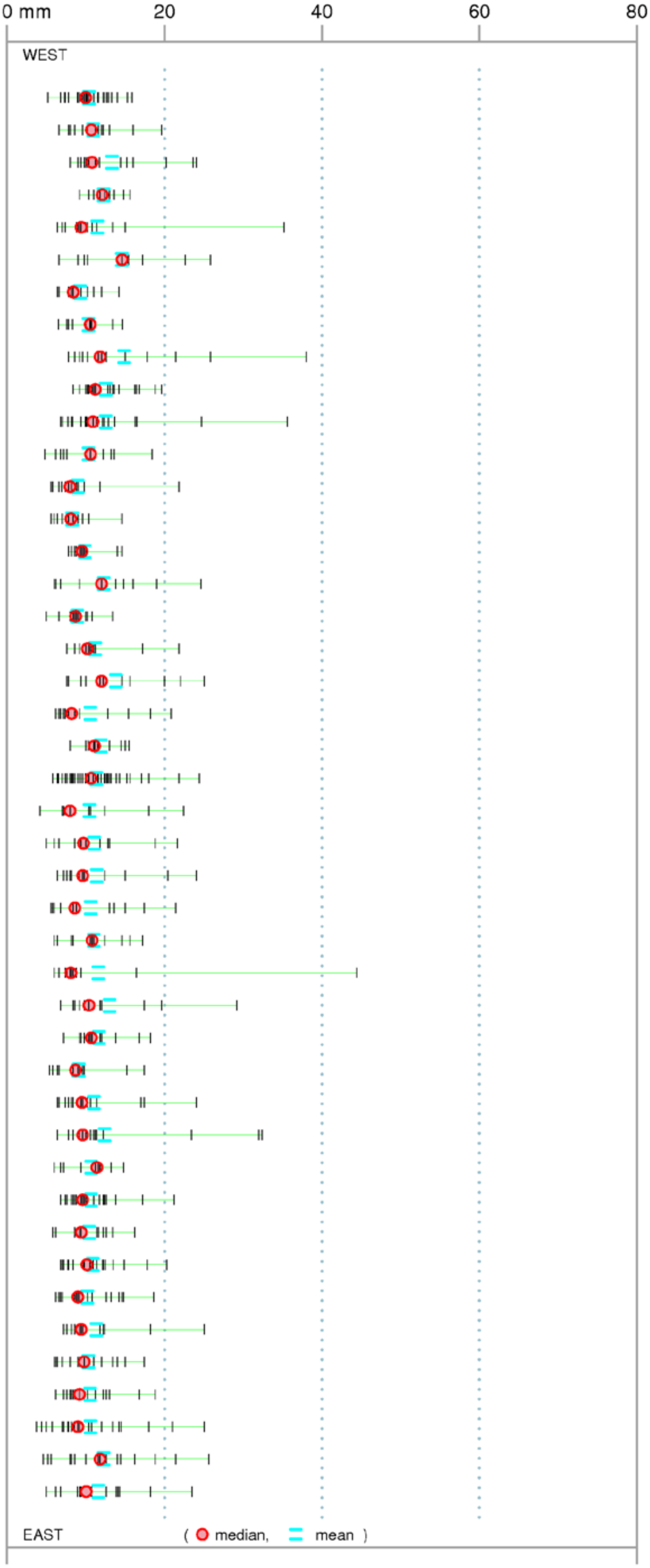


Figure A.16 1 hour annual maxima for GB raingauges between 5200 N and 5699 N

GAUGE	E	N	SAAR	nmax
Amod Farm TBR	1643	6125	1432	10
Machrihanish	1663	6225	1164	37
Dippen	1797	6376	1618	9
Lagafater Lodge TBR	2139	5759	1704	9
Kirriereoch	2362	5871	1880	17
Prestwick Gannet	2369	6277	878	57
North Craig Resr	2438	6412	1205	13
Black Laggan	2469	5777	2420	18
Green Burn	2475	5778	2281	10
Upper Black Laggan	2476	5769	2776	18
South Moorhouse	2525	6512	1784	14
Waulkmill Glen	2525	6582	1235	14
Picketlaw Reservoir	2568	6515	1492	14
Saughall TBR	2598	6364	1327	10
East Kilbride No 2	2638	6535	1221	19
Craigdarroch TBR	2739	5909	1367	16
Eliock	2797	6074	1320	19
Mauldslie	2808	6502	817	11
Capenoch TBR	2845	5940	1214	15
Meadowfoot TBR	2861	6138	1515	14
Newtonairds	2889	5799	1300	19
Gatelawbridge TBR	2900	5965	1054	16
Lochrutton W Wks	2901	5743	1188	11
Drumalbin	2908	6384	839	15
Carnwath	2974	6464	830	12
Moffat: Hydro Gardens	3079	6063	1307	18
Baddinsgill Resr	3126	6554	1129	11
Boreland TBR	3160	5906	1192	11
Eskdalemuir	3235	6026	1536	95
Gladhouse Res.	3299	6544	851	12
Solwaybank TBR	3307	5774	1312	13
Catlowdy Log	3459	5767	1142	12
Braidlie TBR	3477	5967	1479	13
Crewe Fell F.H. Tel	3558	5774	1159	11
Greycrook	3599	6305	664	10
Spadeadam	3599	5720	1264	11
Wileysike Gland Tel	3645	5705	1116	13
Spadeadam No 2	3647	5730	1144	13
Kielder Ridge End A	3658	5959	1098	13
Coalburn Whitehill Log	3694	5778	1196	12
Catcleugh Nursery Au	3749	6031	1098	17
Charterhall	3759	6462	660	14
Redesdale Camp	3824	5990	796	10
Linbriggs	3892	6062	841	22
Goldscleugh Auto	3914	6233	1078	11
Wooler S Wks	3998	6291	700	17
Wallington Hall	4035	5843	786	20
Font Resr P Sta	4052	5938	851	20
Darras Hall Long Me	4147	5712	695	17
Acklington	4225	6007	643	28
Boulmer	4253	6142	655	27

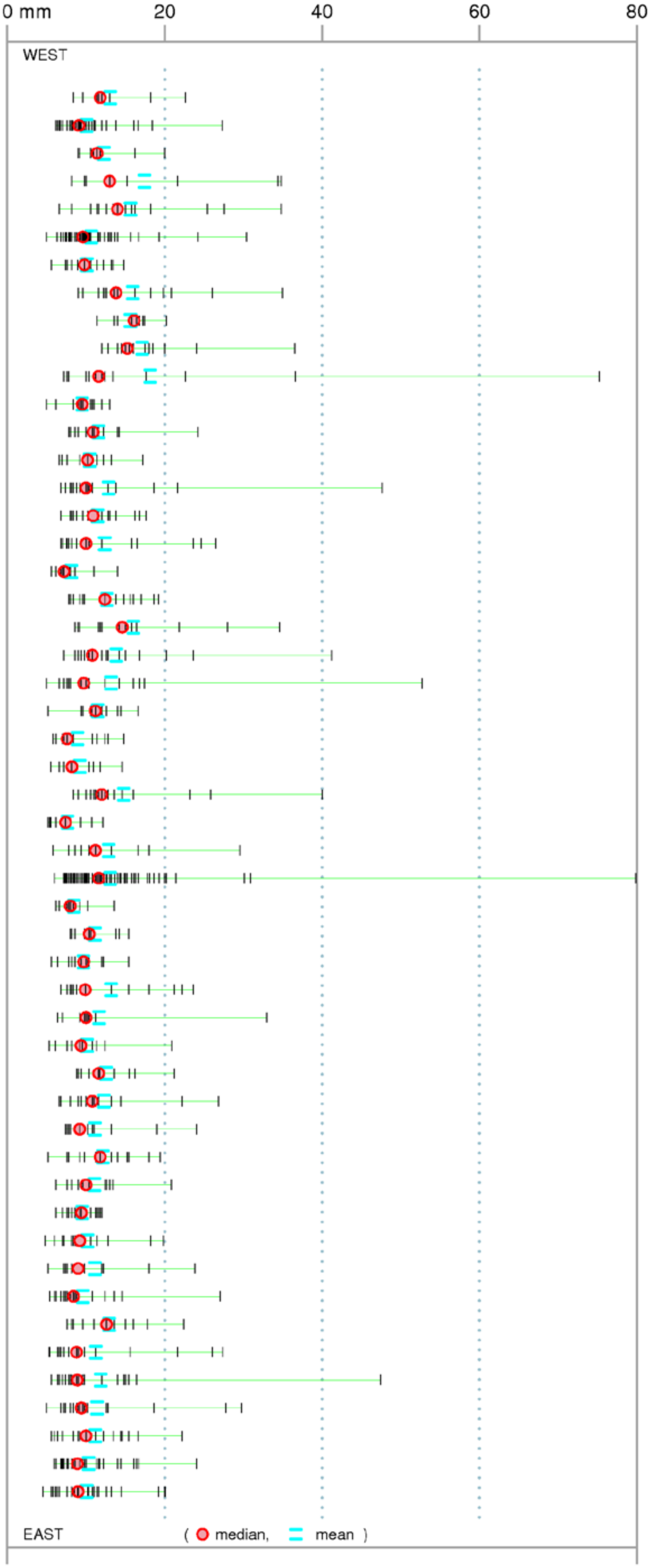


Figure A.17 1 hour annual maxima for GB raingauges between 5700 N and 6599 N

GAUGE	E	N	SAAR	nmax
Tiree	998	7449	1163	47
Clachan–Seil	1773	7182	1679	9
Woodglen TBR	1827	6909	1665	9
Dunstaffnage	1881	7340	1596	9
Dalinlongart Tip Site	2138	6813	2145	9
Stronachlachar	2401	7103	2202	15
Ross Priory	2407	6873	1378	11
Clashmore	2464	6966	2031	10
Duchray Castle	2467	6987	2034	13
Abbotsinch	2480	6667	1037	42
Loch Katrine	2490	7066	2176	11
Renfrew	2508	6663	1016	21
Moar Logger	2535	7451	1763	12
Auchentroig (Buchlyvie)	2544	6935	1375	13
Strathyre	2560	7167	1981	13
Killin Monemore	2564	7321	1634	10
Loch Venachar	2598	7063	1571	13
Thornhill	2666	6999	1143	12
Auchinner Logger	2694	7158	1895	13
North Third	2756	6900	1372	10
Dunnswood Wwtw (Cumb..	2781	6772	1178	14
Stirling S Wks	2808	6935	958	11
Lower Auchnafree Check	2819	7336	1525	11
Braco (Dunduff)	2821	7115	1384	12
Strathallan Airfield	2932	7162	903	15
Kinkell Bridge Logger	2933	7167	967	12
Polmonthill Wwtw	2953	6795	841	11
Bathgate	2961	6703	920	11
Balado	3083	7025	1088	14
Harperrig	3102	6612	946	15
Turnhouse	3159	6739	667	52
Loch Leven Sluices	3171	6994	909	14
Portmoak	3173	7007	934	14
Fife Airport	3243	6995	828	14
Edinburgh Rbg No 2	3244	6755	639	17
Fairmilehead	3249	6684	774	18
Mylnefield	3339	7301	688	14
Crichton	3380	6616	732	11
Leuchars	3468	7208	654	71
Skedsbush (Gifford)	3512	6657	692	15
Haddington	3532	6744	620	11
Nunraw Abbey	3594	6700	824	23
Colliston	3610	7466	705	10
Dunbar	3672	6791	571	24

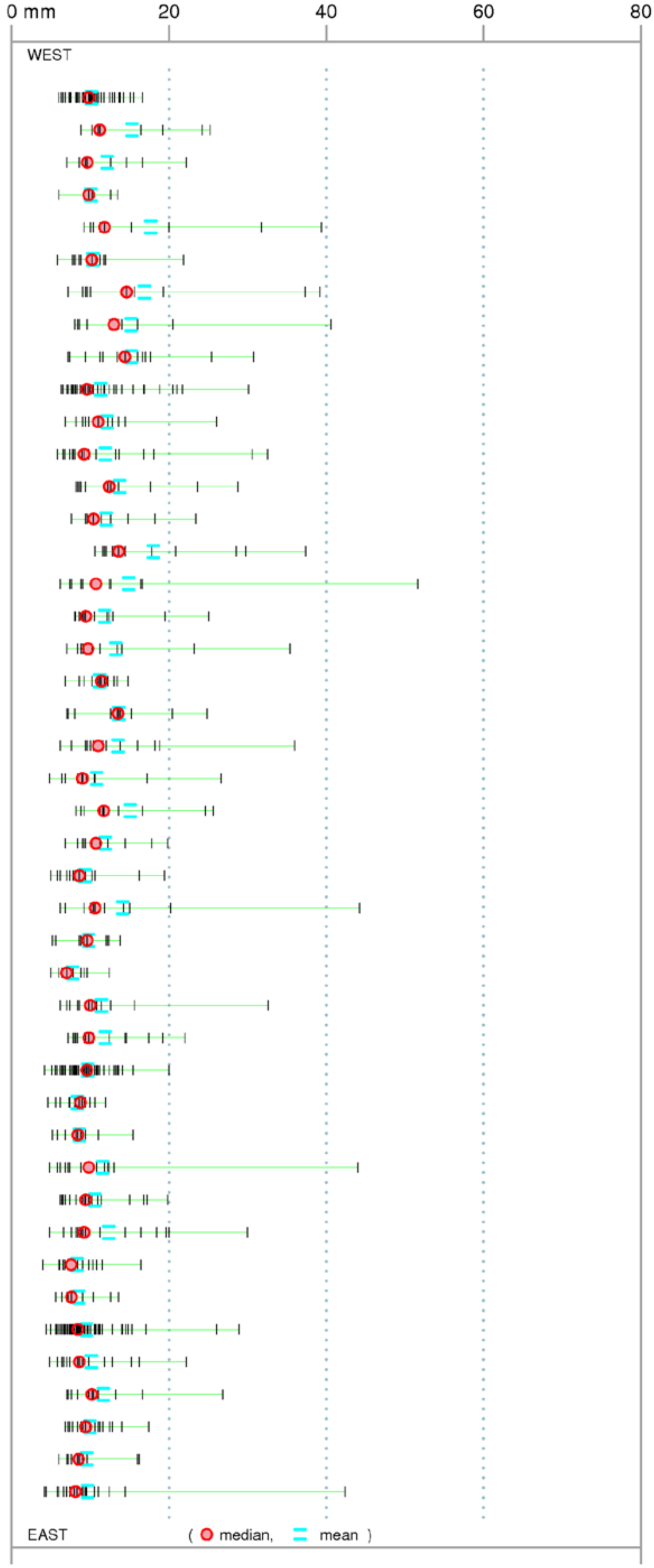


Figure A.18 1 hour annual maxima for GB raingauges between 6600 N and 7599 N

GAUGE	E	N	SAAR	nmax
Rhum: Kinloch	1402	7996	2574	12
Skye: Lusa	1706	8249	1861	9
Polloch TBR	1791	7688	2317	9
Glendessary TBR	1967	7926	3181	14
Fort William No 2	2097	7734	2035	14
Coille Mhorgil TBR	2100	8014	2435	10
Glen Nevis TBR	2127	7717	2047	11
Ben Nevis Observatory	2167	7712	3560	20
Affric Lodge TBR	2188	8231	1576	10
Mullardoch Dam No 2	2223	8310	1924	10
Inchvuilt TBR	2224	8391	1651	9
Inchmore Hatchery TBR	2301	8125	1465	11
Braeroy Lodge TBR	2336	7915	1858	11
Tulloch Bridge	2350	7783	1697	13
Corrimony TBR	2375	8303	1054	10
Spey Dam	2582	7935	1168	10
Flichity TBR	2663	8289	972	11
Coignafearn	2710	8178	1190	19
Dalnamein	2747	7694	1070	13
Freeburn TBR	2795	8300	915	11
Sluggan	2869	8218	755	10
Aviemore	2897	8143	919	18
Lochindorb TBR	2970	8354	790	15
Kindrogan Field Cent	3054	7628	996	13
Inverey	3088	7892	896	12
Tulchan Fish Farm	3132	8352	855	12
Delnashaugh	3184	8352	833	9
Polhollick	3343	7965	813	9
Gella Bridge Logger	3372	7652	1050	13
Aboyne No 2	3491	7986	757	15
Milton Of Noth	3506	8285	902	15
Charr	3615	7830	1115	13
Mongour	3764	7901	1068	9
Westhills	3824	8063	883	11
Inverbervie No 2	3839	7734	658	14
Dyce	3878	8128	790	52
Aberdeen Mannofield Resr	3916	8042	753	23
Esslemont House	3933	8305	777	14
Aberdeen Observatory	3939	8081	744	52

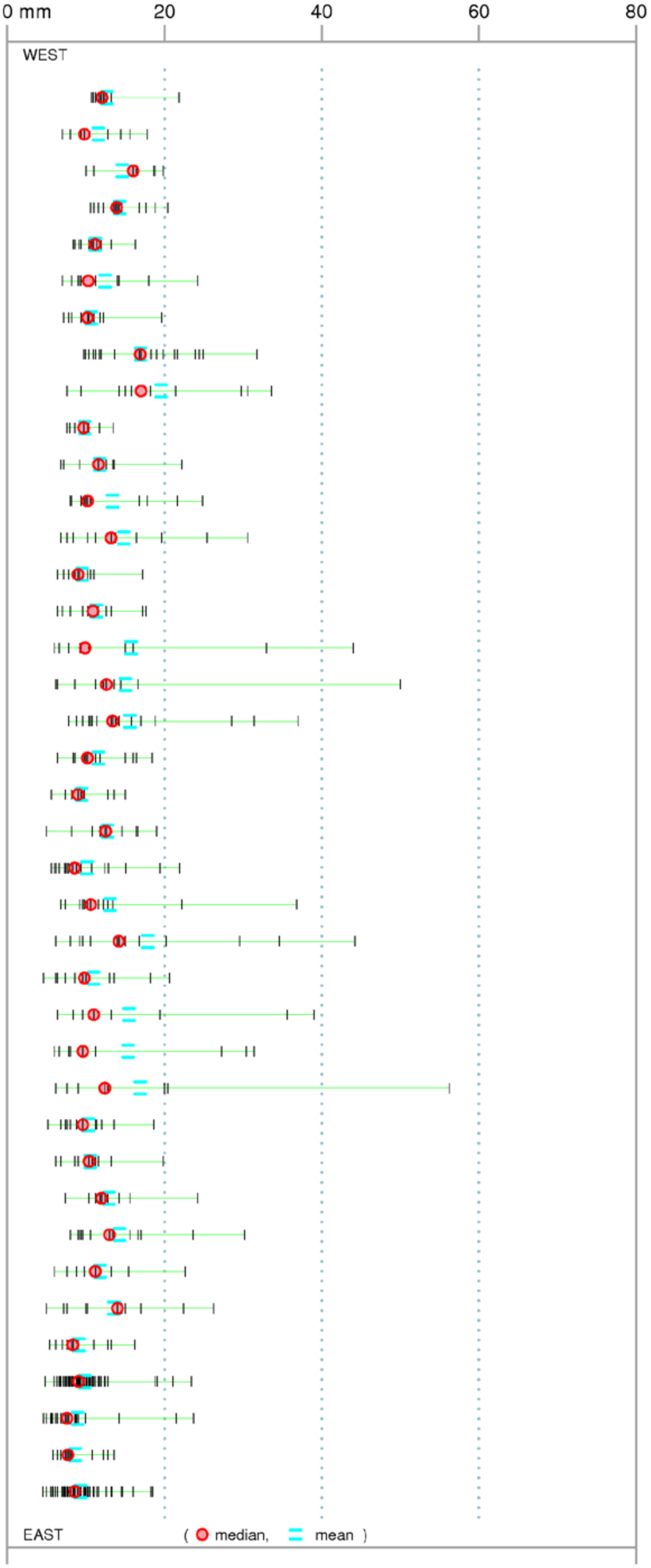


Figure A.19 1 hour annual maxima for GB raingauges between 7600 N and 8399 N

GAUGE	E	N	SAAR	nmax
South Uist Range	763	8425	1235	10
Benbecula Airport	782	8555	1261	41
Stornoway Airport	1464	9331	1171	53
Aultbea No 2	1846	8913	1380	15
New Kelso TBR	1941	8428	1827	12
Kinlochewe	2026	8629	2239	13
Luib Cottage TBR	2131	8547	1886	14
Little Assynt TBR	2147	9250	1473	12
Knockanrock TBR	2186	9088	2024	14
Dosmucheran TBR	2204	8602	1748	12
Scardroy TBR	2217	8519	1610	13
Loch Droma TBR	2252	8752	1741	15
Loch Glascarnoch	2277	8742	1667	13
Benmore Lodge No 2	2324	9121	1976	17
Corriemulzie	2329	8955	1687	17
Allnabad TBR	2453	9428	1771	12
Dingwall	2538	8593	793	19
Rhian Bridge TBR	2564	9166	1209	9
Altnaharra No 2	2569	9358	1123	13
Longman TBR	2666	8468	673	10
Dalvina TBR	2696	9439	1044	14
Allanfearn TBR	2711	8474	666	9
Dalcross	2767	8521	642	14
Tain Range	2833	8827	585	15
Strathy 2	2839	9641	963	14
Kinbrace Hatchery	2872	9284	1007	14
Forsinain	2906	9485	949	19
Kinloss	3068	8628	621	56
Torwinny	3134	8489	860	15
Lossiemouth	3212	8698	627	13
Rothes	3285	8497	851	9
Wick Airport	3365	9522	789	57
Keith	3433	8518	876	12
Kirkwall	3482	10077	1009	60
Sella Ness	4398	11738	1056	10
Lerwick	4454	11397	1202	46
Baltasound No 2	4625	12078	1050	16

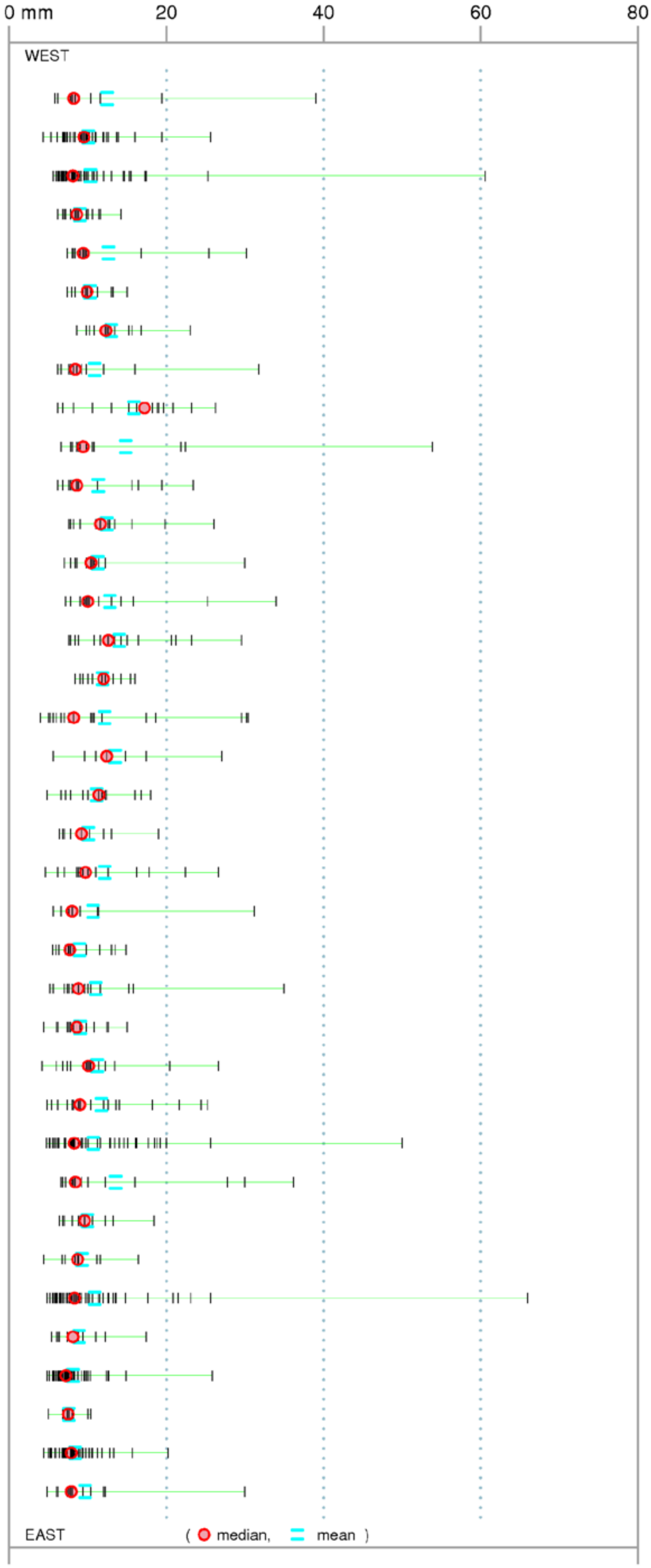


Figure A.20 1 hour annual maxima for GB raingauges between 8400 N and 12099 N

GAUGE	E	N	SAAR	nmax
Ardeemore	2060	3807	1904	19
Castle Archdale Met Of..	2175	3587	1099	13
Portora Sluice	2222	3453	1084	19
St Angelo	2231	3497	1121	14
Castlederg	2273	3844	1118	12
Strabane: Glen Road	2353	3981	1017	10
Malin Head	2422	4591	907	30
Omagh S Wks	2441	3737	963	12
Clones Weather Stn	2500	3263	992	31
Ballykelly	2624	4234	852	24
Ballykelly	2634	4238	852	12
Banagher: Caugh Hill	2663	4047	1324	9
Pomeroy Forest	2705	3724	1107	16
Lough Fea	2764	3865	1329	11
Coleraine Cutts	2854	4303	1009	16
Armagh	2878	3458	813	85
Seagahan Filters	2897	3382	953	9
Glenanne No 2	2976	3331	1002	14
Toomebridge	2990	3906	861	18
Portglenone	2991	4030	921	12
Lurgan Cemetery	3073	3569	834	12
Newry S Wks	3091	3247	951	16
Altnahinch Filters	3116	4237	1418	23
Huntly (Down) S Wks	3118	3467	819	10
Aldergrove	3146	3810	867	80
Broughshane Filters	3165	4090	1117	13
Ballypatrick Forest	3176	4386	1312	20
Hillsborough Met Office	3233	3613	840	19
Hillsborough	3251	3577	883	11
Belfast P Sta	3352	3769	884	10
Hare Island	3504	3495	848	19

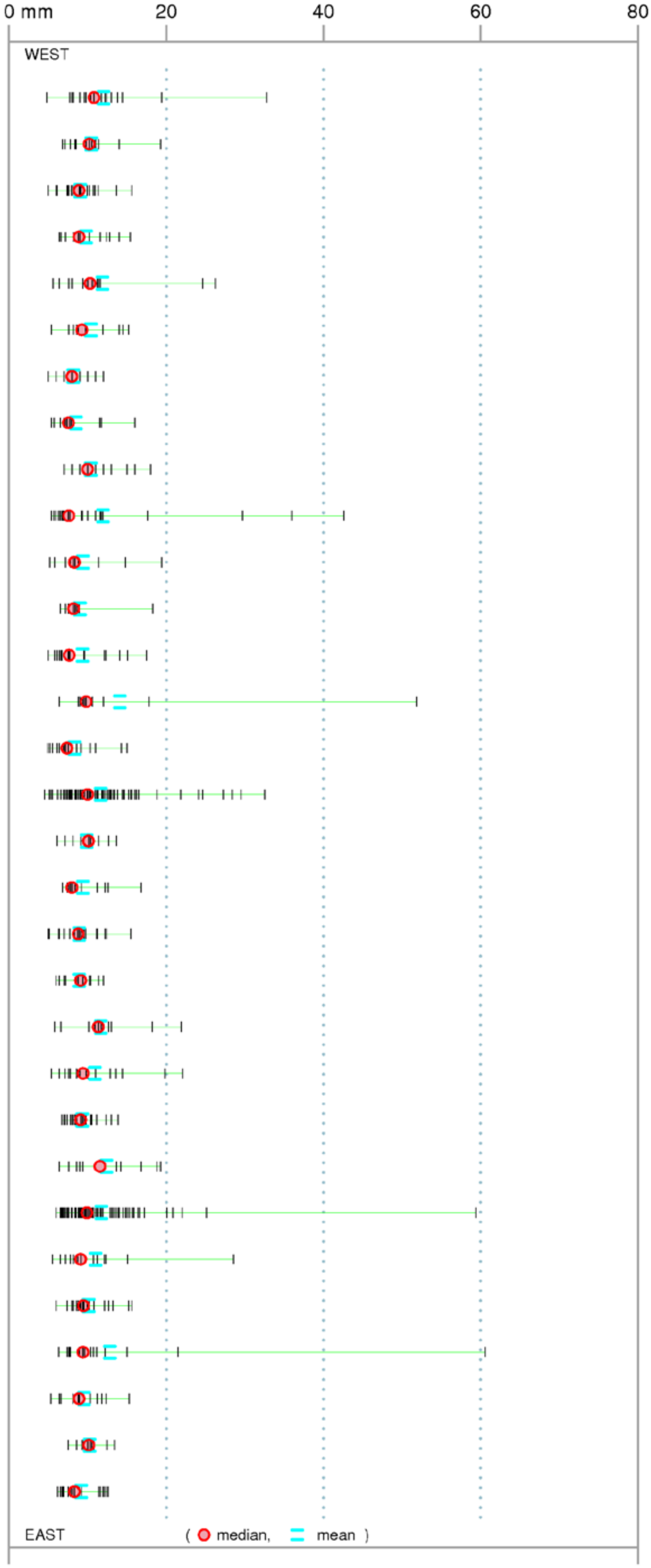


Figure A.21 1 hour annual maxima for Irish raingauges

Table A.1 North-east England

Gauge number	Site name	East	North	First year	Last year
10005185	Acklington	4225	6007	1947	1974
59793	Acomb Landing Logger	4582	4527	1988	2004
15347	Allenheads Allen Lo	3858	5455	1992	2004
10013553	Alston S Wks	3714	5473	1980	2004
75266	Bingley No 2	4089	4350	1995	2005
10001584	Boulmer	4253	6142	1975	2001
64280	Bramham Logger	4441	4412	1987	2004
10021228	Burnhope Resr	3850	5391	1980	2004
10660	Catcleugh Nursery Au	3749	6031	1983	2004
52787	Catterick Met Office	4249	4970	1932	1944
10064421	Church Fenton	4528	4380	1947	2006
68762	Church Houses Logger	4668	4974	1989	2004
10044704	Cottingham P Sta	5048	4342	1986	2004
26644	Cow Green No 1 Auto	3817	5291	1992	2004
30377	Darlington Lingfiel	4322	5146	1992	2004
7533	Darras Hall Long Me	4147	5712	1986	2005
10056316	Dishforth Airfield	4384	4712	1951	2006
42667	Driffield	5004	4565	1948	1958
43533	Driffield Logger	5030	4569	1989	2004
10024725	Durham	4267	5415	1946	2006
10031555	Easby	4584	5087	1982	2004
63518	Eccup Logger	4309	4422	1987	2004
74329	Embsay Logger	4001	4544	1987	2004
68782	Farndale Vicarage	4673	4975	1935	1971
76204	Farnley Hall Logger	4246	4324	1988	2004
10006403	Font Resr P Sta	4052	5938	1982	2004
27035	Forest-In-Teesdale	3872	5295	1951	1970
77336	Gorple Logger	3945	4312	1987	2004
10014555	Haltwhistle	3680	5640	1980	2004
10032822	Harpington Hill Farm	4336	5266	1981	2004
58569	Harrogate	4304	4578	1952	1971
10032602	Hartburn Grange	4407	5185	1959	1986
10076413	Headingley Logger	4273	4374	1987	2004
79621	Heckmondwike Logger	4220	4225	1987	2004
38179	High Mowthorpe Loggr	4888	4685	1986	2004
44877	Hull, Ringrose Street	5067	4281	1963	1973
10019356	Jesmond Dene	4253	5672	1984	2004
70365	Keld Head Logger	4777	4839	1986	2004
8850	Kielder Ridge End A	3658	5959	1992	2004
76550	Knostrop Logger	4323	4315	1987	2004
10028185	Lartington Filters	4011	5183	1982	2004
44228	Leconfield	5026	4438	1960	1968
10044287	Leconfield	5025	4432	1992	2006
10076073	Leeds Weather Centre	4290	4339	1990	2002
10053903	Leeming	4305	4891	1945	2001
10003066	Linbriggs	3892	6062	1982	2004
10057293	Linton On Ouse	4491	4613	1993	2006
34592	Loftus	4736	5192	1997	2006
56505	Lower Dunsforth Logg	4435	4643	1986	2004
49902	Lumley Moor Logger	4224	4706	1990	2004
73422	Malham Tarn Logger	3894	4671	1985	2004
31451	Middleton St George	4376	5132	1952	1968
17651	N/Hall Farne School	4204	5672	1992	2004
10019380	Newcastle Weather Centre	4258	5648	1991	2005
62916	Otley S.Wks Logger	4223	4462	1986	2004
10070676	Pickering	4795	4842	1974	1996

Gauge number	Site name	East	North	First year	Last year
10990	Redesdale Camp	3824	5990	1997	2006
82509	Redmires Logger	4268	3857	1986	2004
52287	Richmond Logger	4172	5016	1987	2004
77836	Ringstone Logger	4050	4178	1988	2004
84851	Rotherham, British Steel	4440	3950	1997	2005
86405	Sandall Logger	4600	4062	1986	2001
57426	Scar House Logger	4066	4766	1988	2004
74374	Skipton Town Hall	3991	4518	1912	1970
10086575	South Elmsall S Wks	4484	4107	1985	2004
25514	Sunderland University	4389	5567	1989	2002
56005	Topcliffe	4399	4789	1998	2006
47281	Tow Hill Logger	3830	4867	1987	2004
22163	Tunstall Resr Auto	4064	5407	1982	2004
80282	Wakefield Logger	4346	4204	1987	2004
10005784	Wallington Hall	4035	5843	1983	2005
80673	Wheldale Logger	4444	4265	1986	2004
83280	Wingerworth No 2	4378	3665	1986	2004
60528	York, Heslington	4631	4512	1967	1979

Table A.2 Anglian region

Gauge number	Site name	East	North	First year	Last year
233754	Andrewsfield	5687	2248	1998	2006
9000469	Barford Bridge (T)	4861	2831	1988	2002
10235389	Basildon Nevendon S Wks	5738	1906	1980	2004
9000453	Baumber (T)	5222	3740	1987	2002
10174062	Bedford	5049	2599	1980	2006
9000550	Bedford Stw (T)	5085	2496	1992	2005
9000455	Belchford (T)	5296	3754	1987	2002
9000454	Benniworth (T)	5203	3826	1987	2002
9000559	Birchmoor Wsw (T)	4943	2348	1992	2005
9000461	Boston Grand Slce(T)	5324	3445	1987	2002
149876	Boston, Church Road P Sta	5335	3435	1946	1970
9000560	Bourn Stw (T)	5337	2579	1992	2005
9000479	Bourne S.T.W (L)	5109	3202	1987	2002
10234682	Bradwell Eastlands Farm	6023	2076	1980	1987
9000572	Brampton Office (T)	5210	2710	1993	2005
9000470	Braunston (T)	4838	3065	1986	2002
9000598	Brentwood (Logger)	5596	1914	1996	2003
9000591	Bressingham(Log)T	6088	2813	1992	2000
10186331	Brooms Barn	5752	2656	1984	1994
9000450	Burgh Sluice (T)	5552	3586	1987	2002
9000467	Cadney (T)	4996	4053	1987	2002
152426	Caldecott P Sta	4865	2932	1951	1971
9000565	Carbrooke Wsw (T)	5940	3026	1993	2005
10174566	Cardington	5081	2463	1954	1979
9000564	Castle Acre	5820	3150	1997	2005
10164086	Castor, Splash Lane	5124	2982	1985	2002
9000595	Cattawade(Logger)	6100	2327	1992	1999
10224243	Cavendish	5801	2469	1980	2004
9000602	Chantry	6149	2414	1996	2004
220389	Charsfield (Logger)	6243	2566	1993	2003
9000500	Chesterton Res. (L)	5148	2946	1989	2002
10214042	Coltishall	6262	3229	1990	2005

Gauge number	Site name	East	North	First year	Last year
10146127	Coningsby	5224	3567	1982	1993
9000480	Corby Glen S.T.W.(L)	4992	3246	1985	2002
10163469	Corby S Wks No 2	4906	2889	1981	2002
10138834	Cottesmore	4909	3153	1951	2006
9000463	Covenham (T)	5351	3967	1988	2002
10146451	Cranwell	5005	3493	1922	1999
10165395	Crowland S Wks	5246	3091	1978	2002
10158521	Daventry, Borough Hill Resr	4584	2619	1989	2001
10152006	Dingley Resr	4774	2867	1985	2002
9000473	Dodford (T)	4627	2607	1988	2002
9000468	Donington Bridge (T)	5174	3356	1987	2002
9000570	Elmdon Stw (T)	5470	2403	1992	2005
9000571	Ely Office	5552	2807	1992	2005
10153445	Empingham P.Sta. Auto.Sta.	4946	3081	1985	2002
9000483	Etton (L)	5143	3051	1985	2002
221299	Felixstowe	6286	2328	1921	1970
9000573	Fleam Dyke	5539	2549	1996	2004
9000575	Foxcote (T)	4713	2358	1992	2005
9000590	Framingham (Logger)	6272	3030	1993	2004
9000452	Fulsby (T)	5241	3611	1987	2001
9000577	Great Gidding	5120	2824	1997	2005
10146966	Guthram Gowt	5171	3225	1978	2002
10151921	Hallaton S.Wks Auto.Sta.	4795	2959	1985	2002
10228562	Halstead	5819	2309	1980	1987
9000596	Halstead(Logger)	5825	2302	1993	2004
9000507	Hannington Res (L)	4826	2712	1988	2002
10223805	Haverhill S Wks	5681	2449	1980	2004
9000578	Heacham	5668	3364	1996	2005
10215803	Hemsby	6493	3162	1979	2000
10157290	Holbeach No 2	5440	3328	1991	2006
19000486	Holbeach S.T.W. (L)	5358	3258	1985	2002
10188832	Honington	5888	2750	1969	2002
9000464	Horncastle (T)	5261	3702	1987	2002
208422	Horsham St Faith, Met Office	6220	3131	1947	1956
9000508	Husbands Bosworth(L)	4645	2847	1988	2001
10232913	Hutton S Wks	5651	1957	1980	2004
19000446	Keelby (L)	5169	4098	1978	2002
19000510	Kibworth Stw (L)	4691	2936	1986	2002
19000475	Kingscliffe (T)	5013	2975	1987	2002
9000611	Kirtling Green	5681	2559	1993	2004
10225619	Langham W Wks Auto	6017	2340	1987	2004
9000551	Letchworth Stw (T)	5207	2344	1993	2005
9000594	Levington (Logger)	6241	2399	1993	2004
10158704	Litchborough S Wks	4624	2551	1985	2002
19000444	Ludford (L)	5208	3893	1978	2002
136580	Manby	5393	3867	1952	1970
10155962	Manthorpe S Wks	5067	3164	1979	2002
10197430	March	5420	2967	1971	1981
9000579	March Stw (T)	5441	2991	1992	2004
10193359	Marham	5737	3090	1951	2001
9000580	Mildenhall	5692	2748	1997	2004
10187228	Mildenhall	5683	2778	1935	1968
9000581	Mundford Road (T)	5865	2845	1993	2004
222173	Needham Market	6095	2549	1996	2004
9000587	North Creake(Logger)	5854	3371	1994	2004
10208467	Norwich Weather Centre	6233	3082	1990	1999
9000552	Olney	4888	2527	1997	2005
10163095	Oundle S Wks	5038	2897	1981	2002

Gauge number	Site name	East	North	First year	Last year
9000616	Poolstreet	5771	2364	1993	2004
9000582	Potton Stw (T)	5222	2485	1992	2004
9000465	Raithby (T)	5319	3859	1987	2002
19000476	Ravensthorpe (T)	4681	2703	1978	2002
19000489	Ridds Farm (L)	4938	3255	1977	1990
9000459	Riseholme (T)	4985	3756	1988	2002
9000490	Ropsley S.T.W (L)	5001	3336	1986	2002
9000583	Rushbrooke Wsw (T)	5873	2624	1992	2004
19000442	Ruskington (L)	5091	3505	1978	2002
9000617	Salle	6126	3244	1996	2004
9000589	Shipdham Stw(Logger)	5958	3060	1996	2004
10236466	Shoeburyness	5948	1857	1980	1995
10236425	Shoeburyness, Landwick	5961	1878	1978	2006
175915	Silsoe	5091	2358	1951	1971
19000445	South Witham (L)	4929	3198	1978	2002
9000492	Spalding S.T.W. (L)	5262	3251	1987	2002
9000477	Stamford (T)	5069	3065	1989	2002
9000456	Stenigot (T)	5259	3829	1987	2002
19000520	Stimpson Ave (L)	4768	2616	1979	1994
9000593	Stowmarket (Logger	6058	2580	1993	2002
10166869	Sutton Bridge	5476	3201	1978	1989
9000462	Tathwell (T)	5323	3830	1987	2002
9000585	Toddington Wbs (T)	5002	2284	1992	2004
9000449	Toft Newton (T)	5033	3873	1987	2002
9000586	Towcester	4717	2488	1996	2004
19000521	Tugby (L)	4760	3005	1977	1990
9000466	Ulceby Cross (T)	5405	3730	1987	2002
10141160	Upton,S.Wks Auto.Sta.	4877	3868	1978	2002
10142001	Waddington	4988	3653	1947	2001
138518	Wainfleet No 2	5522	3570	1997	2006
10221992	Wattisham	6025	2514	1982	2006
9000523	Wellingborough Ps(L)	4908	2674	1987	2002
9000457	Welton Le Wold (T)	5282	3878	1987	2002
206273	West Raynham	5847	3245	1948	1968
10203769	Weybourne	6099	3437	1991	2006
10164638	Whittlesey, Dog-In-A-Doublet Sluice	5272	2993	1984	2001
165129	Wisbech P Sta	5465	3102	1948	1971
10231581	Witham S Wks	5827	2139	1980	2004
163918	Wittering	5048	3032	1947	1986
10164013	Wittering	5043	3026	1980	2006
9000631	Wittlesey (L)	5274	2962	1987	2002
10232671	Writtle	5678	2067	1980	1999
10179624	Wyton	5284	2745	1967	1994
9000478	Yardley Hastings (T)	4867	2574	1985	2002
9000554	Yelden Stw (T)	5014	2674	1992	2005

Table A.3 Thames region

Gauge number	Site name	East	North	First year	Last year
10260991	Abingdon	4479	1991	1943	1975
10261021	Abingdon S Wks No 2	4493	1952	1986	2004
10277568	Aldenham School No 2	5157	1973	1980	1992
261923	Aylesbury Stw Auto	4791	2148	1995	2003
270669	Basingstoke R27	4676	1552	1989	2004

Gauge number	Site name	East	North	First year	Last year
10287864	Beddington, New S Wks	5299	1661	1972	2004
10264250	Benson	4625	1917	1950	2006
264254	Benson R12	4613	1913	1991	2004
10259110	Bicester S Wks	4581	2212	1985	2004
10281186	Bordon	4804	1362	1980	2004
276177	Boreham Wood	5213	1967	1996	2004
10253340	Bourton-On-The-Water S Wks	4182	2203	1986	2004
278264	Bovingdon	5007	2038	1954	1966
274918	Bracknell R06	4858	1718	1987	2004
10272734	Bracknell, Beaufort Park	4846	1664	1972	2000
241510	Bragbury Park	5273	2213	1989	2002
242313	Braughing Friars	5420	2245	1989	2004
10246847	Brent Resr	5208	1870	1949	2002
10252448	Brize Norton	4292	2067	1982	2001
284231	Broadfield	5263	1345	1951	1970
10284703	Burstow S Wks	5305	1437	1980	2004
256345	Byfield Stw Auto	4523	2525	1995	2004
10271491	Camberley S Wks	4862	1598	1980	2004
246187	Camden Square	5296	1845	1881	1920
246180	Camden Square No 2	5291	1838	1881	1920
10265923	Caversham R10	4720	1740	1951	2004
287141	Cheam Ps	5247	1641	1984	2004
279941	Chertsey R08	5016	1674	1990	2004
10268851	Chieveley S Wks	4468	1739	1980	2004
239315	Chigwell Stw	5423	1926	1985	1991
241961	Chipping	5357	2323	1989	2004
254829	Chipping Norton R13	4294	2268	1990	2004
10287451	Chipstead, How Green Resr	5283	1581	1973	2004
283596	Chobham	4976	1611	1997	2004
243045	Clavering Stw	5476	2318	1991	2004
264845	Cleeve R19	4601	1818	1987	2004
9000368	Colnpen Lc	4070	2080	1996	2004
10282290	Cranleigh S Wks	5041	1393	1980	2004
287764	Croydon Airport	5312	1633	1923	1955
10238097	Dagenham, Central Park Nursery	5499	1863	1961	2004
241790	Dane End Sw	5334	2219	1990	2004
244569	Darnicle Hill	5309	2048	1990	2004
289102	Deptford Ps	5377	1771	1989	2004
247060	Ealing, Castlebar	5170	1819	1962	1975
247119	Ealing/Greenford Cmt	5141	1815	1989	2004
246738	Edgware, Chandos Park	5189	1911	1942	1973
239258	Epping Forest	5412	1981	1990	2004
10254336	Eynsham Lock	4445	2087	1983	2004
280826	Farnham R30	4856	1481	1992	2004
239579	Gascoigne Road	5447	1830	1990	2004
10284324	Gatwick	5265	1407	1959	1996
10289129	Greenwich	5387	1776	1954	1995
257039	Grimsbury R31	4458	2418	1990	2004
288963	Grove Park	5415	1715	1990	2002
282781	Guildford R28	5002	1518	1991	2004
245310	Hackney, Clapton Pond	5349	1860	1960	1976
245074	Hadley Road	5303	1980	1989	2004
10246690	Hampstead	5262	1863	1933	2004
284152	Hampton W Wks	5131	1695	1954	1974
243679	Hatfield Heath	5524	2141	1990	2004
10247536	Heathrow	5077	1767	1947	2004
242501	Hertford S Wks	5338	2134	1952	1971
274546	High Wycombe Auto	4884	1920	1995	2004

Gauge number	Site name	East	North	First year	Last year
274319	High Wycombe Hqstc	4826	1988	1996	2006
10286392	Hogsmill Valley S Wks	5194	1683	1961	2004
10246425	Holland Park	5246	1795	1989	2004
245176	Hornsey	5308	1894	1989	2004
10247669	Isleworth, Mogden S Wks	5154	1753	1969	2004
288749	Kelsey Park	5374	1692	1989	2004
287675	Kenley Airfield	5331	1578	1993	2006
246327	Kensington Palace	5259	1801	1922	1973
10287049	Kew	5171	1757	1886	1980
10287052	Kew (Rbg)	5187	1774	1981	2003
287059	Kew S Wks	5197	1767	1967	1990
269627	Kingsclere R05	4531	1609	1990	2004
286405	Kingston, Canbury Gardens	5179	1700	1948	1976
10285630	Leatherhead, Elmer Wks	5159	1557	1980	2004
10251530	Lechlade, St Johns Lock	4222	1990	1985	2004
240662	Lilley Manor	5112	2278	1991	2004
10253699	Little Rissington	4212	2181	1942	2006
10246211	London Weather Centre	5311	1820	1975	2006
275169	Maidenhead S Wks	4893	1804	1944	1971
276956	Markyate S.W.- Auto	5071	2155	1990	2004
266474	Marlborough, Salisbury Hill Auto.Sta.	4184	1686	1986	2004
10285587	Mickleham	5173	1526	1985	1992
240470	Mill Green	5245	2098	1990	2004
246627	Mill Hill Cemetery	5231	1917	1961	2004
10287946	Mitcham, London Road Cemetery	5278	1701	1965	2004
287909	Morden Hall	5261	1685	1960	1976
238777	Moreton	5533	2068	1991	2004
9000374	Mortimer Lc	4668	1642	1990	2004
237740	Nag'S Head Lane	5565	1914	1989	2004
10247344	Northolt	5099	1845	1947	2006
10271975	Odiham	4737	1494	1980	2006
9000373	Ogbourne Works Lc	4191	1763	1993	2004
10256230	Osney Lock	4504	2058	1986	2004
10256225	Oxford	4509	2072	1980	2000
247570	Perry Oaks	5060	1759	1989	2002
247281	Pinner Cemetery	5130	1893	1992	2004
10287722	Purley, Oaks Depot	5321	1623	1965	2004
10287283	Putney Heath Resr	5234	1737	1967	2004
10277407	Radlett, Blackbird S Wks	5148	2002	1984	2004
10248966	Rapsgate Resr	3996	2104	1985	2004
239320	Ray Park Nur.	5417	1923	1994	2004
287203	Raynes Park P Sta	5237	1695	1961	1976
10276541	Rothamsted	5132	2133	1952	2005
279502	Ruislip, Manor Farm Bowling Green	5090	1876	1958	1990
240201	Runley Wood Ps	5064	2217	1989	2004
244027	Rye Meads	5394	2105	1990	2004
248332	Shorncote R09	4034	1971	1990	2004
10271418	South Farnborough	4857	1541	1922	2006
245117	Southgate	5299	1952	1971	1987
10246262	St James Park	5298	1801	1973	2006
260221	Stanford R02	4343	1929	1992	2004
238944	Stanford Rivers	5546	1999	1991	2004
246719	Stanmore, Uxbridge Road	5155	1921	1942	1971
10243350	Stansted	5531	2226	1957	1996
10243131	Stansted Mountfitchet, S Wks	5504	2243	1985	2004
249744	Swindon R25	4132	1855	1989	2004
243543	Takeley	5548	2210	1991	2004
238605	Thornwood	5476	2048	1989	2004

Gauge number	Site name	East	North	First year	Last year
259480	Upper Heyford Met Office	4513	2263	1928	1943
245281	Walthamstow, Lowhall Farm Depot	5363	1881	1971	1981
239374	Wanstead P.S.-Redbr.	5415	1882	1992	2004
9000371	Wantage Lc	4403	1915	1995	2004
242534	Warebroadmeads	5353	2140	1995	2004
241243	Weston Stw	5276	2296	1991	2004
240350	Wheathampstead Sw	5181	2142	1991	2004
263541	Wheatley R22	4608	2052	1992	2004
240816	Whitwell Stw	5194	2209	1990	2004
242819	Widford Stw	5417	2164	1990	2004
9000369	Witney Stw Lc	4348	2084	1993	2004
247449	Wood End Nurseries	5094	1813	1929	1973
253861	Worsham R29	4301	2105	1985	2004
265415	Yattendon	4558	1743	1997	2004

Table A.4 Southern England

Gauge number	Site name	East	North	First year	Last year
328520	Andover Tbr	4368	1467	1989	2004
9000423	Bewl Bridge Res Tbr	5674	1334	1991	2004
324739	Bishops Sutton Tbr	4605	1320	1988	2004
323863	Bishops Waltham Tbr	4545	1169	1988	2004
9000431	Bough Beech Res Tbr	5490	1437	1991	2004
332380	Brockenhurst Tbr	4310	1028	1988	2004
9000338	Burnt Oak Tbr	5509	1269	1991	2004
334267	Calbourne Tbr	4425	859	1988	2002
331445	Calshot	4489	1025	1920	1958
302770	Canterbury S Wks	6169	1597	1962	1973
333011	Chale Tbr	4490	806	1989	2002
9000350	Chichester Tbr	4878	1050	1991	2004
9000627	Chiddingfold Tbr	4968	1366	1988	2002
9000328	Cornish Farm Ww Tbr	5575	968	1990	2004
19000426	Cowden Stw Tbr	5466	1403	1991	2004
334510	Cowes Tbr	4491	952	1988	2004
9000340	Cowfold Tbr	5215	1220	1989	2004
322341	Cowplain, Greenfield Crescent	4691	1114	1987	2004
9000414	Coxheath Stw Tbr	5750	1521	1991	2004
10290007	Cross Ness S Wks	5486	1805	1966	2004
9000412	Cuxton Ps Tbr	5689	1669	1993	2004
291467	Danson Park	5468	1754	1990	2004
9000407	Dartford Stw Tbr	5553	1766	1991	2004
9000329	Deep Dean Tbr	5537	1022	1992	2004
332709	Efford Tbr	4301	940	1989	2003
10290578	Eynsford P.S.	5535	1655	1990	2004
9000437	Felbridge Stw Tbr	5362	1412	1993	2004
9000410	Grain Eacompound Tbr	5888	1770	1994	2004
9000411	Ham Hill Stw Tbr	5707	1610	1991	2003
9000344	Hardham Ps 2 Tbr	5033	1177	1991	2004
9000425	Hartfield Stw Tbr	5482	1361	1994	2004
10309038	Hastings	5810	1094	1979	2004
9000323	Hastings Beauport Ww Tbr	5790	1132	1995	2004
9000635	Hastings Newgate Tbr	5806	1102	1995	2005
9000324	Hazards Green Tbr	5681	1122	1995	2004
9000420	Headcorn Stw Tbr	5818	1443	1991	2004

Gauge number	Site name	East	North	First year	Last year
10309902	Herstmonceux	5645	1099	1981	1992
10309753	Herstmonceux, West End	5630	1127	1993	2006
297708	Hockers Lane Ps Tbr	5790	1574	1993	2004
299665	Hollingbourne Tbr	5844	1552	1991	2004
9000327	Horseye Tbr	5627	1083	1996	2004
9000629	Horsham Stw Tbr	5149	1296	1989	2004
9000421	Horsmonden Stw Tbr	5721	1406	1991	2004
9000433	Kent Hatch Res Tbr	5436	1515	1993	2004
291211	Keston	5422	1636	1989	2002
333747	Knighton Tbr	4566	871	1997	2004
294452	Leigh Tbr	5563	1464	1993	2004
9000436	Limpsfield&Oxted Tbr	5398	1501	1991	2004
301621	Lympne Airport	6112	1355	1921	1954
10301095	Manston	6324	1661	1936	2006
10329462	Middle Wallop	4302	1390	1994	2006
9000345	Midhurst Tbr	4918	1211	1990	2004
9000333	Newhaven	5453	1007	1988	1996
9000409	Northfleet Stw Tbr	5619	1735	1991	2004
9000628	Ockley Tbr	5151	1401	1989	2005
10291241	Orpington P Sta	5459	1652	1963	2004
326675	Overton Tbr	4519	1507	1989	2004
9000422	Paddock Wood Stw Tbr	5678	1453	1991	2004
10323139	Peel Common Tbr	4566	1034	1988	2004
9000326	Pevensey Bay Tbr	5661	1043	1991	2004
10307815	Playden Scots Float	5933	1226	1963	1984
322485	Portsea: Eastney	4684	993	1950	1970
10322487	Portsea: Eastney P Sta	4675	992	1987	2004
326115	Portswood Tbr	4434	1146	1988	2004
9000347	Princes Marsh Tbr	4772	1270	1991	2004
9000429	Redgate Mill Tbr	5552	1320	1991	2004
306679	Robertsbridge Tbr	5728	1235	1994	2004
330252	Romsey Tbr	4357	1216	1988	2004
307132	Sandhurst Stw Tbr	5808	1290	1992	2004
290320	Sevenoaks Ps Tbr	5532	1571	1991	2004
326214	Southampton	4420	1115	1993	2000
9000441	Stelling Minnis Tbr	6143	1474	1995	2004
290200	Sundridge Ps	5489	1556	1990	2004
10320198	Tangmere	4911	1064	1947	1957
330973	Testwood Tbr	4354	1150	1989	2004
10321374	Thorney Island	4760	1022	1958	2006
9000428	Tunbridge Wells Tbr	5585	1395	1991	2004
9000335	Uckfield Auto	5464	1205	1988	1996
9000331	Vines Cross Ww Tbr	5595	1170	1995	2004
9000348	Walderton Tbr	4786	1103	1991	2004
9000417	Wateringbury Stw Tbr	5693	1532	1991	2004
9000439	Weir Wood Res Tbr	5407	1354	1991	2004
298019	West Malling	5677	1553	1947	1968
9000408	Westerham Ps Tbr	5429	1558	1993	2004
9000413	Whitewall Creek Tbr	5751	1702	1993	2004
322933	Worlds End Tbr	4629	1118	1989	2004

Table A.5 South-west England

Gauge number	Site name	East	North	First year	Last year
417635	Barrow Gurney Auto	3537	1679	1992	2004
10336376	Boscombe Down	4173	1403	1931	2001
9000542	Bowerhill Stw	3903	1623	1992	2003
413900	Bradford On Avon Stw	3815	1603	1992	2004
10418362	Bristol Weather Centre	3584	1728	1990	2001
404581	Brymore School Log	3244	1394	1993	2004
10382430	Camborne	1627	407	1980	2006
376660	Cardinham Bodmin	2110	703	1992	2006
9000530	Castleton	3646	1169	1995	2002
417081	Chew Magna Ps Auto	3565	1631	1992	2004
10395162	Chivenor	2496	1344	1950	2006
10380837	Culdrose	1671	256	1981	2006
406210	Darshills Wks Logger	3600	1440	1990	2000
414608	Downhead Resr Auto	3686	1457	1992	2004
10358326	Dunkeswell Aerodrome	3128	1075	1992	2006
416798	East Harptree Auto	3579	1536	1992	2004
412867	Easterton	4026	1545	1992	2004
348093	Evershot Tbr	3578	1043	1997	2004
10355363	Exeter	3001	933	1947	1990
9000544	F. Cotterell Mill Ln	3666	1822	1992	2003
379758	Falmouth	1802	325	1886	1947
10418120	Filton	3601	1805	1937	2006
9000549	Frome Stw	3773	1487	1992	2002
402746	Fulwood Wks Auto	3211	1197	1995	2004
405278	Gold Corner Logger	3367	1430	1990	2004
9000540	Gt Somerford Stw	3965	1832	1992	2003
9000538	Hardenhuish Reserv'R	3912	1750	1992	2003
358235	Hemyock (Tbr)	3138	1128	1994	2004
10346474	Hurn	4116	978	1954	2006
9000539	Keynsham Stw	3663	1687	1992	2004
10336402	Larkhill	4137	1447	1961	2006
356452	Liscombe	2874	1332	1993	2006
10396384	Lundy: Stoneycroft	2133	1443	1980	1989
10411686	Lyneham	4006	1783	1947	2001
412023	Lyneham Met Office	4012	1786	1951	1970
402074	Maundown	3065	1291	1967	2002
405434	North Brewham	3721	1370	1995	2004
10403219	Northmoor P Sta	3332	1330	1946	2003
9000545	Parkfield Stw	3689	1777	1992	2004
415472	Paulton Stw Auto	3655	1575	1992	2004
9000527	Penridge	3753	1318	1995	2002
10368484	Plymouth, Mountbatten	2492	527	1922	2006
397104	Porlock	2892	1460	1995	2003
339816	Porton	4210	1366	1954	1979
9000536	Priddy	3552	1505	1995	2002
10363474	Princetown, Prison	2583	740	1942	1999
403538	Rivers House	3301	1377	1995	2004
381599	Scilly: St Marys Airport	917	105	1993	2005
9000535	Shapwick Heath	3423	1411	1994	2004
9000533	Somerton	3484	1297	1995	2002
9000537	St Georges	3377	1630	1995	2003
10383477	St Mawgan	1872	642	1951	2006
414416	Stoke Bottom P S Aut	3657	1481	1992	2004
400409	Sutton Bingham	3556	1116	1996	2004
9000547	Tetbury Stw	3894	1927	1992	2003
397782	Treborough Auto	3016	1361	1995	2004

Gauge number	Site name	East	North	First year	Last year
9000548	Upton Scudamore P.S.	3863	1483	1992	2003
9000528	West Dunkery	2874	1417	1994	2004
397159	Wilmersham Farm	2874	1437	1995	2003
411276	Wootten Bassett Stw	4072	1813	1992	2004
10401004	Yeovilton	3550	1232	1981	2000

Table A.6 Wales and the Midlands

Gauge number	Site name	East	North	First year	Last year
489902	Aberdare Filters Logger	2998	2021	1991	2004
529316	Aberdaron	2153	3248	1994	2006
523654	Aberdyfi Log	2605	2960	1995	2004
10522987	Aberllefni Cymau Log	2776	3106	1995	2004
9000401	Abernant Telem	2892	2460	1991	2003
10517546	Aberporth	2241	2521	1946	2002
517573	Aberporth Stw	2266	2513	1996	2004
102367	Ashbourne, St Oswald'S Hospital Auto.Sta.	4173	3465	1985	1995
10109084	Ashover No 2	4349	3629	1970	2004
10099321	Atherstone S. Wks. Auto Sta.+Tg1150	4318	2980	1967	2004
10429082	Bagley	3413	3277	1983	2004
10107268	Barbrook	4281	3770	1982	2004
10091267	Barnhurst W Wks	3901	3017	1979	2004
533913	Bethesda Log	2619	3654	1995	2004
10441009	Bettws-Y-Crwyn	3203	2814	1982	2004
530240	Betws Garmon Log	2537	3572	1996	2004
535817	Betws-Y-Coed Log	2802	3570	1995	2004
9000204	Bishops Castle	3338	2873	1991	2004
10093536	Blithfield Resr	4071	3226	1975	2004
521053	Bontgoch Log	2683	2861	1995	2004
529039	Botwnnog Log	2262	3313	1995	2004
19000167	Braunston	4533	2658	1982	2004
10511956	Brawdy	1851	2248	1974	1992
483040	Brecon Wtw Logger	3037	2276	1993	2004
10475212	Bredenbury Telemetry	3609	2565	1991	2003
9000217	Brimfield	3503	2682	1987	1996
10113774	Brooksby Hall No 2	4679	3154	1981	2004
471317	Broomy Hill Logger	3496	2395	1994	2004
538482	Brynhyfryd Log	3133	3584	1995	2004
10468345	Builth Wells, Cefndyrys	3038	2530	1981	1995
9000215	Caersws	3040	2925	1985	2000
9000391	Caio	2674	2396	1994	2004
9000393	Canaston Bridge	2065	2148	1992	2004
535672	Capel Curig No 3	2701	3570	1994	2006
490900	Cardiff Weather Centre	3182	1761	1992	2005
19000249	Carsington Dam	4242	3503	1987	2004
19000246	Cauldon Low	4058	3480	1985	2004
10423198	Cefn Coch P.Sta. Auto.Sta.	3042	3026	1983	2004
544878	Cefn Mawr Log	3274	3422	1995	2004
531386	Cefni Log	2444	3771	1995	2004
9000171	Chapel Res	4068	3794	1985	2004
548682	Chester Log	3419	3666	1995	2004
10453096	Chipping Campden, W Wks	4164	2393	1981	2004
10448620	Church Lawford	4456	2736	1991	2006
548546	Churton Log	3418	3564	1995	2004

Gauge number	Site name	East	North	First year	Last year
10101151	Claymills W Wks	4265	3259	1983	2004
96514	Coleshill	4211	2870	1998	2006
19000184	Colwick	4613	3393	1986	2004
536843	Colwyn Bay Log	2858	3784	1995	2004
10435507	Cosford W Wks No 3	3782	3047	1983	2004
10443093	Craven Arms S Wks	3437	2811	1980	2004
419923	Cromhall Sw Auto	3685	1893	1992	2004
479238	Cross Ash Logger	3406	2198	1992	2003
10457597	Crowle W.Recl.Wks Auto.Sta.	3934	2558	1981	2004
10527222	Cwm Dyli Log	2653	3541	1997	2004
520455	Cwm Rheidol	2708	2792	1996	2004
487078	Cwmtillery Telemetry	3220	2068	1997	2004
527998	Cwmystradllyn Log	2556	3441	1995	2004
525468	Cynnwch Log	2735	3203	1995	2004
511628	Dale	1823	2051	1994	2004
457944	Defford Met Office	3899	2422	1949	1968
539242	Denbigh Stw Log	3070	3664	1996	2004
10108786	Derwent Divn.	4228	3553	1982	2004
9000168	Derwent Res	4174	3899	1986	2004
10444887	Ditton Priors No.2 Auto.Sta.	3604	2882	1979	2004
10421140	Dolydd	2873	2905	1980	2004
9000157	Dowdeswell	3987	2196	1979	2004
10096892	Elmdon	4176	2839	1949	1998
9000212	Ercall	3665	3233	1985	2004
485217	Estarvarney Farm Logger M	3353	2032	1994	2004
9000378	Fforch Dwm	2820	1972	1994	2004
10449958	Finham W Wks	4334	2740	1983	2004
125843	Finningley	4658	3995	1951	1970
10125842	Finningley	4659	3989	1951	1994
546191	Five Fords	3361	3480	1995	2004
19000181	Fleckney	4657	2945	1986	2004
19000227	Frankley	4007	2801	1986	2004
10520624	Frongoch	2605	2825	1966	2004
10499582	Gorslas Resr	2563	2147	1981	2004
10446802	Great Malvern	3791	2470	1985	2004
527409	Hafod Wydr Log	2575	3498	1996	2004
10438925	Hartlebury Auto.Sta.	3846	2698	1979	2004
10549025	Hawarden Airport	3341	3646	1947	2003
19000151	Henley-In-Arden	4154	2679	1981	2004
9000397	Highmead	2501	2433	1994	2004
10098210	Hinckley S Wks	4420	2927	1963	2004
10091860	Hollies P Sta	3816	3224	1982	2004
10101204	Hollinsclough Auto Sta.	4066	3665	1986	2004
9000390	Johnstown	2402	2191	1993	2004
10089542	Keele	3820	3447	1952	1999
10095646	Kingstanding, Perry Barr Resr	4084	2952	1986	1995
10419869	Kingswood S Wks	3743	1929	1979	2004
19000173	Kirk Langley	4293	3392	1981	1993
10450777	Knightcote Farm	4398	2545	1979	2004
10425001	Lake Vyrnwy	3017	3188	1985	2004
425000	Lake Vyrnwy No 2	3012	3187	1995	2006
19000188	Langar	4733	3339	1990	2004
9000150	Langley	4002	2281	1983	2004
9000244	Lea Marston	4208	2937	1994	2004
10459794	Ledbury W Wks	3702	2371	1981	2004
473152	Leominster Logger	3503	2580	1991	2003
545178	Llanarmon Dc Log	3155	3326	1997	2003
541338	Llanasa Log	3124	3832	1997	2004

Gauge number	Site name	East	North	First year	Last year
465928	Llanbadarn Logger	3098	2778	1991	2004
10522340	Llanbrynmair Log	2919	3068	1995	2004
467004	Llandrindod Logger	3049	2605	1995	2002
499324	Llanelli Filters	2516	2024	1940	1970
467282	Llanerch-Yrfa Logger	2835	2555	1992	2004
10426593	Llanfyllin W Wks	3154	3188	1980	2004
464225	Llangurig Logger	2907	2797	1993	2004
10426853	Llangynog W Wks	3053	3259	1982	2004
9000394	Llanychaer	1985	2355	1993	2004
521490	Llanymawddwy Log	2888	3170	1995	2004
489093	Llwynon Logger	3011	2112	1991	2004
532551	Llyn Alaw Log	2376	3852	1995	2004
495038	Llyn Fawr Logger	2919	2035	1991	2005
547251	Loggerheads Log	3200	3621	1995	2004
10459426	Longford W.Recl.Wks Auto.Sta.	3847	2209	1980	2004
10478535	Lower Maes-Coed	3348	2308	1982	2004
10454433	Lye Bridge W Wks	4032	2717	1981	2004
10437694	Lye W Wks	3919	2849	1982	2004
473822	Lyonshall	3335	2577	1980	1994
492902	Maesteg Park	2847	1913	1950	1964
10446964	Malvern Met Office	3787	2447	1977	1985
9000379	Margam Park	2809	1854	1992	2004
9000176	Meynell Langley	4284	3402	1995	2004
10453925	Milcote W Wks	4182	2528	1979	2004
511466	Milford Haven Conserv.Bd	1891	2055	1996	2006
526536	Minafon Logger	2716	3432	1995	2004
10095802	Minworth S Wks	4164	2922	1976	1992
10461468	Miserden	3937	2087	1982	2004
10547371	Moel-Y-Crio	3193	3698	1982	2004
9000398	Morfa Fawr	2501	2658	1994	2004
10115296	Mount St Bernard Abbey	4459	3158	1986	2004
10497262	Mumbles Head	2627	1871	1990	2006
9000202	Nantgwyn	2979	2768	1989	2004
500543	Nantymaen	2761	2584	1991	2004
490109	Nant-Yr-Ysfa Logger	3034	1963	1991	2005
10111398	Narborough S Wks	4549	2966	1971	1997
549619	Ness Log	3302	3754	1995	2004
473260	Newchurch Logger	3217	2508	1991	2004
541672	Northop Log	3249	3686	1997	2004
10096110	Norton Green S Wks	4185	2749	1984	1993
10117626	Nottingham Watnall	4503	3456	1948	2006
10443216	Oakly Park	3491	2762	1980	1990
10109141	Ogston Resr	4380	3598	1964	2004
508284	Orielton	1953	1991	1994	2004
10100449	Overseal S Wks	4291	3149	1974	2004
499552	Pembrey Sands	2365	2044	1994	2006
508580	Pembroke Dock Met Office	1952	2033	1948	1956
9000386	Penclacwydd	2532	1985	1995	2004
493274	Pencoed	2967	1819	1994	2004
10497412	Penmaen	2531	1888	1980	2004
10425646	Pen-Y-Coed Auto.Sta.	2978	3144	1982	2004
10457096	Pershore	3973	2500	1958	2006
540361	Plas Pigot Log	2951	3646	1995	2003
10489274	Pontsticill Upper Wtw Log	3058	2118	1937	1999
9000216	Prees	3573	3351	1988	2004
519358	Pwllpeiran	2772	2749	1991	2004
495247	Resolven	2824	2026	1993	2004
10464675	Rhayader S Wks	2979	2674	1980	2004

Gauge number	Site name	East	North	First year	Last year
490848	Rhiwbina Resr Logger	3149	1824	1997	2005
526213	Rhiwgoch Log	2592	3304	1995	2004
10491860	Rhoose	3066	1677	1954	1997
505084	Rhydargaeau	2446	2260	1992	2004
10525371	Rhydymain Log	2797	3238	1995	2004
541029	Rhyl No 2	2994	3747	1992	2006
19000219	Rodbaston	3920	3116	1986	2004
9000203	Rorrington	3304	3005	1987	2004
19000237	Roway Lane	3986	2902	1982	1993
10448545	Rugby	4507	2749	1980	1995
10432811	Rushmoor S Wks	3617	3135	1985	2004
10423601	Sarn S.Wks Auto.Sta.	3206	2906	1981	2004
516043	Saron	2374	2376	1993	2004
493601	Schwyll P.S.	2885	1769	1992	2004
549210	Sealand Met Office	3332	3701	1926	1957
467642	Sennybridge No 2	2894	2418	1996	2006
10433709	Shawbury	3553	3221	1951	2006
115324	Shepshed	4483	3207	1997	2005
10453420	Shipston On Stour, W Wks	4268	2411	1980	2004
472771	Shobdon Airfield	3396	2609	1993	2005
10430296	Shrewsbury, Monkmoor S Wks	3517	3136	1985	2004
10096006	Solihull, Tudor Grange Farm	4147	2789	1987	2004
19000174	Spondon	4395	3345	1986	2001
492140	St Athan	2999	1684	1998	2006
506927	St Clears	2282	2178	1993	2004
512277	St Davids	1742	2245	1994	2004
507964	St Florence	2085	2009	1995	2004
10508167	St Twynnells	1955	1969	1980	1989
540677	St. Asaph Log	3033	3751	1997	2004
10447787	Stanford Resr	4596	2804	1964	2004
10103072	Stanley Resr	3929	3519	1981	2004
10090803	Stone No 2	3878	3321	1964	2004
10122707	Sutton-In-Ashfield S Wks	4510	3595	1986	2004
10438110	The Bratch W Wks	3868	2937	1987	2004
9000175	Tideswell	4154	3745	1981	2004
19000621	Titley Mill Telem	3328	2584	1993	2002
501683	Tonn	2765	2352	1993	2004
519579	Trawsgoed	2674	2736	1992	2006
9000384	Trebanos	2712	2023	1995	2004
470081	Tregoyd Logger	3195	2378	1995	2004
10437138	Trimpley W Wks	3772	2789	1985	2004
542518	Tryweryn Dam Logger	2881	3399	1997	2004
497880	Upper Lliw	2662	2058	1994	2004
10532207	Valley	2309	3758	1924	2001
497135	Victoria Park	2642	1922	1993	2004
19000238	Walsall Wood	4038	3042	1977	2004
9000180	Wanlip	4597	3114	1986	2004
19000229	Warley Park	4010	2861	1965	1988
9000161	Wellesbourne	4271	2565	1982	2004
10424216	Welshpool S Wks	3233	3073	1980	2004
9000182	Whissendine	4834	3146	1986	2004
10094320	Willenhall S Wks No 2	3979	2983	1963	2004
10095458	Winterbourne Uni.Birmin'M	4052	2841	1989	2006
9000395	Wolfscastle	1958	2266	1994	2004
19000187	Worksopmanton	4608	3791	1983	2004
475752	Yarkhill Logger	3596	2431	1993	2004
534547	Ysbyty Ifan Log	2810	3455	1995	2004
19000377	Ystradfellte Telem.	2940	2144	1993	2004

Gauge number	Site name	East	North	First year	Last year
9000389	Ystradffin	2787	2471	1993	2004
496431	Ystradgynlais	2774	2087	1995	2003

Table A.7 North-west England

Gauge number	Site name	East	North	First year	Last year
577794	Abbeystead Gdns Log	3567	4547	1991	2004
577805	Abbeystead Tel Log	3556	4539	1994	2004
596026	Abbeytown K'Side Log	3158	5514	1993	2004
575108	Accrington, Oak Hill Park	3764	4277	1951	1970
10567423	Aigburth (Rtc)	3384	3852	1968	1991
10559025	Arnfield Reservoir Log	4012	3972	1951	1995
10595739	Aspatria	3154	5423	1982	2003
10568454	Aughton	3394	4063	1980	1995
578009	Barnacre Reservoir	3528	4481	1996	2004
598145	Barras Tel Log	3845	5121	1995	2004
584917	Beetham Hall Log	3499	4790	1993	2004
10577267	Blackpool, Squires Gate	3317	4316	1949	2004
598691	Brackenber Log	3722	5195	1991	2004
586898	Brathay Hall Tel	3366	5032	1990	2004
601304	Burnbanks Tel Log	3507	5159	1993	2004
574488	Buttock Log	3807	4401	1990	2004
605543	Calebreck Hall Log	3345	5361	1993	2004
10606335	Carlisle	3383	5603	1961	2006
604142	Castle Carrock Tel	3546	5551	1994	2004
574006	Chipping Log	3614	4441	1991	2004
551717	Cholmondeley	3552	3505	1945	1996
575332	Churn Clough Reservoir Lo	3785	4382	1990	2004
582837	Clapham Turnerford Log	3722	4661	1992	2004
576925	Clifton Marsh Auto	3454	4282	1997	2004
603111	Coalburn Whitehill Log	3694	5778	1993	2004
574718	Colne Swinden Log	3871	4394	1991	2004
570788	Common Bank Log	3568	4176	1991	2004
10594201	Cornhow S Wks	3150	5222	1980	2005
573427	Croasdale House Log	3704	4550	1990	2000
567734	Crosby	3299	4006	1997	2006
602749	Cumwhinton Log	3462	5528	1993	2004
10592850	Dale Head Hall	3313	5175	1997	2004
10577882	Damas Ghyll Log	3575	5537	1994	2004
575935	Darwen Sunnyhurst	3679	4221	1994	2004
595611	Dearham Log	3081	5365	1993	2004
606680	Drumbergh Log	3259	5602	1994	2004
10565548	Dunham Massey Log	3726	3875	1948	1996
586871	Elterwater Tel Log	3329	5039	1995	2004
591642	Ennerdale Twks Tel	3084	5154	1996	2004
10590602	Eskmeals	3085	4931	1978	2000
571479	Far Gearstones	3783	4801	1994	2004
584772	Fisher Tarn Reservoir Log	3549	4927	1992	2004
577417	Fleetwood Auto	3330	4462	1997	2004
10568596	Formby Hightown Log	3295	4045	1951	2004
575384	Great Harwood Log	3722	4327	1990	2004
566652	Great Sankey	3552	3889	1953	1970
560854	Greenfold Resr No 1	3823	4261	1951	1970
10593038	Groove Beck	3375	5223	1980	2000

Gauge number	Site name	East	North	First year	Last year
576578	Haighton Reservoir Log	3574	4352	1990	2004
602253	Haresceugh Ctle Log	3610	5428	1993	2004
586493	High Newton Reservoir Log	3399	4838	1992	2004
593415	High Snab Farm Log	3222	5190	1991	2004
10560942	Holden Wood Resr No 2	3767	4226	1982	1995
10592466	Honister Pass	3225	5135	1982	2004
585022	Kentmere H'Bank Tel	3466	5054	1995	2004
593331	Keswick	3254	5249	1992	2006
10558490	Kinder Filters Tel	4054	3880	1942	1996
600023	Kirkbythore Log	3644	5267	1993	2004
589777	Lanthwaite Log	3166	4851	1991	2004
10586056	Levens, Bridge End	3474	4858	1952	2004
567866	Liverpool N. Stw Log	3394	3963	1991	2004
575663	Longridge Spade Log	3620	4372	1990	2004
569709	Lower Rivington	3631	4126	1996	2004
593023	Mungrisedale Log	3360	5278	1993	2004
574767	Nelson (Lancs)	3872	4384	1953	1996
604742	Newton Rigg Log	3493	5310	1992	2004
601742	Nunwick Hall Log	3554	5360	1993	2004
580058	Orton S'Ford Log	3626	5083	1991	2004
587873	Oxen Park Log	3317	4873	1993	2004
588886	Palace Nook Tel	3191	4718	1990	2004
584098	Pedder Potts No 2 Log	3535	4705	1994	2004
575975	Pickup Bank Log	3721	4237	1990	2004
10564769	Prestbury S.Wks Tel	3897	3782	1950	1995
10576634	Preston Moor Park	3537	4311	1960	2004
576478	Preston Borough Town Hall	3541	4295	1996	2005
595273	Quarry Hill F. Log	3219	5412	1993	2004
10564419	Ringway	3814	3844	1942	2004
10608160	Ronaldsway	2279	4687	1980	2004
10560557	Sale C'Ton Ln Log	3764	3927	1950	1995
598929	Scalebeck Tel Log	3673	5144	1995	2004
10592448	Seathwaite	3235	5121	1980	2004
589294	Seathwaite Log	3249	4984	1994	2004
581026	Sedbergh F'Field Log	3677	4918	1991	2004
600988	Shap	3557	5120	1993	2006
596013	Silloth	3125	5537	1949	1960
605936	Skelton Tel	3436	5361	1990	2004
603649	Spadeadam	3599	5720	1960	1970
603171	Spadeadam No 2	3647	5730	1994	2006
10567345	Speke	3437	3820	1954	1976
10592199	St Bees Head	2941	5143	1976	1986
592207	St Bees Head No 2	2955	5148	1992	2006
592860	St Johns Beck Tel	3313	5195	1995	2004
571894	Stainforth Log	3822	4675	1990	2004
573342	Stocks Reservoir Tel Log	3717	4548	1994	2004
591878	Summergrove Tel	2999	5160	1994	2004
10593893	Sunderland S Wks	3179	5351	1980	2004
592765	Thirlmere Nook Log	3319	5129	1992	2004
596791	Thursby Wwtw Log	3317	5504	1993	2004
564572	Trentabank Resr	3962	3712	1946	1996
589359	Ulpha Duddon Tel Log	3209	4947	1991	2004
588705	Ulverston P.F. Log	3241	4778	1991	2004
588848	Walney Island	3179	4706	1992	2006
603742	Walton H.F. Log	3530	5653	1993	2004
598678	Warcop Range	3734	5198	1992	2006
590691	Wastwater Hotel Log	3187	5087	1995	2004
582970	Wennington Clint Log	3627	4698	1991	2004

Gauge number	Site name	East	North	First year	Last year
603315	Wileysike Gland Tel	3645	5705	1992	2004
10553563	Worleston S Wks	3665	3574	1976	1995

Table A.8 Scotland

Gauge number	Site name	East	North	First year	Last year
10660285	Abbotsinch	2480	6667	1936	1998
10849814	Aberdeen Mannofield Resr	3916	8042	1972	1998
841720	Aberdeen Observatory	3939	8081	1886	1937
845988	Aboyne No 2	3491	7986	1991	2005
794467	Affric Lodge Tbr	2188	8231	1995	2004
838465	Alford	3566	8169	1996	2004
888888	Allanfearn Tbr	2711	8474	1996	2004
749151	Allnabad Tbr	2453	9428	1993	2004
751649	Altnaharra No 2	2569	9358	1993	2005
674671	Amod Farm Tbr	1643	6125	1995	2004
890120	Auchentroig (Buchlyvie)	2544	6935	1991	2003
880276	Auchinner Logger	2694	7158	1992	2004
738538	Aultbea No 2	1846	8913	1991	2005
10817692	Aviemore	2897	8143	1983	2000
10906423	Baddinsgill Resr	3126	6554	1982	1995
886704	Balado	3083	7025	1990	2005
10759235	Baltasound No 2	4625	12078	1991	2006
738179	Barra (W.I)	695	8059	1998	2005
897399	Bathgate	2961	6703	1988	1998
691880	Ben Nevis Observatory	2167	7712	1885	1904
10736633	Benbecula Airport	782	8555	1954	1995
778575	Benmore Lodge No 2	2324	9121	1986	2002
10627059	Black Laggan	2469	5777	1983	2004
617716	Boreland Tbr	3160	5906	1994	2004
893702	Braco (Dunduff)	2821	7115	1992	2004
696147	Braeroy Lodge Tbr	2336	7915	1994	2004
612371	Braidlie Tbr	3477	5967	1992	2004
632945	Brigton Tbr	2361	5744	1997	2004
613467	C.A.D.Longtown Log	3363	5682	1993	2004
622646	Capenoch Tbr	2845	5940	1990	2004
10652673	Carnwath	2974	6464	1981	1995
613211	Catlowdy Log	3459	5767	1993	2004
848008	Charr	3615	7830	1991	2004
918848	Charterhall	3759	6462	1992	2005
680407	Clachan-Seil	1773	7182	1996	2004
889958	Clashmore	2464	6966	1990	1999
10808493	Coignafearn	2710	8178	1986	2004
798787	Coille Mhorgil Tbr	2100	8014	1995	2004
9000115	Colliston	3610	7466	1995	2004
10779232	Corriemulzie	2329	8955	1987	2004
804128	Corrimony Tbr	2375	8303	1995	2004
623550	Craigdarroch Tbr	2739	5909	1989	2004
613905	Crewe Fell F.H. Tel	3558	5774	1993	2004
9000111	Crichton	3380	6616	1994	2004
626421	Dalbeattie Wwtw Tbr	2833	5600	1996	2004
10805708	Dalcross	2767	8521	1980	1993
9000104	Dalinlongart Tip Site	2138	6813	1993	2001
868260	Dalnamein	2747	7694	1992	2004

Gauge number	Site name	East	North	First year	Last year
752677	Dalvina Tbr	2696	9439	1991	2004
822582	Delnashaugh	3184	8352	1996	2004
10788069	Dingwall	2538	8593	1986	2004
9000105	Dippen	1797	6376	1996	2004
788593	Dosmucheran Tbr	2204	8602	1993	2004
653522	Drumalbin	2908	6384	1992	2006
9000120	Duchray Castle	2467	6987	1992	2004
10903797	Dunbar	3672	6791	1969	2002
10626887	Dundrennan	2710	5472	1991	2006
896458	Dunnswood Wwtw (Cumbernauld)	2781	6772	1992	2005
10683629	Dunstaffnage	1881	7340	1980	2006
10841490	Dyce	3878	8128	1946	1997
10660629	East Kilbride No 2	2638	6535	1986	2004
10899979	Edinburgh Rbg No 2	3244	6755	1980	2004
10621336	Eliock	2797	6074	1982	2004
10610122	Eskdalemuir	3235	6026	1910	2006
835635	Esslemont House	3933	8305	1991	2004
10900175	Fairmilehead	3249	6684	1986	2004
10870623	Faskally	2918	7599	1981	1995
9000121	Fife Airport	3243	6995	1992	2005
806169	Flichity Tbr	2663	8289	1994	2004
10754402	Forsinain	2906	9485	1986	2004
691870	Fort William No 2	2097	7734	1891	1904
616575	Fourmerkland Tbr	3101	5865	1997	2004
809284	Freeburn Tbr	2795	8300	1994	2004
622001	Gatelawbridge Tbr	2900	5965	1989	2004
855111	Gella Bridge Logger	3372	7652	1992	2004
900931	Gladhouse Res.	3299	6544	1992	2003
692138	Glen Nevis Tbr	2127	7717	1994	2004
692783	Glendessary Tbr	1967	7926	1990	2004
921083	Goldscleugh Auto	3914	6233	1994	2004
627084	Green Burn	2475	5778	1995	2004
10913046	Greycrook	3599	6305	1980	1998
10903329	Haddington	3532	6744	1983	2004
899578	Harperrig	3102	6612	1989	2003
801845	Inchmore Hatchery Tbr	2301	8125	1994	2004
796683	Inchvuilt Tbr	2224	8391	1996	2004
851405	Inverbervie No 2	3839	7734	1992	2005
842880	Inverey	3088	7892	1993	2004
10827902	Keith	3433	8518	1982	1995
860657	Killin Monemore	2564	7321	1993	2004
10773654	Kinbrace Hatchery	2872	9284	1990	2005
875920	Kindrogan Field Cent	3054	7628	1992	2004
881658	Kinkell Bridge Logger	2933	7167	1993	2004
866800	Kinloch Rannoch Ps	2664	7588	1997	2004
10713572	Kinlochewe	2026	8629	1960	1972
10811394	Kinloss	3068	8628	1951	2006
619155	Kinmount House Tbr	3136	5693	1990	2004
634314	Kirkcowan Tbr	2326	5611	1989	2004
10767475	Kirkwall	3482	10077	1947	2006
10632473	Kirriereoch	2362	5871	1987	2004
741963	Knockanrock Tbr	2186	9088	1990	2004
636401	Lagafater Lodge Tbr	2139	5759	1996	2004
10763886	Lerwick	4454	11397	1953	1999
10885313	Leuchars	3468	7208	1936	2006
744217	Little Assynt Tbr	2147	9250	1993	2004
740862	Loch Droma Tbr	2252	8752	1990	2004
10631269	Loch Fleet Craigwhinnie	2557	5698	1986	1995

Gauge number	Site name	East	North	First year	Last year
790636	Loch Glascarnoch	2277	8742	1993	2005
9000112	Loch Katrine	2490	7066	1994	2004
10887239	Loch Leven Sluices	3171	6994	1980	1995
10892605	Loch Venachar	2598	7063	1981	1995
810605	Lochindorb Tbr	2970	8354	1990	2004
10624348	Lochrutton W Wks	2901	5743	1981	1995
777777	Longman Tbr	2666	8468	1995	2004
10811540	Lossiemouth	3212	8698	1994	2006
9000117	Lower Auchnafree Check	2819	7336	1994	2004
788397	Luib Cottage Tbr	2131	8547	1991	2004
10675177	Machrihanish	1663	6225	1965	2006
10654630	Mauldslie	2808	6502	1983	1995
620785	Meadowfoot Tbr	2861	6138	1990	2004
617960	Merton Bank Lochmaben Tbr	3083	5832	1997	2004
826902	Milton Of Noth	3506	8285	1990	2004
9000116	Moar Logger	2535	7451	1992	2004
10615449	Moffat, Hydro Gardens	3079	6063	1987	2004
850365	Mongour	3764	7901	1996	2004
795625	Mullardoch Dam No 2	2223	8310	1962	1971
10859313	Mylnefield	3339	7301	1980	1995
709378	New Kelso Tbr	1941	8428	1993	2004
10624033	Newtonairds	2889	5799	1985	2004
10646766	North Craig Resr	2438	6412	1980	2001
894300	North Third	2756	6900	1995	2005
10903638	Nunraw Abbey	3594	6700	1981	2004
660649	Picketlaw Reservoir	2568	6515	1991	2004
844465	Polhollick	3343	7965	1996	2004
702911	Polloch Tbr	1791	7688	1996	2004
897649	Polmonthill Wwtw	2953	6795	1991	2004
9000122	Portmoak	3173	7007	1992	2005
10645588	Prestwick Gannet	2369	6277	1947	2006
10659049	Renfrew	2508	6663	1946	1966
782561	Rhian Bridge Tbr	2564	9166	1996	2004
719395	Rhum: Kinloch	1402	7996	1961	1972
9000107	Ross Priory	2407	6873	1994	2004
823897	Rothes	3285	8497	1984	1994
645885	Saughall Tbr	2598	6364	1995	2004
789964	Scardroy Tbr	2217	8519	1992	2004
761156	Sella Ness	4398	11738	1993	2003
903147	Skedsbush (Gifford)	3512	6657	1989	2003
721758	Skye: Lusa	1706	8249	1998	2006
819164	Sluggan	2869	8218	1994	2004
614583	Solwaybank Tbr	3307	5774	1992	2004
635522	Sorbie Tbr	2438	5467	1997	2004
660546	South Moorhouse	2525	6512	1991	2004
737056	South Uist Range	763	8425	1997	2006
813732	Spey Dam	2582	7935	1995	2004
10894219	Stirling S Wks	2808	6935	1984	1995
10727288	Stornoway Airport	1464	9331	1954	2006
10881879	Strathallan Airfield	2932	7162	1992	2006
10753986	Strathy 2	2839	9641	1986	1999
891690	Strathyre	2560	7167	1992	2004
10891986	Stronachlachar	2401	7103	1959	1985
785356	Tain Range	2833	8827	1991	2005
890782	Thornhill	2666	6999	1992	2003
894987	Tillicoultry	2926	6970	1992	2003
10719008	Tiree	998	7449	1954	2000
811618	Torwinny	3134	8489	1989	2004

Gauge number	Site name	East	North	First year	Last year
815787	Tromie Bridge	2788	7995	1997	2004
820400	Tulchan Fish Farm	3132	8352	1992	2003
695548	Tulloch Bridge	2350	7783	1991	2003
10899407	Turnhouse	3159	6739	1948	1999
10627056	Upper Black Laggan	2476	5769	1985	2004
9000108	Waulkmill Glen	2525	6582	1991	2004
637496	West Freugh	2117	5555	1991	2006
637507	West Freugh	2109	5546	1946	1975
849197	Westhills	3824	8063	1994	2004
10770765	Wick Airport	3365	9522	1948	2006
682222	Woodglen Tbr	1827	6909	1995	2003
10920359	Wooler S Wks	3998	6291	1980	2004

Table A.9 Northern Ireland and the Republic of Ireland

Gauge number	Site name	East	North	First year	Last year
10955817	Aldergrove	3146	3810	1926	2006
10963676	Altnahinch Filters	3116	4237	1971	2004
10930761	Ardeemore	2060	3807	1982	2004
947811	Armagh	2878	3458	1886	1970
938575	Ballykelly	2624	4234	1946	1970
938585	Ballykelly	2626	4239	1947	1970
938594	Ballykelly	2634	4238	1995	2006
10965443	Ballypatrick Forest	3176	4386	1966	2006
10939064	Banagher, Caugh Hill	2663	4047	1984	1996
968133	Belfast P Sta	3352	3769	1985	1994
10953020	Broughshane Filters	3165	4090	1971	1985
996613	Castle Archdale Forest	2189	3593	1943	1970
996635	Castle Archdale Met Office	2175	3587	1943	1955
931912	Castlederg	2273	3844	1995	2006
8000001	Clones (Town)	2501	3248	1960	1971
8000074	Clones Weather Stn	2500	3263	1960	1990
10962647	Coleraine Cutts	2854	4303	1966	1981
942074	Glenanne No 2	2976	3331	1993	2006
10972770	Hare Island	3504	3495	1966	1985
10969274	Hillsborough	3251	3577	1971	1981
10969329	Hillsborough Met Office	3233	3613	1981	1999
941654	Huntly (Down) S Wks	3118	3467	1962	1971
957324	Lough Fea	2764	3865	1995	2006
10949451	Lurgan Cemetery	3073	3569	1965	1984
8000080	Malin Head	2422	4591	1961	1990
10977464	Newry S Wks	3091	3247	1965	1988
10927736	Omagh S Wks	2441	3737	1971	1986
956927	Pomeroy Forest	2705	3724	1966	1985
959970	Portglenone	2991	4030	1995	2006
995505	Portora Sluice	2222	3453	1967	1986
947599	Seagahan Filters	2897	3382	1958	1967
995614	St Angelo	2231	3497	1993	2006
10932611	Strabane, Glen Road	2353	3981	1985	1996
10959461	Toomebridge	2990	3906	1966	1985

Appendix B List of extreme events studied in detail

Event	Date	Location	NGR Eastings	NGR Northings	Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
1	25/07/1886	Methley, West Yorkshire	4380	4265	104.1	2	Convective	635	159	65	British Rainfall
2	17/07/1890	Thames Valley (Rickmansworth)	5078	1929	106.4	4	Convective	497	200	53	British Rainfall
3	24-25/08/1891	Seathwaite	3236	5122	260.1	48	Frontal/orographic	8.3	432	60	British Rainfall
4	26/06/1895	West Yorkshire (Sowerby Brdg)	4061	4234	91.7	2.5	Convective	474	170	54	British Rainfall
5	26/06/1895	Welsh Borders & Midlands	3264	2933	122.7	2	Convective	3,768	161	76	British Rainfall
6	12/11/1897	Seathwaite	3236	5122	204	24	Orographic	17	360	57	British Rainfall
7	12/07/1900	Ilkley	4120	4470	137.2	1.25	Convective	3,785	146	94	Met Mag Aug 1900 & British Rainfall
8	12/07/1901	Maidenhead	4886	1814	107.7	1	Convective	566	141	76	British Rainfall
9	30/05/1903	Croydon	5300	1650	93.2	1	Convective	831	141	66	British Rainfall
10	21/10/1908	Portland, Dorset	3696	0742	175	5	Frontal (with signif. convective component)	3,848	204	86	British Rainfall
11	09/06/1910	Reading	4597	2058	139.4 (n/s rg)	2	Convective	3,361	164	85	British Rainfall

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
12	26/08/1912	Norwich (Brundall)	6332	3084	186	22	Frontal	2,089	275	68	British Rainfall
13	25/09/1915	Inverness	2778	8482	179.3	40	Frontal	1,373	268	67	British Rainfall
14	16/06/1917	Kensington	5255	1795	118	2.3	Convective	572	195	61	Met Mag July 1917
15	28/06/1917	Bruton, Somerset	3684	1350	243	8	Frontal (with significant convective component)	11,077	238	102	British Rainfall
16	29/05/1920	Louth	5296	3881	119	3	Convective	902	179	66	British Rainfall
17	18-19/08/1924	Cannington (200) & Brymore (225)	3246	1394	225	5	Convective (with significant frontal forcing)	13,322	218	103	Weather Aug 2005, Vol 60 No 8
18	28/06/1928	Blaenau	2695	3463	197.4	24	Orographic	42	350	56	British Rainfall
19	11/11/1929	Rhondda	2975	1965	211.1	18	Orographic	406	338	62	British Rainfall & Weather Aug 2005 Vol 60 No 8
20a	22/7/1930	N Yorkshire (Castleton)	4688	5080	144.8	24	Frontal	230	310	47	British Rainfall
20b	20-23/07/1930	N. Yorkshire	4688	5080	304	60	Frontal	2,393	348	87	British Rainfall
21	08/08/1931	Boston, Lincs.	5330	3430	155	11	Frontal (with significant convective component)	997	241	64	British Rainfall

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
22	02-03/11/1931	W. Britain (Rydall)	3369	5055	226.3	36	Orographic	156	365	62	Met Mag Jan 1932 & British Rainfall
23	11/07/1932	Cranwell, Lincs	5000	3499	130.6	2	Convective	1,587	182	72	British Rainfall
24	26/09/1933	Fleet, Hampshire	4808	1507	131	4	Convective	1,139	199	66	British Rainfall
25	22/07/1934	West Wickham, Kent	5382	1654	119.4	1.66	Convective	1,134	165	72	British Rainfall
26	25/06/1935	Swainswick (Bath)	3756	1681	152	2.75	Convective (with significant frontal forcing)	4,173	190	80	British Rainfall
27	15/07/1937	(1) Boston, Lincs. (2) E Leics (Waltham on the Wolds))	(1) 5327 (2) 4799	3433 3259	(1) 138.7 (2) 146.3	12	Frontal (with significant convective component)	(1) 636 (2) 835	(1) 246 (2) 252	(1) 56 (2) 58	British Rainfall
28	04/08/1938	(1) Torquay (2) Bovey Tracey	2910 2817	0637 0784	142.5 148.8	2.25	Convective (with significant frontal forcing)	(1) 3,033 (2) 3,624	(1) 160 (2) 167	(1) 89 (2) 89	Met Mag Sept 1938 & British Rainfall
29	22/06/1941	Newcastle	4240	5640	110	2.33	Convective	2,620	149	74	British Rainfall
30	23/11/1946	Princetown	2587	0738	173.5	24	Orographic	51	390	44	British Rainfall

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
31	16/07/1947	Wisley, Surrey	5060	1597	128	1.25	Convective	1,462	151	85	British Rainfall
32	12/08/1948	SE Scotland, Tweed	3710	6347	157.7	15	Frontal	4,935	261	60	Met Mag Jan 1949
33	15/07/1949	March	5420	2967	104.6	1.75	Convective	822	154	68	British Rainfall
34	15/08/1952	Lynmouth	2708	1428	228.6	12	Frontal (with significant convective component)	1,870	328	70	Met Mag. Dec 1952 & British Rainfall; Dobbie & Wolf, The Lynmouth Flood of 1952, Proc. ICE, 3, 2, 1953
35	17-18/12/1954	Loch Quoich	1932	7994	256.5	22.5	Orographic	232	345	74	British Rainfall & Daily Weather Report
36	19/07/1955	Martinstown, Dorset	3648	0888	280	15	Frontal (with signif. convective component)	6,919	278	101	British Rainfall
37	11/06/1956	Bradford, Hewenden Res.	4072	4355	165	2	Convective	5,051	168	98	British Rainfall
38	08/06/1957	Camelford, Cornwall	2105	0833	203.2	6hrs?	Convective	3,414	238	85	Met Mag Vol 86 Nov 1957 pp 339-343

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
39	05/08/1957	Rodsley, Derbyshire	4194	3401	152	8.5	Convective	2,120	230	66	British Rainfall
40	05/09/1958	Knockholt, Kent	5467	1585	131	2.5	Convective	920	184	71	Met Mag Oct 1960 & British Rainfall
41	07/10/1960	Horncastle, Lincs	5251	3695	183.9	3	Convective (with significant frontal forcing)	3,819	182	101	British Rainfall 1959-1960
42	06/06/1963	Southery, Norfolk	5612	2932	150	3	Convective	2,386	175	86	British Rainfall
43	17/12/1966	Glen Etive	2190	7510	199	18	Orographic	80	325	61	British Rainfall
44	08/08/1967	Dunsop Valley, Lancs.	3653	4533	117	1.5	Convective	962	140	84	British Rainfall
45	10/07/1968	Chew Stoke, Bristol	3570	1617	175	9	Frontal (with signif. convective component)	2,094	255	69	British Rainfall
46	14-15/09/1968	Whitstable, Kent	6112	1665	190	20	Frontal (with significant convective component)	1,328	288	66	Met Mag. Sep 1974 Vol 103. 255-268, 288-300
47	31/10/1968	Tollymore Park, Co. Down	3334	3328	159	24	Frontal	80	298	53	British Rainfall
48	01/08/1973	Norwich	6235	3085	138	4	Convective	1,694	202	68	
49	20/09/1973	West Stourmouth (Manston)	6255	1625	191	24	Frontal	1,006	290	66	
50	09/11/1973	Blaenau Ffestiniog	2700	3458	147	15	Orographic	27	268	55	

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
51	17/01/1974	Loch Sloy	2280	7124	238	30	Orographic	294	365	65	
52	14/08/1975	Hampstead	5265	1825	171	3	Convective	1,624	195	88	Met Mag June 1981
53	25/06/1980	Sevenoaks	5525	1555	116	1.75	Convective	780	172	67	Met Mag. Vol 109 1980 pp 362-363
54	05/08/1981	Tarporley (Cheshire)	3555	3625	132	5	Convective	2,546	192	69	
55	05/02/1989	W. Highland	2321	7098	186	24	Orographic	81	310	60	
56	19/05/1989	Halifax, Walshaw Dean	3967	4336	193	2	Convective	5,798	162	119	Weather. Vol 46 7;1991
57	10/06/1993	N. Weald	5483	2045	121	3.25	Convective	662	190	64	
58	31/08/1994	Bungay	6335	2895	146	12	Frontal	1,067	248	59	
59	9-11/12/1994	Loch Sloy	2280	7120	250	48	Orographic/ Frontal	159	372	67	250mm in Hydrological Data 1994.
60	07/05/2000	Bracknell	4872	1692	87	1.25	Convective	294	145	60	Weather Vol 57, Feb 2002 pp73-77
61	04/02/2004	Capel Curig	2728	3579	260	48	Orographic	220	432	60	Weather Vol 59, Apr 2004 "Weather Log" insert.

Event	Date	Location	NGR Eastings Northings		Total rainfall (mm)	Duration (h)	Basic Type	FEH Return Period (years)	FSR Probable Maximum Precipitation (mm)	Rainfall as % of PMP	Reference
62	16/08/2004	Boscastle	2130	0903	200	5	Convective	4,160	210	95	Weather Aug 2005; Vol 60 No. 8.Refer EA/MetO post event report
63	07/01/2005	Cumbria, Honister (Carlisle Flood)	3225	5135	164	24	Orographic	55	360	46	Max rainfall at Honister Refer EA/ MetO post event report

Note: Rainfalls highlighted in green are those which exceed the FSR estimate of PMP (Nos 15, 17, 36, 41, 56). Rainfalls highlighted in blue do not exceed the selection threshold (Nos 2, 4, 13, 20a), but were included for other reasons, see Section 3.7. For some events, estimates of return period based on the procedures developed in this project are shown in Table 9.12. Some characteristics for events number 1 and 32 have been updated since the publication of Dempsey and Dent (2009) in February 2009.

Appendix C Seasonal analysis

C.1 Introduction

This appendix contains some further details of the seasonal analysis outlined in Section 4.3. In particular it contains Tables C.1 and C.2 which are tables of winter/annual and summer/annual ratios for given return periods, where these ratios vary with the duration being considered and with the standard annual average rainfall (SAAR) of the particular location. These are provided as a possibly more convenient alternative, for practical use, to the graphical versions of these same results that were presented in Figures 4.7 and 4.8.

As noted in Section 4.3, two seasons have been defined: winter (November to April) and summer (May to October). It should also be recalled that the annual maxima under analysis have been abstracted using calendar years, which may have led to some minor inconsistencies.

C.2 Details of seasonal analysis

An analysis was undertaken using the whole dataset of seasonal maxima to look for patterns in the variability of seasonal ratios with return period. A series of GEV distributions were fitted to the full set of seasonal maxima using the method of L-moments (Hosking & Wallis, 1997). A separate distribution was fitted to the record for each gauge with at least 9 seasonal maxima for each of the key durations. Similarly, GEV distributions were also fitted to the annual maxima at each of these gauges. Estimates of winter, summer and annual rainfall of each duration were derived for return periods of 2, 5, 10, 20 and 100 years.

Values of winter/annual and summer/annual rainfall were calculated for each duration and return period and the variation of these ratios with the available site descriptors (National Grid coordinates, altitude and average annual rainfall (SAAR)) was examined. After considering various combinations of these descriptors, it was concluded that the ratios had an approximately linear relationship with the reciprocal of SAAR. For this reason, a transformed variable *rsaar1* was constructed where

$$rsaar1 = 1.5 - 1000/\text{SAAR}. \qquad \text{(C.1)}$$

This transformation was selected so that *rsaar*1 increases with increasing SAAR for ease of understanding, and so that zero is within the range of transformed values. Some initial investigation had suggested the possibility of using different functional forms to predict the seasonal ratios for positive and negative values of *rsaar*1, but this was later dropped in favour of the approach described below.

Some example plots of the values of the winter/annual and summer/annual ratios against *rsaar*1 are shown in Figures C.1 to C.4. Each plot shows two fitted lines, the first of which (plotted in red) is a modified linear function, truncated so as not to yield values greater than one. The second line (plotted in green) is a modified quadratic function which has again been truncated so as not to give values greater than one and, in addition, has been modified to be monotonic, either increasing or decreasing in the direction appropriate to the data. These functions have been fitted to each case separately by weighted non-linear least squares.

The true values of the seasonal ratios cannot exceed one, and the functions fitted have been selected to obey this rule. There are several reasons why the sample estimates of these ratios do not necessarily follow this rule, including:

- the definition of the seasons means that winter straddles two calendar years, so that winter and annual series do not match closely;
- seasonal and annual series do not match because of the rules for accepting valid maxima. Specifically, in the first and last years, or if there are periods of missing records, if more than 3 months of data are missing, then there may not be a valid annual maximum although the summer maximum may still exist;
- records of annual maxima may be available for years where seasonal maxima are not.

Figures C.1 to C.4 show the fitted modified quadratic relationships for the ratios as functions of SAAR, duration and return period. It can be seen that the ratios vary most markedly with SAAR, although there are also more minor variations with duration and return period. Tables C.1 and C.2 present an alternative version of these results which may be more convenient for practical use.

The development of a fully seasonal rainfall DDF model was beyond the scope of the current study, as was the extension of the approach described in this appendix to very long return periods. However, the set of seasonal correction factors presented here may be useful alongside the all-year model for annual maximum rainfalls to allow seasonal rainfall estimates to be used within rainfall-runoff models if appropriate.

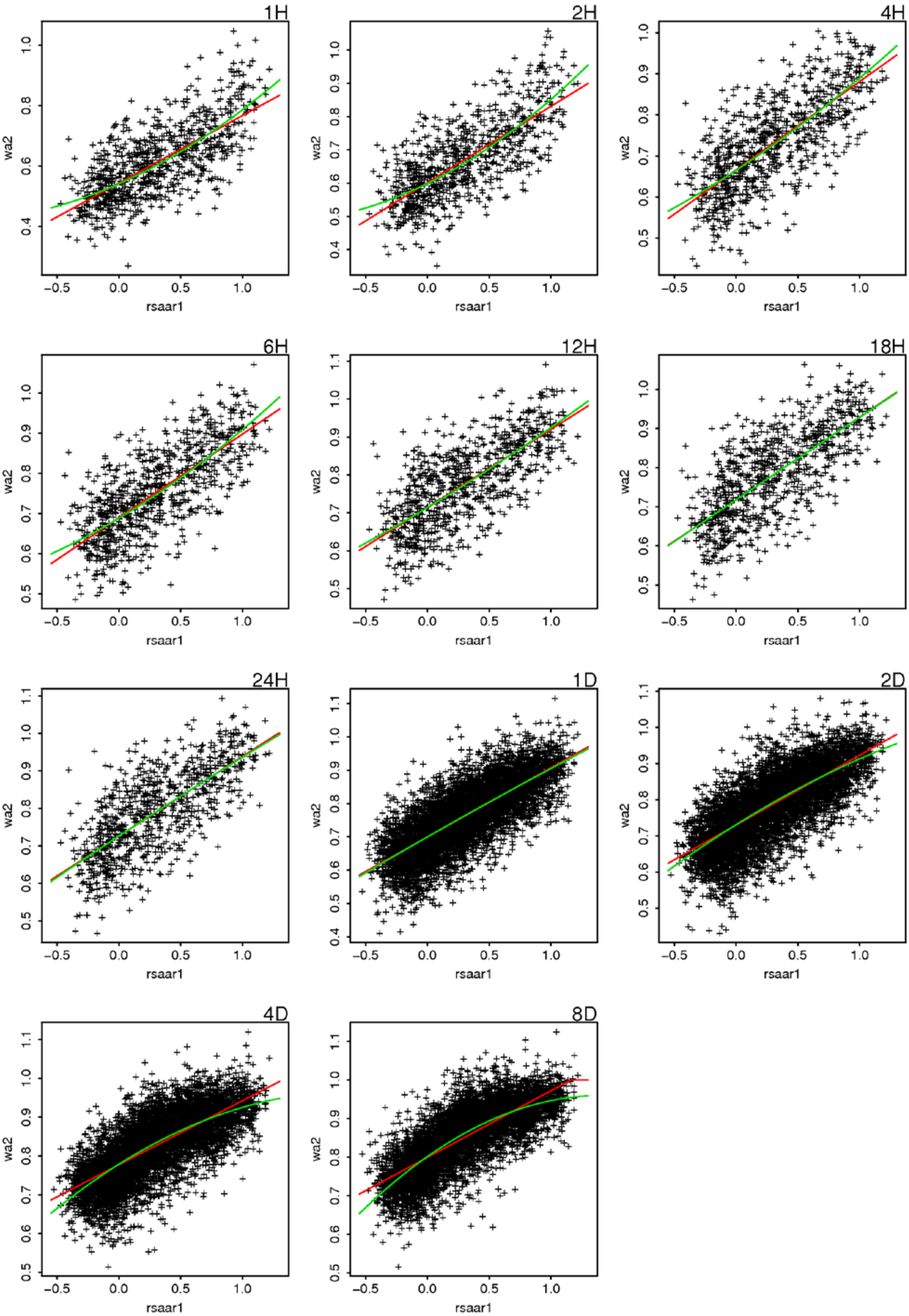


Figure C.1 Plots showing the ratio of the 2-year rainfalls (winter/annual) in relation to rsaar1

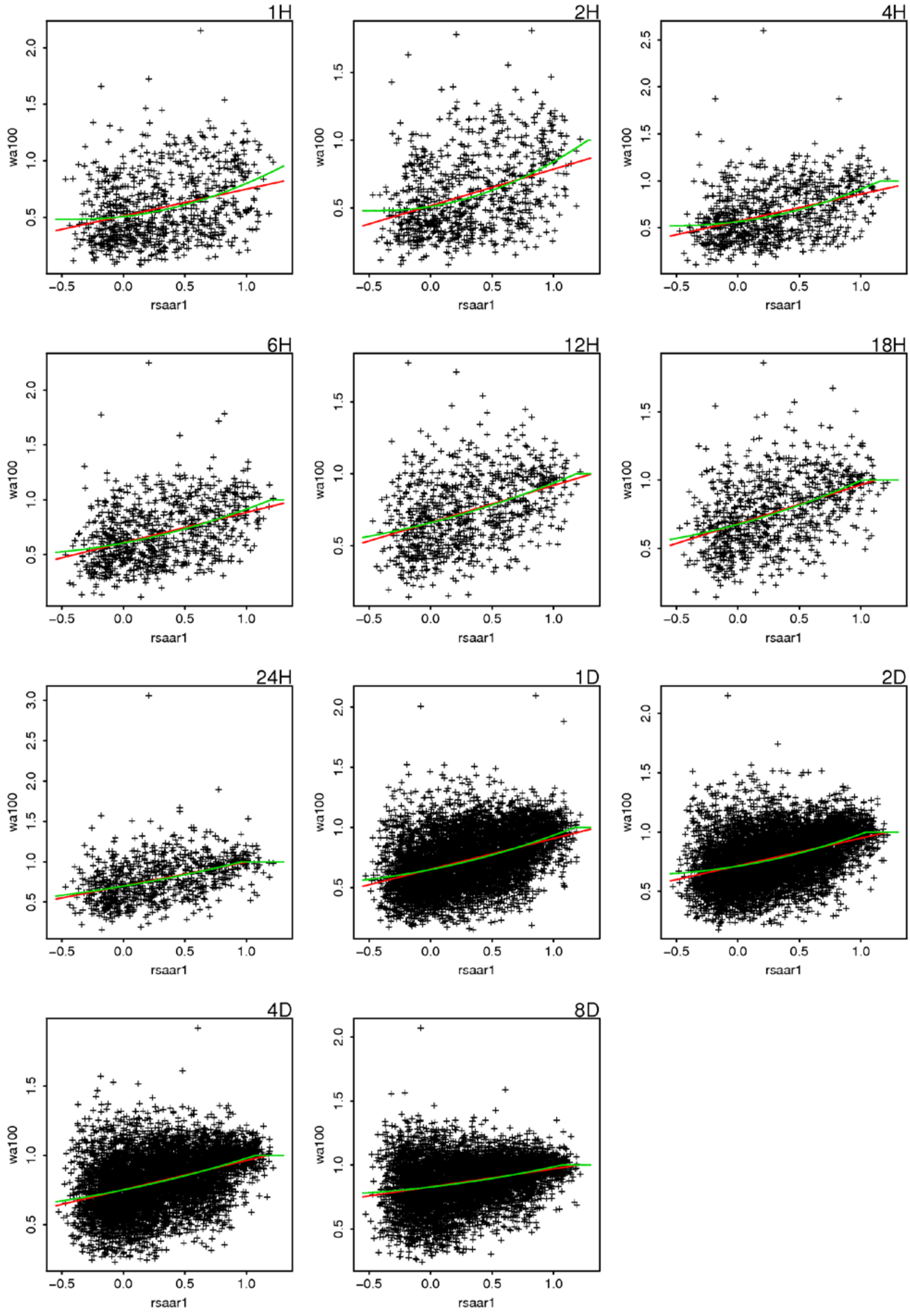


Figure C.2 Plots showing the ratio of the 100-year rainfalls (winter/annual) in relation to rsaar1

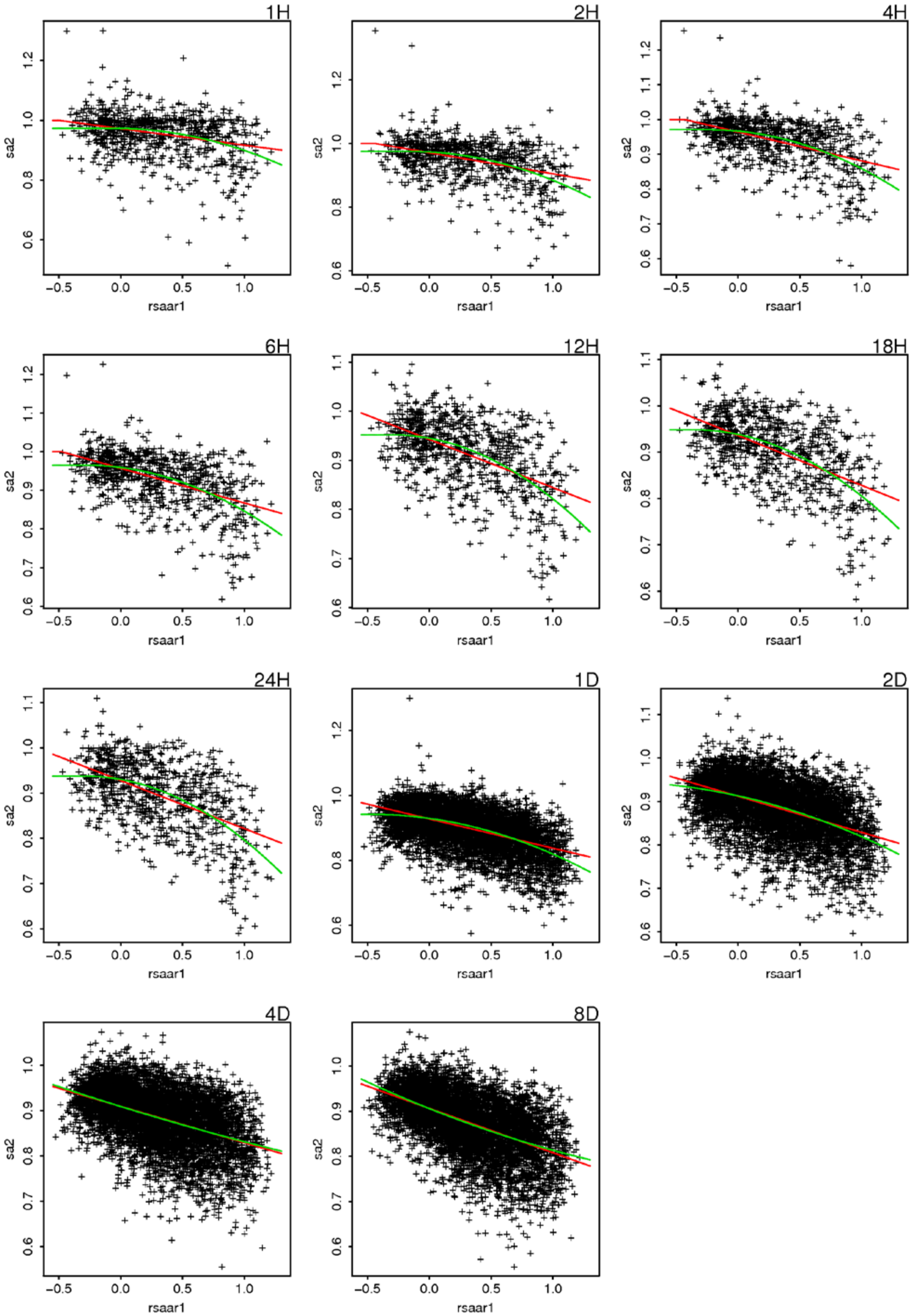


Figure C.3 Plots showing the ratio of the 2-year rainfalls (summer/annual) in relation to rsaar1

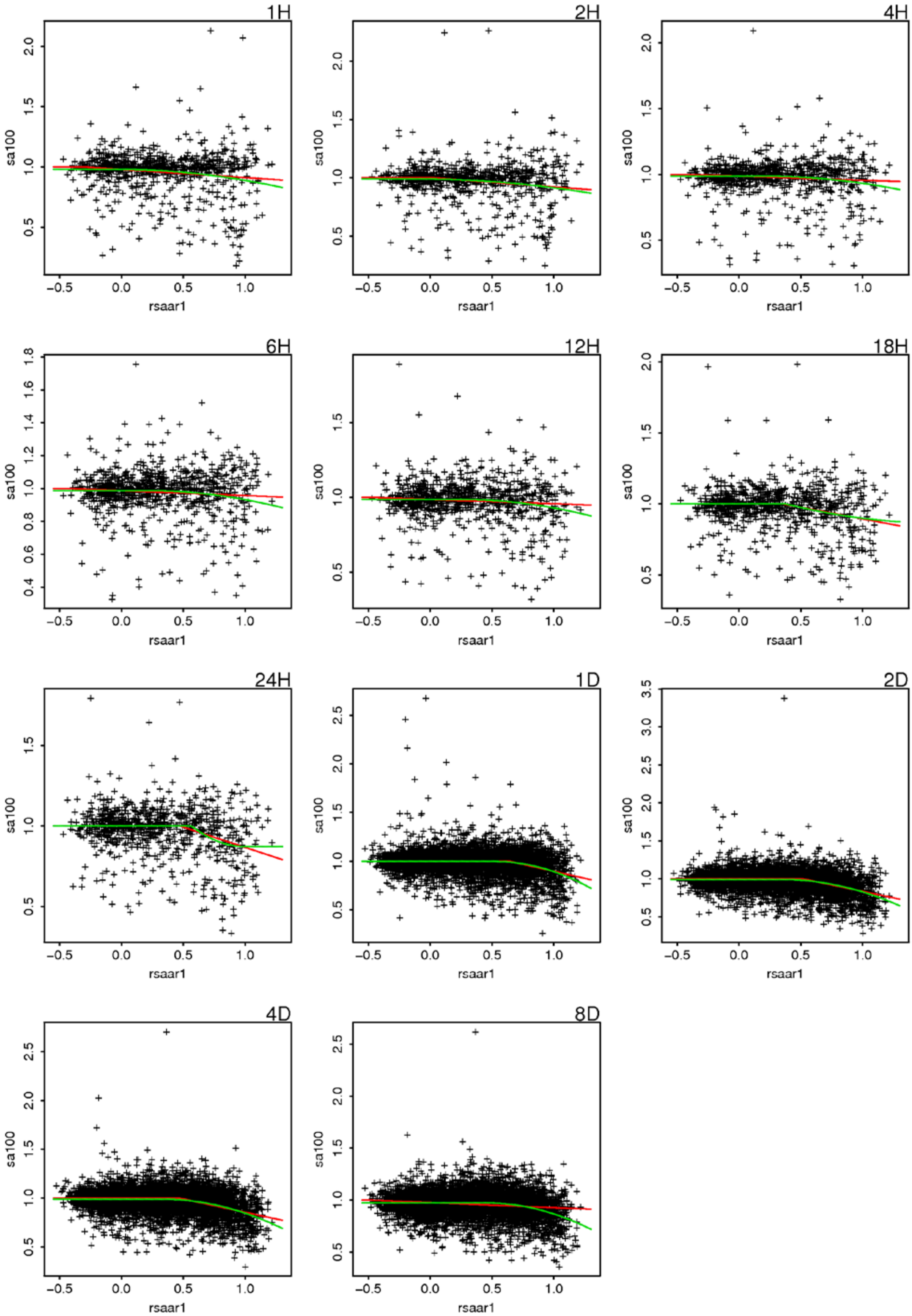


Figure C.4 Plots showing the ratio of the 100-year rainfalls (summer/annual) in relation to rsaar1

Table C.1 Winter/Annual ratios of rainfalls having given return periods

SAAR (mm)	Return period	1 hour	2 hours	4 hours	6 hours	12 hours	18 hours	24 hours	1 day	2 days	4 days	8 days
500	2y	0.43	0.49	0.56	0.59	0.61	0.61	0.62	0.60	0.63	0.69	0.71
	5y	0.39	0.43	0.51	0.54	0.58	0.58	0.59	0.58	0.63	0.69	0.72
	10y	0.38	0.41	0.48	0.52	0.56	0.56	0.58	0.56	0.63	0.68	0.72
	20y	0.37	0.39	0.46	0.50	0.55	0.55	0.56	0.55	0.62	0.67	0.73
	100y	0.39	0.38	0.43	0.47	0.53	0.54	0.55	0.52	0.60	0.65	0.76
750	2y	0.58	0.64	0.70	0.72	0.75	0.75	0.76	0.73	0.76	0.80	0.83
	5y	0.55	0.60	0.67	0.70	0.74	0.75	0.76	0.73	0.77	0.81	0.84
	10y	0.54	0.58	0.65	0.69	0.73	0.74	0.75	0.72	0.76	0.80	0.84
	20y	0.53	0.57	0.64	0.67	0.72	0.73	0.75	0.71	0.76	0.80	0.84
	100y	0.55	0.56	0.62	0.66	0.70	0.73	0.75	0.69	0.75	0.79	0.85
1000	2y	0.66	0.72	0.77	0.79	0.82	0.82	0.83	0.80	0.83	0.86	0.89
	5y	0.63	0.69	0.76	0.78	0.82	0.83	0.84	0.80	0.83	0.87	0.90
	10y	0.62	0.67	0.74	0.77	0.81	0.83	0.84	0.80	0.83	0.87	0.90
	20y	0.61	0.66	0.73	0.76	0.80	0.83	0.84	0.79	0.83	0.86	0.90
	100y	0.63	0.65	0.71	0.75	0.79	0.82	0.85	0.78	0.83	0.86	0.90
1250	2y	0.70	0.76	0.82	0.84	0.86	0.87	0.87	0.85	0.87	0.89	0.92
	5y	0.68	0.74	0.81	0.83	0.86	0.88	0.89	0.85	0.87	0.90	0.93
	10y	0.67	0.72	0.79	0.82	0.86	0.88	0.90	0.85	0.87	0.90	0.94
	20y	0.66	0.71	0.78	0.82	0.85	0.88	0.90	0.84	0.87	0.90	0.93
	100y	0.68	0.71	0.77	0.80	0.84	0.88	0.91	0.83	0.88	0.90	0.93
1500	2y	0.73	0.79	0.85	0.86	0.89	0.89	0.90	0.87	0.89	0.91	0.94
	5y	0.71	0.77	0.84	0.86	0.90	0.91	0.92	0.88	0.90	0.93	0.96
	10y	0.70	0.76	0.83	0.86	0.89	0.92	0.93	0.88	0.90	0.93	0.96
	20y	0.69	0.75	0.82	0.85	0.89	0.92	0.94	0.87	0.90	0.93	0.96
	100y	0.71	0.74	0.81	0.84	0.88	0.92	0.95	0.87	0.91	0.93	0.95
2000	2y	0.77	0.83	0.88	0.90	0.92	0.93	0.94	0.91	0.92	0.94	0.97
	5y	0.75	0.82	0.88	0.90	0.93	0.95	0.97	0.92	0.93	0.96	0.99
	10y	0.74	0.80	0.87	0.90	0.93	0.96	0.98	0.92	0.94	0.96	0.99
	20y	0.73	0.79	0.87	0.90	0.93	0.96	0.98	0.91	0.94	0.96	0.99
	100y	0.75	0.79	0.86	0.88	0.92	0.97	1.00	0.91	0.95	0.96	0.97
2500	2y	0.79	0.85	0.90	0.92	0.94	0.95	0.96	0.93	0.94	0.96	0.99
	5y	0.77	0.84	0.90	0.93	0.96	0.98	0.99	0.94	0.95	0.98	1.00
	10y	0.76	0.83	0.90	0.93	0.96	0.99	1.00	0.94	0.96	0.98	1.00
	20y	0.76	0.82	0.89	0.92	0.96	0.99	1.00	0.94	0.96	0.98	1.00
	100y	0.77	0.81	0.89	0.91	0.94	0.99	1.00	0.93	0.97	0.98	0.98
3000	2y	0.80	0.87	0.92	0.93	0.95	0.96	0.97	0.94	0.96	0.97	1.00
	5y	0.79	0.86	0.92	0.94	0.97	0.99	1.00	0.95	0.97	0.99	1.00
	10y	0.78	0.85	0.92	0.94	0.98	1.00	1.00	0.96	0.97	0.99	1.00
	20y	0.77	0.84	0.91	0.94	0.97	1.00	1.00	0.96	0.98	1.00	1.00
	100y	0.79	0.83	0.91	0.93	0.96	1.00	1.00	0.95	0.99	1.00	0.99
3500	2y	0.82	0.88	0.93	0.94	0.96	0.97	0.98	0.95	0.96	0.98	1.00
	5y	0.80	0.87	0.93	0.96	0.99	1.00	1.00	0.97	0.97	1.00	1.00
	10y	0.79	0.86	0.93	0.96	0.99	1.00	1.00	0.97	0.98	1.00	1.00
	20y	0.78	0.85	0.92	0.95	0.99	1.00	1.00	0.97	0.99	1.00	1.00
	100y	0.80	0.84	0.92	0.94	0.97	1.00	1.00	0.96	1.00	1.00	1.00
4000	2y	0.82	0.89	0.93	0.95	0.97	0.98	0.99	0.96	0.97	0.98	1.00
	5y	0.81	0.88	0.94	0.96	0.99	1.00	1.00	0.97	0.98	1.00	1.00
	10y	0.80	0.87	0.94	0.97	1.00	1.00	1.00	0.98	0.99	1.00	1.00
	20y	0.79	0.86	0.93	0.96	0.99	1.00	1.00	0.98	0.99	1.00	1.00
	100y	0.81	0.85	0.93	0.95	0.98	1.00	1.00	0.97	1.00	1.00	1.00
4500	2y	0.83	0.89	0.94	0.96	0.98	0.99	1.00	0.97	0.98	0.99	1.00
	5y	0.81	0.89	0.95	0.97	1.00	1.00	1.00	0.98	0.99	1.00	1.00
	10y	0.81	0.88	0.95	0.97	1.00	1.00	1.00	0.98	0.99	1.00	1.00
	20y	0.80	0.87	0.94	0.97	1.00	1.00	1.00	0.98	1.00	1.00	1.00
	100y	0.81	0.86	0.94	0.96	0.99	1.00	1.00	0.98	1.00	1.00	1.00
5000	2y	0.83	0.90	0.95	0.96	0.98	0.99	1.00	0.97	0.98	0.99	1.00
	5y	0.82	0.89	0.95	0.98	1.00	1.00	1.00	0.99	0.99	1.00	1.00
	10y	0.81	0.88	0.95	0.98	1.00	1.00	1.00	0.99	1.00	1.00	1.00
	20y	0.81	0.87	0.95	0.98	1.00	1.00	1.00	0.99	1.00	1.00	1.00
	100y	0.82	0.87	0.94	0.97	1.00	1.00	1.00	0.98	1.00	1.00	1.00

Table C.2 Summer/Annual ratios of rainfalls having given return periods

SAAR (mm)	Return period	1 hour	2 hours	4 hours	6 hours	12 hours	18 hours	24 hours	1 day	2 days	4 days	8 days
500	2y	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.95	0.95	0.96
	5y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
	10y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	20y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	100y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750	2y	0.96	0.96	0.95	0.94	0.93	0.92	0.91	0.91	0.90	0.90	0.89
	5y	0.97	0.98	0.98	0.97	0.96	0.96	0.95	0.95	0.94	0.94	0.93
	10y	0.97	0.99	0.99	0.99	0.98	0.97	0.97	0.97	0.96	0.95	0.94
	20y	0.97	0.99	1.00	1.00	1.00	0.99	0.98	0.99	0.97	0.97	0.95
	100y	0.97	0.99	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	0.97
1000	2y	0.94	0.94	0.92	0.91	0.89	0.88	0.87	0.88	0.87	0.87	0.86
	5y	0.95	0.96	0.95	0.94	0.93	0.92	0.91	0.92	0.91	0.91	0.90
	10y	0.95	0.96	0.96	0.96	0.95	0.93	0.92	0.94	0.92	0.92	0.91
	20y	0.95	0.96	0.97	0.97	0.96	0.95	0.94	0.96	0.93	0.94	0.93
	100y	0.95	0.96	0.97	0.97	0.97	0.98	0.99	1.00	1.00	0.99	0.95
1250	2y	0.93	0.92	0.91	0.89	0.87	0.86	0.85	0.86	0.85	0.85	0.84
	5y	0.94	0.94	0.93	0.93	0.91	0.89	0.89	0.90	0.89	0.89	0.88
	10y	0.94	0.94	0.94	0.94	0.92	0.91	0.90	0.92	0.90	0.91	0.90
	20y	0.94	0.95	0.95	0.95	0.94	0.92	0.91	0.93	0.91	0.92	0.91
	100y	0.93	0.95	0.96	0.97	0.97	0.94	0.94	0.98	0.94	0.94	0.94
1500	2y	0.93	0.92	0.89	0.88	0.86	0.85	0.84	0.85	0.84	0.84	0.82
	5y	0.93	0.93	0.92	0.91	0.90	0.88	0.87	0.89	0.87	0.88	0.87
	10y	0.93	0.93	0.93	0.92	0.91	0.89	0.88	0.91	0.89	0.89	0.89
	20y	0.93	0.93	0.94	0.93	0.92	0.90	0.89	0.92	0.89	0.90	0.90
	100y	0.92	0.94	0.96	0.96	0.96	0.92	0.91	0.94	0.89	0.90	0.93
2000	2y	0.92	0.90	0.88	0.87	0.84	0.83	0.82	0.84	0.83	0.83	0.81
	5y	0.93	0.92	0.90	0.90	0.88	0.86	0.85	0.87	0.86	0.87	0.85
	10y	0.92	0.92	0.91	0.91	0.89	0.87	0.86	0.89	0.87	0.88	0.87
	20y	0.92	0.92	0.92	0.91	0.90	0.87	0.87	0.90	0.87	0.89	0.89
	100y	0.91	0.92	0.96	0.96	0.96	0.89	0.87	0.90	0.83	0.85	0.93
2500	2y	0.91	0.90	0.87	0.86	0.83	0.82	0.81	0.83	0.82	0.82	0.80
	5y	0.92	0.91	0.90	0.89	0.87	0.85	0.84	0.86	0.85	0.86	0.84
	10y	0.92	0.91	0.90	0.90	0.88	0.86	0.85	0.88	0.86	0.87	0.86
	20y	0.91	0.91	0.91	0.90	0.89	0.86	0.85	0.89	0.86	0.88	0.88
	100y	0.91	0.91	0.95	0.95	0.95	0.88	0.84	0.87	0.80	0.83	0.92
3000	2y	0.91	0.89	0.87	0.85	0.83	0.81	0.80	0.82	0.81	0.82	0.79
	5y	0.92	0.91	0.89	0.88	0.86	0.84	0.83	0.86	0.84	0.85	0.84
	10y	0.91	0.90	0.90	0.89	0.87	0.85	0.84	0.87	0.85	0.87	0.86
	20y	0.91	0.91	0.91	0.90	0.88	0.85	0.85	0.88	0.85	0.87	0.88
	100y	0.90	0.91	0.95	0.95	0.95	0.87	0.82	0.85	0.78	0.81	0.92
3500	2y	0.90	0.89	0.86	0.85	0.82	0.81	0.80	0.82	0.81	0.81	0.79
	5y	0.91	0.90	0.89	0.88	0.86	0.83	0.83	0.85	0.84	0.85	0.83
	10y	0.91	0.90	0.89	0.88	0.86	0.84	0.83	0.87	0.85	0.86	0.85
	20y	0.91	0.90	0.90	0.89	0.87	0.84	0.84	0.87	0.85	0.87	0.87
	100y	0.90	0.90	0.95	0.95	0.95	0.86	0.81	0.83	0.76	0.80	0.92
4000	2y	0.90	0.89	0.86	0.85	0.82	0.80	0.79	0.81	0.81	0.81	0.78
	5y	0.91	0.90	0.88	0.88	0.85	0.83	0.82	0.85	0.84	0.84	0.83
	10y	0.91	0.90	0.89	0.88	0.86	0.84	0.83	0.86	0.84	0.86	0.85
	20y	0.91	0.90	0.90	0.89	0.87	0.84	0.83	0.87	0.84	0.87	0.87
	100y	0.90	0.90	0.95	0.95	0.95	0.85	0.80	0.82	0.75	0.79	0.91
4500	2y	0.90	0.89	0.86	0.84	0.82	0.80	0.79	0.81	0.81	0.81	0.78
	5y	0.91	0.90	0.88	0.87	0.85	0.82	0.82	0.85	0.83	0.84	0.83
	10y	0.91	0.89	0.89	0.88	0.86	0.83	0.83	0.86	0.84	0.86	0.85
	20y	0.90	0.90	0.90	0.88	0.86	0.84	0.83	0.87	0.84	0.86	0.87
	100y	0.89	0.90	0.95	0.95	0.95	0.85	0.80	0.82	0.74	0.78	0.91
5000	2y	0.90	0.88	0.86	0.84	0.82	0.80	0.79	0.81	0.80	0.81	0.78
	5y	0.91	0.90	0.88	0.87	0.85	0.82	0.82	0.85	0.83	0.84	0.82
	10y	0.91	0.89	0.88	0.88	0.85	0.83	0.82	0.86	0.84	0.85	0.85
	20y	0.90	0.89	0.90	0.88	0.86	0.83	0.83	0.86	0.84	0.86	0.87
	100y	0.89	0.90	0.95	0.95	0.95	0.84	0.79	0.81	0.73	0.77	0.91

Appendix D Details of analysis leading to new standardisation

D.1 Introduction

This project has introduced a revised type of standardisation of the following form:

$$R_{revised} = 1 + \frac{R - RMED}{f \times RMED} = 1 + \frac{1}{f}\left(R_{standardised} - 1\right). \qquad \text{(D.1)}$$

Here, $R_{revised}$ is the revised standardised rainfall, and f is a new scaling factor which varies from site to site. This replaces the median-based standardisation used by FEH, which was of the form

$$R_{standardised} = \frac{R}{RMED} = 1 + \frac{R - RMED}{RMED}. \qquad \text{(D.2)}$$

The formula for the revised standardisation can readily be reversed to allow the determination of a design rainfall from the corresponding value of the standardised value:

$$R = RMED \times \left\{1 + f\left(R_{revised} - 1\right)\right\}. \qquad \text{(D.3)}$$

This appendix gives some details of how the form of the revised standardisation model was selected and of how it was fitted.

D.2 Possible alternative approaches

Other forms of standardisation have been considered briefly, along with analyses parallel to those presented here. In particular, one possibility is to work in terms of the logarithm of rainfall, and to created a revised standardised log-rainfall, $L = \log R$, of the form

$$L_{revised} = \frac{1}{f}\left(L - LMED\right) = \frac{1}{f}\left(\log R - \log RMED\right). \qquad \text{(D.4)}$$

Then the corresponding alternative revised standardised rainfall would be defined as the exponential of this

$$R_{alt-revised} = \left(\frac{R}{RMED}\right)^{1/f}. \qquad \text{(D.5)}$$

Preliminary investigations of this alternative did not suggest that it would work any more effectively than the revised standardisation that has been adopted. This revised standardisation is a relatively minor change to that used in the FEH and is arguably more easily understood than the alternative. In addition, adoption of a logarithmic transformation would raise the question of how much of the later FORGEX and DDF analyses should deal with the transformed values before employing the inverse transformation. There would clearly be several variants to consider.

D.3 Relationship with location descriptors

The formulation of the revised standardised rainfalls, $R_{revised}$, meant that it was possible to examine alternative ways of specifying the standardisation factor, f, by analysing the possible relationship of the following quantity to any available descriptors. The specific quantity is termed "*lcmed*", where

$$lcmed = \frac{\lambda_2}{RMED} . \qquad \text{(D.6)}$$

In particular, values of the L-scale (λ_2) and the median (*RMED*) for the maxima data for each gauge were computed, and combined to form a value of this median-based version of the coefficient of variation.

The relation of *lcmed* to the available site descriptors (NGR coordinates, altitude and SAAR (Standard Annual Average Rainfall) was examined. This analysis was conducted for seasonal (summer and winter) and annual maxima and for 11 durations over which the rainfall is totalled before extracting the maxima. Each of these 33 cases was treated separately. After considering various combinations of the variables noted above, a decision was made to construct a transformed variable *rsaar*1, where

$$rsaar1 = 1.5 - \frac{1000}{SAAR} . \qquad \text{(D.7)}$$

This transformation was selected so that *rsaar*1 is increasing for increasing SAAR (for ease of understanding), and so that zero is within the range of transformed values. Another reason for selecting this transformation of SAAR was that the relationship between *lcmed* and SAAR could reasonably well be represented by a linear relationship between *lcmed* and *rsaar*1, albeit with substantial error. Analyses of the residuals from such a single variable model suggested that, for the higher durations, an improvement could be made by using a predictive model of the form

$$lcmed = \alpha + \beta \times rsaar1 + \gamma \times ngy . \qquad \text{(D.8)}$$

Here *ngy* is the northing of the National Grid coordinates expressed in units of 1000 km: this leads to the range of *ngy* being between 0 and about 1.2. The parameter γ is fixed at zero for the sub-daily durations but is fitted for durations of 1 day and above.

In deciding on the structure of the above relationship, limited use could be made of standard statistical theory because of the existence of statistical dependence (spatial dependence) between the sample values of *lcmed* for raingauges in the same region. Decisions were made based on all of the following: an intuitive feel for what seemed a substantial improvement to the model; use of graphical plots to look for further possible improvements (variable selection); consistency of the selected structure across durations and across the seasonal and annual analyses. In the course of these considerations, the following descriptors of descriptors were considered:

- northing, *ngy*
- easting, *ngx*
- altitude, *alt*
- transformed SAAR, *rsaar*1.

Part of the analysis involved starting from regression models including these four variables, together with the six pair-wise combinations of these, and then successively omitting terms which could be considered unimportant. When this was done separately across the range of durations and seasons, different selections of the basic variables and the cross-products occurred in the final combinations with no consistency across the various cases.

Figure D.1 shows examples of the fitted relationships for annual maxima. This figure shows scatter plots for each duration of the sample values of *lcmed* against *rsaar*1, together with values from the fitted relationship as described above. The fitted relationship appears as a straight line for durations up to 24 hours but, for the higher durations, a separate predicted value is shown for each raingauge which includes a contribution from the gauge's northing. The plots also identify (as small green circles) the sample values of *lcmed* for those raingauges whose northing (*ngy*) is greater than 1.0. The reason for highlighting these values arises in the following discussion.

Figure D.2 and D.3 show residuals for the models predicting *lcmed* for the 11 durations for the case of annual maximum rainfall. Here the residuals are plotted against *ngy* (the variable representing the gauge's northing). For each duration, the residuals from either one or two models are shown, together with lines showing a regression model for the residuals fitted against *ngy*. For durations up to 24 hours, residuals from the simple model based on a regression against *rsaar*1 are shown and these do not indicate any useful relationship with *ngy*: the model including both variables has not been fitted. In Figure D.3, residuals from two models are shown for each of the durations from 1 day to 8 days. The first is as for the sub-daily durations and here it seems that a reasonable, if modest, benefit can be obtained by including *ngy* in addition to *rsaar*1. For each of the 1-day to 8-day durations, the second residual plot shows the residuals when both variables are included in the model. It is apparent in these plots that a group of generally negative residuals (where sample values of *lcmed* are lower than those suggested by the model) occur for large values of *ngy.* The highlighting in green of points in Figure D.1 has been done to indicate where the corresponding points lie when considering *rsaar*1: the gauges with *ngy* greater than 1.0 are highlighted.

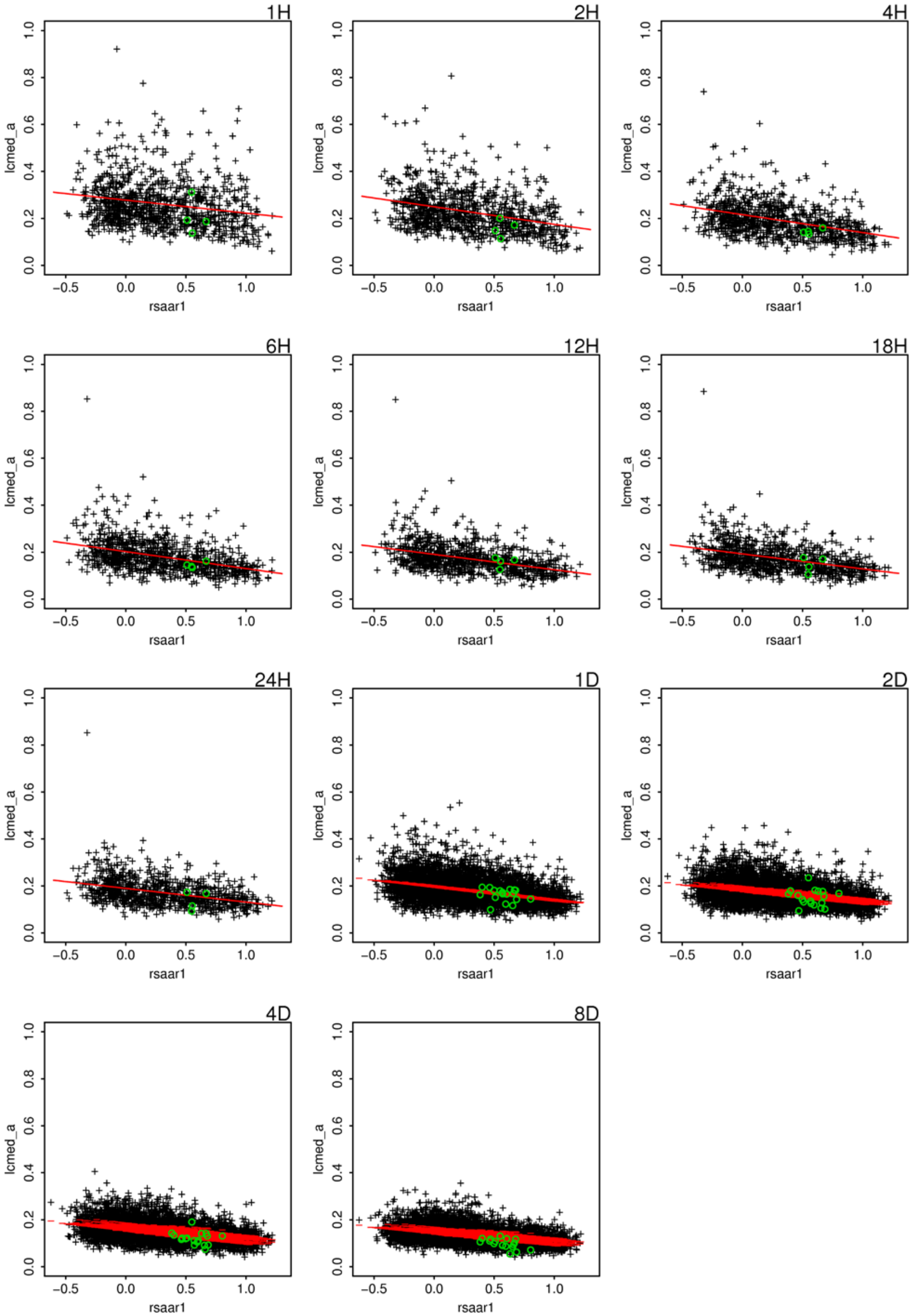


Figure D.1 Relationship between *lcmed* and *rsaar1* for durations of 1 hour to 8 days for annual maxima. Red lines show predictions from the model which includes *ngy* in the case of daily durations

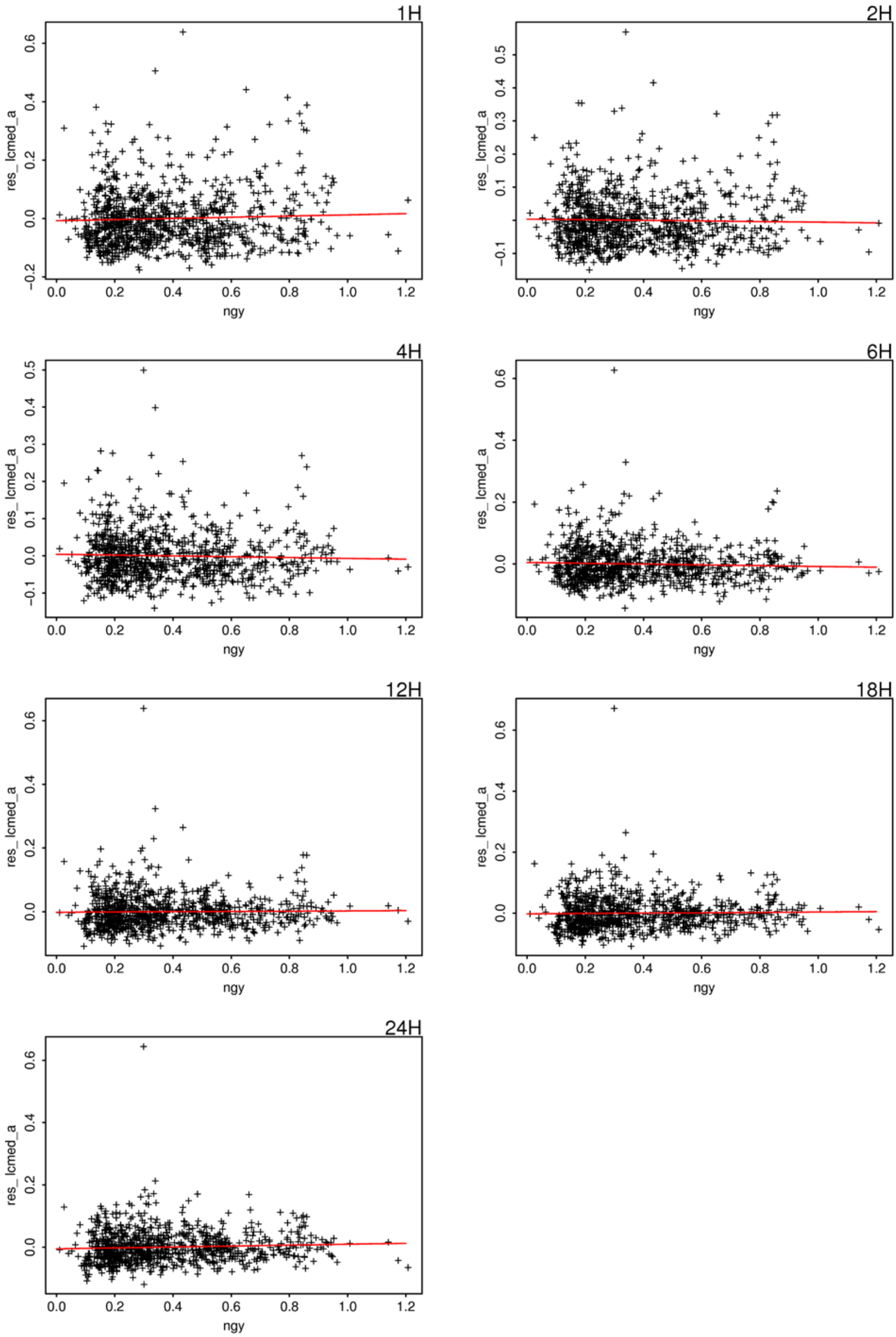


Figure D.2 Residuals from models for *lcmed* of annual maxima based on *rsaar1* only, for hourly durations: shows no need for *ngy* in the model

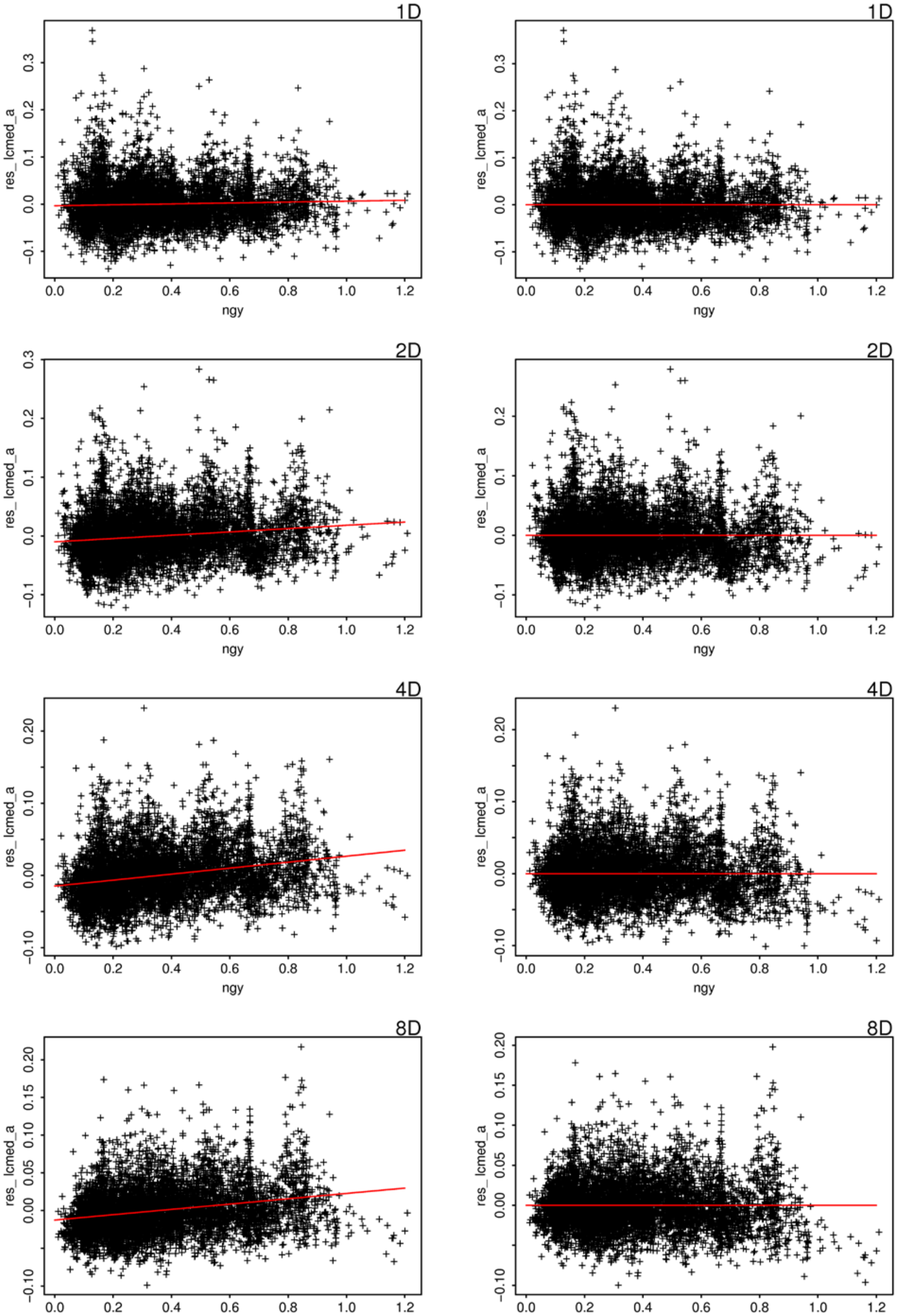


Figure D.3 Residuals from models for *lcmed* of annual maxima based on *rsaar1* only (left), and on *rsaar1* and *ngy* (right): shows improvement with *ngy*

Figure D.4 shows a colour-coded map of the residuals from the model for *lcmed* for the case where the duration is 8 days. This shows that a dominance of negative residuals occurs in the Scottish islands which may relate to some type of maritime effect. Other patterns might be discernible: there is an indication of generally positive residuals to the east of the Pennines and the Welsh mountains. Thus there seems to be the possibility of further improving the prediction of *lcmed* by using an extended set of location descriptors if these become available in the future.

D.4 Standardisation coefficients

The final stage of the analysis was to replace the set of equations for lcmed with an equivalent set of equations for a standardisation factor based on lcmed. An overall scaling constant was used so that the L-scale of the standardised data would be approximately constant across the range of durations. The scaling factor was selected to give values of the standardisation factor in the region of 1.

The final version of the additional standardisation factor f which appears in Equation D.1 is defined in terms of coefficients a, b and c as

$$f = a + b\frac{1000}{SAAR} + c \times ngy \quad . \qquad \text{(D.9)}$$

The values of the coefficients are derived from the regression coefficients for lcmed by dividing them by 0.15; this final scaling results in values of f being near one, and thus the results of the revised standardisation are of a similar range to those from the original standardisation. Values of the coefficients *a, b* and *c* are given in Tables D.1 to D.3.

Table D.1 Coefficients for the additional standardisation factor f for different durations for summer maxima

Duration	a	b	c
1 hours	1.29985	0.38881	0
2 hours	1.05815	0.44731	0
4 hours	0.91526	0.41491	0
6 hours	0.88589	0.39292	0
12 hours	0.87173	0.38145	0
18 hours	0.88256	0.39023	0
24 hours	0.87220	0.40395	0
1 day	0.96082	0.37475	0.04974
2 days	0.82859	0.38901	0.14259
4 days	0.75016	0.34979	0.12402
8 days	0.77295	0.25020	0.13679

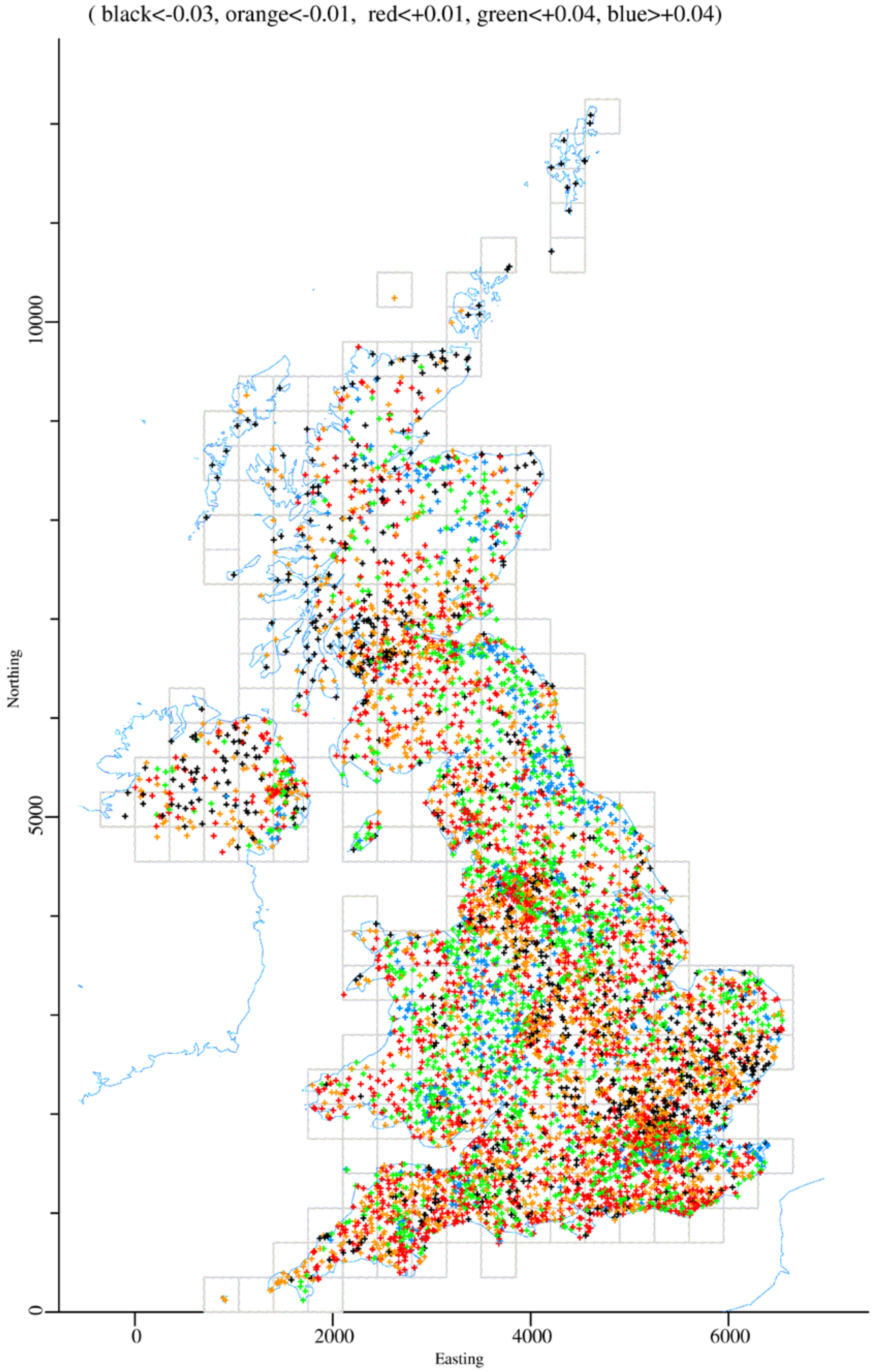


Figure D.4 Map of residuals from the model for *lcmed* of 8-day annual maxima

Table D.2 Coefficients for the additional standardisation factor *f* for different durations for winter maxima

Duration	a	b	c
1 hours	1.34548	0.09005	0
2 hours	1.02776	0.13374	0
4 hours	0.86267	0.16300	0
6 hours	0.82607	0.17860	0
12 hours	0.82464	0.21018	0
18 hours	0.93392	0.15527	0
24 hours	0.96225	0.14728	0
1 day	0.70497	0.26967	0.32592
2 days	0.63544	0.32224	0.33825
4 days	0.52586	0.28257	0.39353
8 days	0.52129	0.30157	0.20626

Table D.3 Coefficients for the additional standardisation factor *f* for different durations for annual maxima

Duration	a	b	c
1 hours	1.29824	0.36999	0
2 hours	0.91692	0.49781	0
4 hours	0.67617	0.50930	0
6 hours	0.62770	0.48146	0
12 hours	0.61677	0.43695	0
18 hours	0.64625	0.42577	0
24 hours	0.68146	0.38093	0
1 day	0.71025	0.38894	0.06988
2 days	0.63118	0.34949	0.20412
4 days	0.44217	0.36348	0.30147
8 days	0.42520	0.32103	0.25632

D.5 Summary

The analyses relating to the standardisation of rainfall maxima have led to a simple improvement to the standardisation implemented in the FEH. The effect should be that the distributions of standardised maximum rainfall will be more similar between sites in a region than previously. Some examples of the effect of the revised standardisation are presented in Section 5.

Appendix E Testing the “constant shift” model

This appendix considers the question of whether there is evidence against the simple spatial dependence model assumed by FORGEX as used in the FEH, as discussed in Sections 6.3 and 6.4.1. Rather than undertaking formal statistical tests, applying these to regions centred about selected locations and then summarising these across the whole country, the approach taken is a rather more informal one. A graphical approach has been sought which produces a single plot that summarises for the whole study region the agreement of the available data with the constant shift model.

The graphical approach is based on comparing a particular statistic which describes the frequency curve of the network maxima, with the corresponding value predicted by the constant shift model. In particular, the L-scale has been chosen as the statistic to be used for the comparison. This statistic is one which is related to the slope of the rainfall frequency curve when plotted against a Gumbel reduced variate. The idea is that the constant shift model can be regarded as matching the location of the frequency curve of the network maximum on the standard Gumbel plot, so that a test of whether the model is adequate can be based on whether the slope of the curve is reproduced adequately. Note that, while the constant shift model does, in a sense, predict that the slope of the network maximum curve is the same as that of a single raingauge, this applies to slopes evaluated at different locations on the probability scale. In order to achieve a plausible procedure that uses statistics that are reasonably well estimated from the available data, the decision to use the L-scale as an overall measure of slope has been adopted, rather than attempting to estimate the slopes of the frequency curve at points in the tail of one or other of the distributions where the estimation would inevitably be poor. It turns out that the constant shift model does not predict that the L-scales of the network maximum and single raingauge distributions should be the same, for the reasons described below.

The L-scale can be considered as measuring the slope of the frequency curve in a way which concentrates on the centre of the distribution. If the frequency curve is other than a straight line when plotted on the Gumbel scale, the slope (in the centre of the distribution) of the left-shifted curve changes with the amount of shift applied (see Figure E.1).

Earlier studies for this project, summarised in Section 4, have indicated that the GEV distribution is a reasonable match to the distributions of the annual maximum rainfall at individual raingauges across a range of durations across the UK. For this particular family of distributions it is possible to determine moderately simple formulae relating the L-scale predicted by the constant shift model to that of the single raingauge distribution. The formulae allow the amount of shift to be estimated (implicitly) from the data used for the assessment so that there is no further complication of relying on an additional formula to determine the amount of shift required.

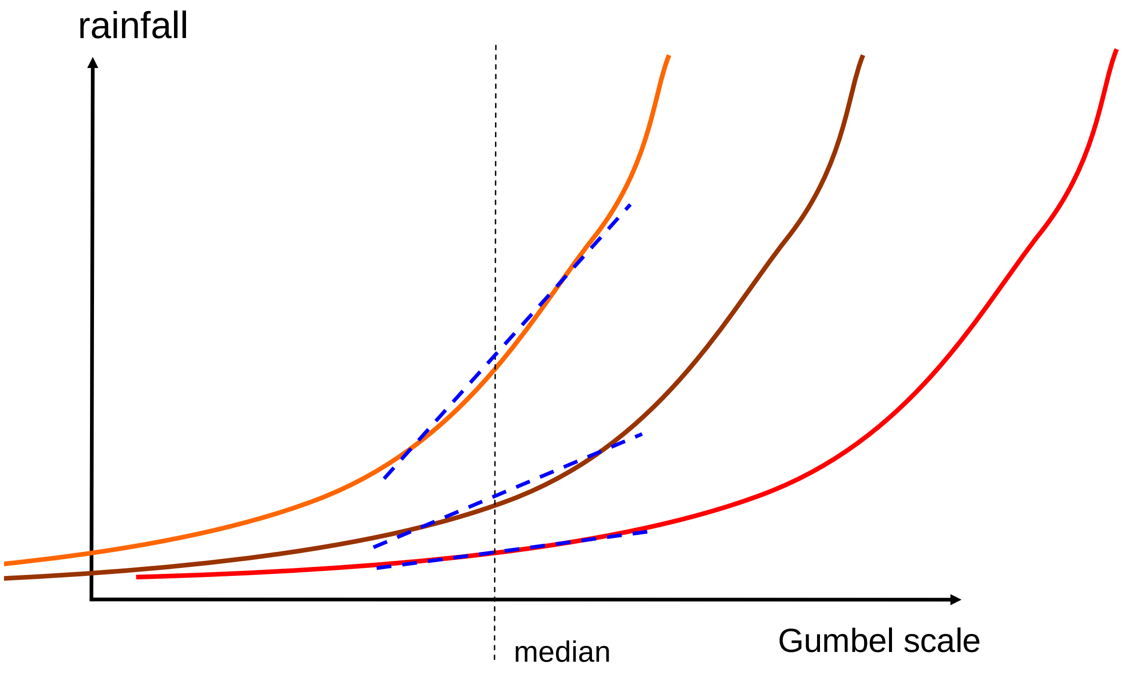


Figure E.1 The constant shift model applied in a case where the single gauge frequency curve is not a straight line (a Gumbel distribution). Each coloured curve is a shifted version of the others. Given that the L-scale summarises the slope of the curve in the centre of the distribution, it is clear that the L-scale will vary with the amount of shift.

In the following, N is used to determine the amount of shift in the constant shift model. It is the same as the "equivalent number of independent gauges". The actual number of gauges in the network being considered does not appear in the theory here.

It is assumed that the distribution of annual maximum rainfall for a single raingauge is in the GEV family, with the distribution function given by

$$F(x) = \exp\left[-\left\{ 1 - k\frac{x-u}{\alpha} \right\}_{+}^{1/k} \right],$$

where u, α, k are the location, shift and scale parameters respectively. Here the subscript + indicates the positive value function:

$$x_{+} = \begin{cases} x & x \geq 0 \\ 0 & x < 0. \end{cases}$$

According to the constant shift model, with shift determined by N, the distribution function of the network maxima, F_N, is determined by $F_N(x) = \{F(x)\}^N$, where N is the effective number of independent gauges. Then the distribution function $F_N(x)$ is also GEV, with parameters u_N, α_N, k_N given by

$$k_N = k$$

$$\alpha_N = \alpha N^{-k}$$

$$u_N = \begin{cases} u + \alpha \dfrac{1-N^{-k}}{k}, & k \neq 0, \\ u + \alpha \ln N, & k = 0. \end{cases}$$

For the single gauge distribution the probability weighted moments are given by

$$\beta_r = \begin{cases} \dfrac{1}{r+1}\left[u + \dfrac{\alpha}{k}\left\{1-(r+1)^{-k}\,\Gamma(1+k)\right\}\right], & k \neq 0, \\ \dfrac{1}{r+1}\left[u + \alpha\left\{\gamma + \ln(r+1)\right\}\right], & k = 0. \end{cases}$$

It follows that the probability weighted moments, $\beta_r^{(N)}$, of the distribution of the network maximum are given by

$$\beta_r^{(N)} = \begin{cases} \dfrac{1}{r+1}\left[u + \dfrac{\alpha}{k}\left\{1-N^{-k}(r+1)^{-k}\,\Gamma(1+k)\right\}\right], & k \neq 0, \\ \dfrac{1}{r+1}\left[u + \alpha\left\{\gamma + \ln N + \ln(r+1)\right\}\right], & k = 0. \end{cases}$$

where $\gamma = 0.57721...$ is Euler's constant.

Equations for the mean values

The mean values for the single gauge and (modelled by the constant shift assumption) network maximum distributions are given by

$$\beta_0 = \begin{cases} u + \dfrac{\alpha}{k}\left\{1-\Gamma(1+k)\right\}, & k \neq 0, \\ u + \alpha\gamma, & k = 0, \end{cases}$$

and

$$\beta_0^{(N)} = \begin{cases} u + \dfrac{\alpha}{k}\left\{1-N^{-k}\Gamma(1+k)\right\}, & k \neq 0, \\ u + \alpha\left\{\gamma + \ln N\right\}, & k = 0. \end{cases}$$

Therefore the difference in the means is given by

$$\beta_0^{(N)} - \beta_0 = \begin{cases} \dfrac{\alpha}{k}\Gamma(1+k)\left(1-N^{-k}\right), & k \neq 0, \\ \alpha \ln N, & k = 0. \end{cases} \qquad \text{(E.1)}$$

Equations for the L-scales

The L-scales for the single gauge and (modelled by the constant-shift assumption) network-maximum distributions are given by

$$\lambda_2 = 2\beta_1 - \beta_0 = \begin{cases} \left(1-2^{-k}\right)\dfrac{\alpha}{k}\Gamma(1+k), & k \neq 0, \\ \alpha \ln 2, & k = 0, \end{cases} \qquad \text{(E.2)}$$

$$\lambda_2^{(N)} = 2\beta_1^{(N)} - \beta_0^{(N)} = \begin{cases} N^{-k}\left(1-2^{-k}\right)\dfrac{\alpha}{k}\Gamma(1+k), & k \neq 0, \\ \alpha \ln 2, & k = 0. \end{cases} \quad \text{(E.3)}$$

It follows that

$$\lambda_2^{(N)} = N^{-k}\lambda_2 .$$

Predicted value for the network maximum L-scale

The formula for the prediction from the constant shift model of the L-scale of the network maximum is obtained as follows. The idea is to eliminate the unknown quantities α and N from Equations (E.1-3). Firstly, for the case $k = 0$, the prediction is

$$\lambda_2^{(N)} = N^{-k}\lambda_2 = \lambda_2 .$$

For $k \neq 0$,

$$\begin{aligned} \lambda_2^{(N)} - \lambda_2 &= -\left(1 - N^{-k}\right)\left(1-2^{-k}\right)\frac{\alpha}{k}\Gamma(1+k) \\ &= -\left(1-2^{-k}\right)\left(\beta_0^{(N)} - \beta_0\right). \end{aligned}$$

Since the right hand side of this equation is zero if $k = 0$ is substituted, it follows that a single formula can be used to give the prediction from the constant shift model of the L-scale of the network-maximum distribution:

$$\lambda_2^{(N)} = \lambda_2 - \left(1-2^{-k}\right)\left(\beta_0^{(N)} - \beta_0\right). \quad \text{(E.4)}$$

This result depends strongly on the assumption that a GEV distribution is appropriate to describe the distribution of the annual maximum at single raingauges. If the constant shift model does not hold, then it follows that the distribution of the network maxima may not be a GEV distribution, although it is still possible that a GEV distribution might usually be a reasonable approximation to sample data.

For application of Equation (E.4) to assess whether the constant shift model is adequate for the UK raingauge dataset, the following steps are required:

(i) find sample estimates of the mean β_0, the L-scale λ_2 and the shape parameter k for the single-gauge distribution using a collection of raingauge data;

(ii) find the sample estimates of the mean $\beta_0^{(N)}$ and the L-scale $\lambda_2^{(N)}$ for the network maximum distribution using the same collection of raingauge data (the sample derived value of $\lambda_2^{(N)}$ will be denoted by $\lambda_2^{(Net)}$);

(iii) calculate the predicted value of $\lambda_2^{(N)}$ by applying Equation (E.4) to the data-derived values of β_0, λ_2, k and $\beta_0^{(N)}$ (this model-derived value of $\lambda_2^{(N)}$ will be denoted by $\lambda_2^{(Test)}$);

(iv) compare the model-predicted value of $\lambda_2^{(N)}$ found in (iii) with the sample estimate found in (ii).

The results presented here have been obtained by using the sample L-moments to fit the GEV distribution in order to calculate the estimate of the shape parameter k. In an attempt to be clear, the sample estimate of $\lambda_2^{(N)}$ (obtained in (ii), specifically $\lambda_2^{(Net)}$) is described as the L-scale for the network maximum, while the value calculated from Equation (E.4) (in step (iii), specifically $\lambda_2^{(Test)}$) is described as the adjusted typical L-scale, since it is derived as a correction to λ_2 which is itself described as the typical L-scale.

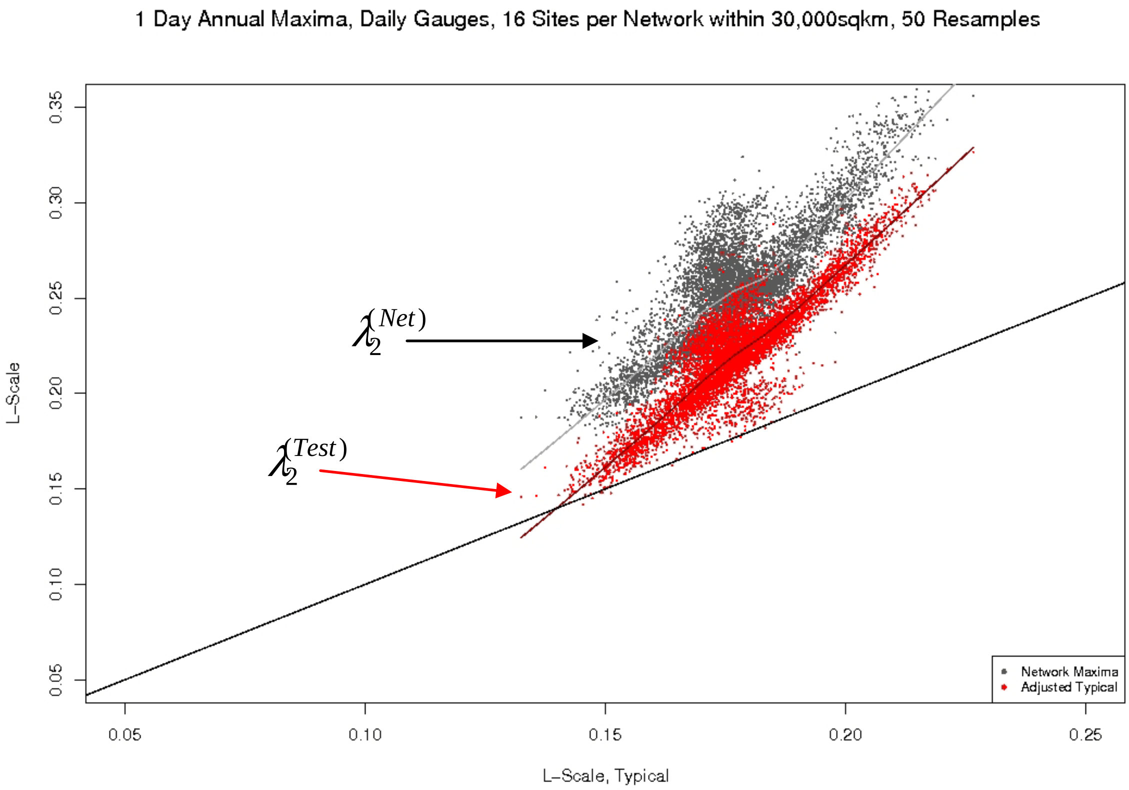


Figure E.2 Comparison of the data-derived L-scale of the network maximum (black points) with the value predicted by the constant-shift model (red points, lower cloud).

Figure E.2 shows one way of comparing the values of the data-derived L-scale for the network maxima, $\lambda_2^{(Net)}$, with the value predicted by the constant-shift model $\lambda_2^{(Test)}$. These quantities are plotted in different colours as scatter plots against the typical L-scale λ_2. Each point (or pair of points of different colours) relates to a similar analysis to that used to produce Figures 6.2 and 6.3. Specifically, each point relates to a given target location (*i.e.* a daily raingauge location) about which a region of radius approximately 100 km is defined (corresponding to the 30,000 km^2 area quoted in the figure). As before, resampled series of network maxima were created by selecting for each year a random set of 16 gauges within the region. Fifty series of resampled network maxima were generated and used to create average values for the L-scale statistics. It can be seen in Figure E.2 that the sample-based values of the L-scale for the network maxima are generally larger than the predictions from the constant shift model. Figure E.2 relates to just a single duration (1 day) and for a single case of network density and extent (16 raingauges in a 100 km radius) for raingauges across the UK. A conclusion to be drawn from Figure E.2 is that the sample values of L-scale for network maxima ($\lambda_2^{(Net)}$) usually exceed those predicted by the constant-shift model ($\lambda_2^{(Test)}$) and thus there is reasonably strong evidence that the constant-shift model does not hold.

In Figure E.2, the cloud of points seems to fall along lines with slopes which are greater than the 1:1 line which is included on the plot. For the adjusted typical L-scales this may be in part be related to the form of Equation (E.4), where the adjustment to the typical L-scale depends on the shape parameter of the GEV distribution. Points above the 1:1 line correspond to cases where the estimated shape parameter is negative while those below the line correspond to cases where the estimated shape parameter is positive. The points further away from the 1:1 line correspond to either a larger difference from 0 of the shape parameter or a larger difference of the means of the network maxima and typical single gauge distributions.

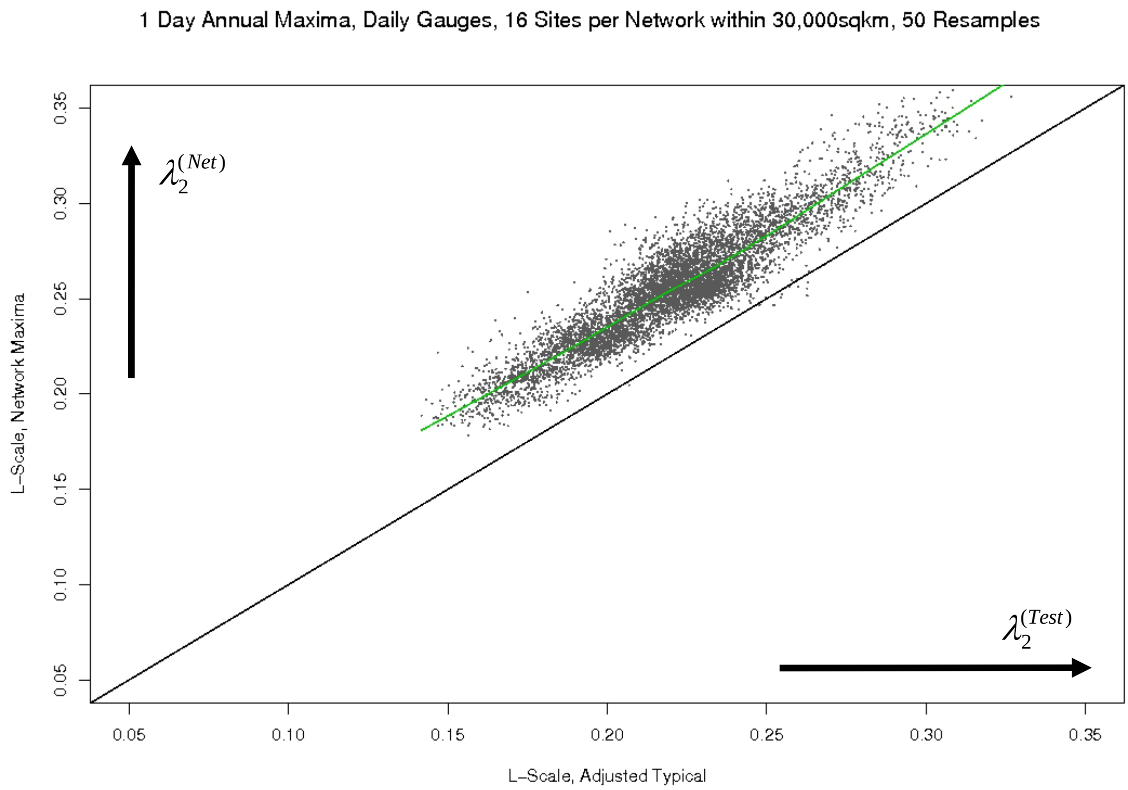


Figure E.3 Comparison of the data-derived L-scale of the network maximum (x-axis) with the value predicted by the constant-shift model (y-axis).

In Figure E.3, the same comparison is made by showing a scatter plot of the sample-derived L-scale of the network maxima against the model-derived adjusted typical L-scale, since this provides a means of directly comparing these values for any given target location. A notable feature of Figure E.3 is that, for this style of plot, the cloud of points seems to fall along a line parallel to the 1:1 line. This corresponds to the clouds of points in Figure E.2 being parallel to each other.

Figures E.4 and E.5 allow the effects of the revised standardisation procedure to be assessed within the above analysis. For these plots, the analysis has been revised to use as target points the centres of the 35 km grid-squares that are used elsewhere and has been further revised to restrict the selection of networks for each year to ensure that these have an area of coverage within a certain target range. For these plots, networks of 16 gauges within 80 km of the target location have been used. The main difference between Figures E.4 and E.5 is seen to lie in the range of values taken by the “typical” L-Scale value across the target locations. This shows that the revised standardisation is having a substantial effect in reducing the variability of the slopes of the standardised growth curves across the country. In contrast to the results in the earlier section, which showed the variation of individual sample values of λ_2 and which showed only a limited benefit, the results here show variations in a type of locally-averaged value of λ_2.

Figures E.6 and E.7 show plots of the same type, for cases where the revised standardisation is used by for networks of 64 and 256 gauges within the same 80 km radius of the target point. In the case of Figure E.7, the number of points plotted is markedly reduced because, for any of the target points, no point is plotted if the analysis cannot find at least 9 years in which 256 gauges have recorded annual maxima.

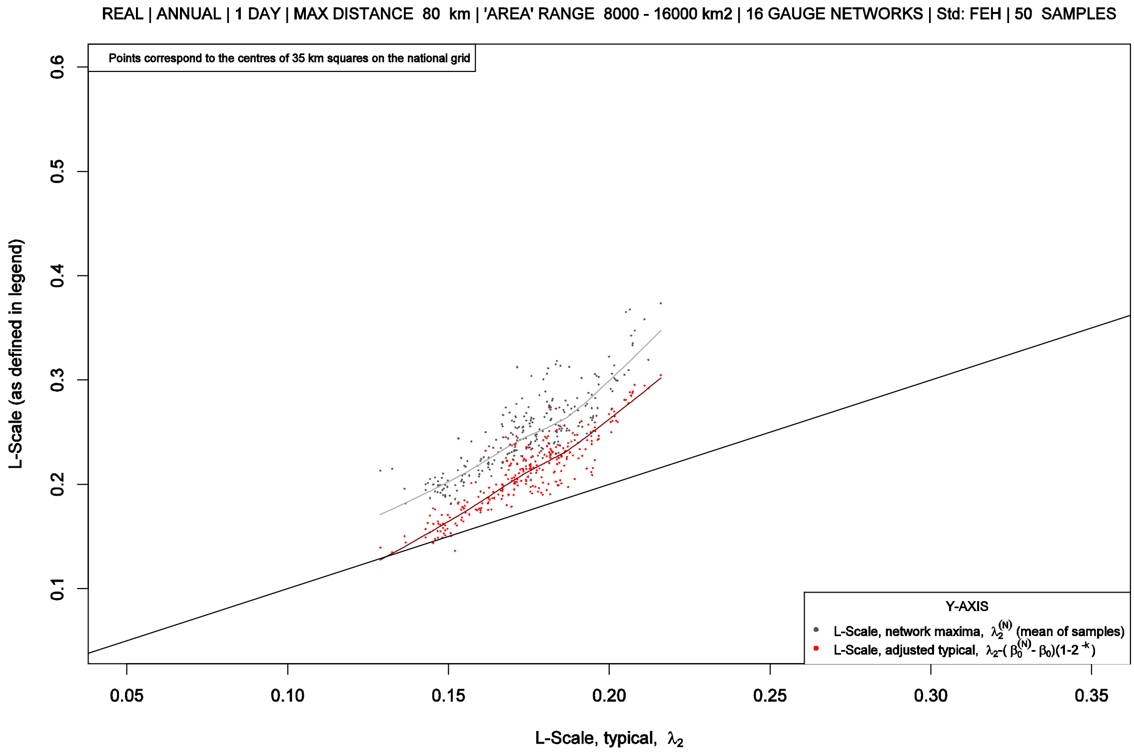


Figure E.4 Results of analysis using median-standardised rainfalls (16 gauges)

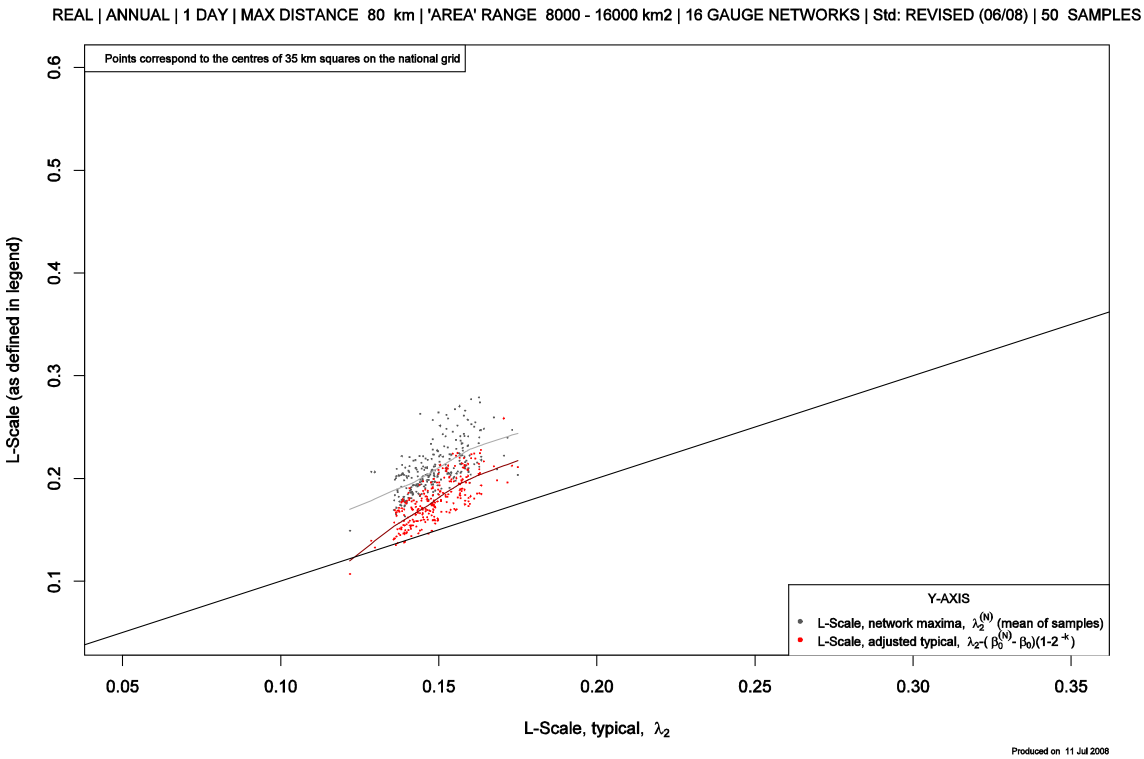


Figure E.5 Results of analysis using the revised standardisation (16 gauges)

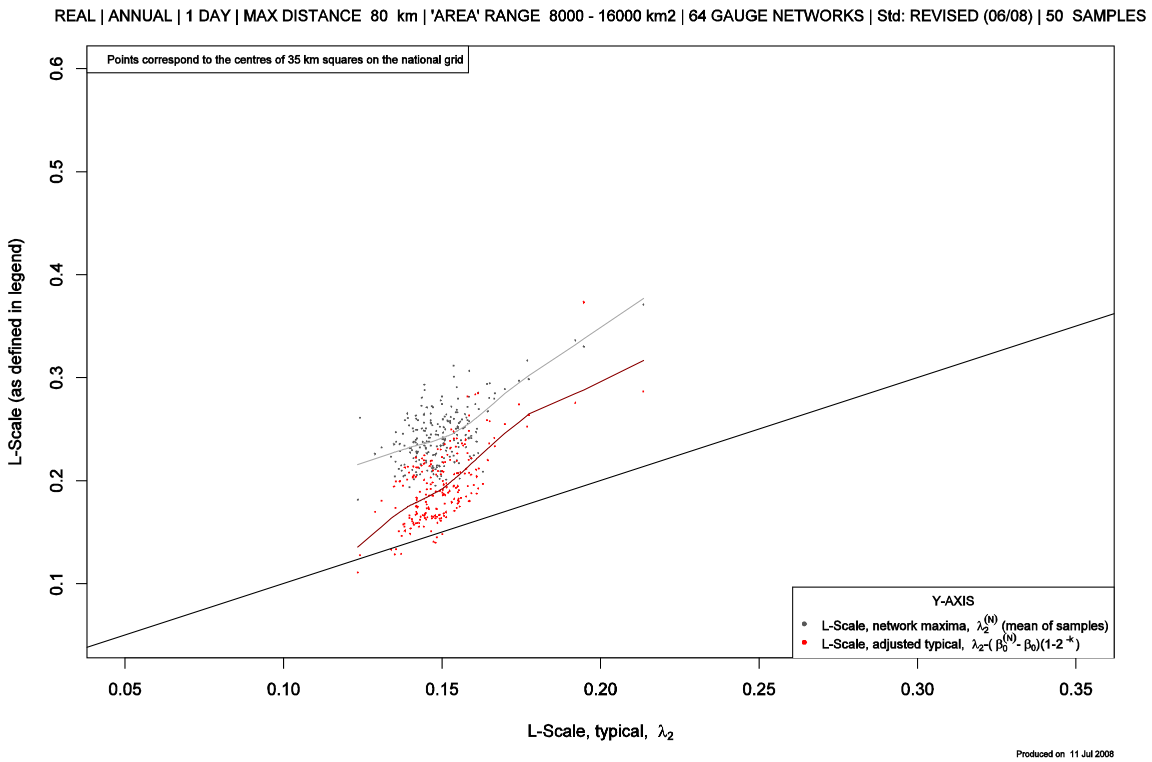


Figure E.6 Results of analysis using the revised standardisation (64 gauges)

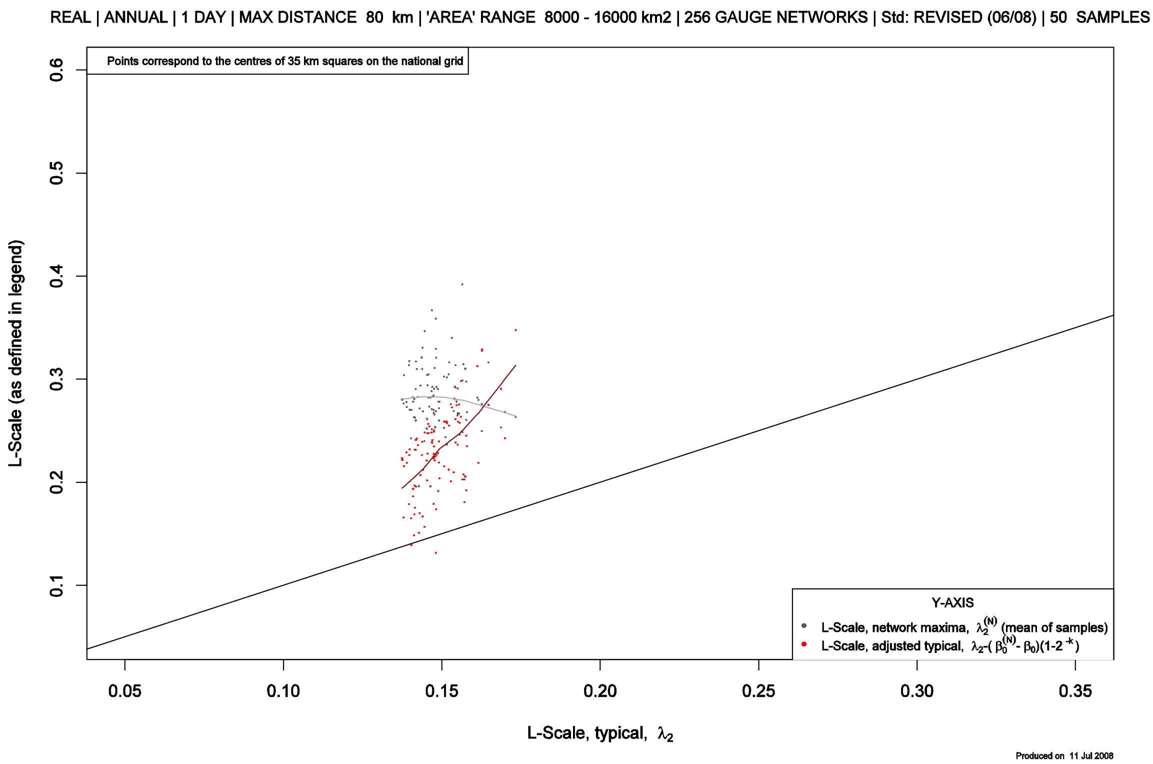


Figure E.7 Results of analysis using the revised standardisation (256 gauges)

Figures E.8 onwards show the results of analyses similar to that in Figure E.7 but showing the collection of results for a number of target points in map-like forms. A simplification has been made by including only the summary of the network-maximum analysis consisting of the line which shows the median of the 50 re-samples. The maps show plots within a grid of 35 km boxes and the plot within each box shows the results for the analysis for the location at the centre of the 35 km box. As before, the networks considered include all gauges within 80 km of the target location and are restricted to networks whose area of coverage, according to the Dales and Reed measure, is within the range 8000 to 16000 km^2.

Figure E.8 shows the results for networks of 16 gauges, while Figures E.9 to E.13 show results for cases of networks of 32, 64, 128, 256 and 512 gauges. The number of boxes for which sufficient years having enough gauges are available reduces considerably as the required number of gauges increases.

In some cases in Figures E.8 to E.13, the estimates provided by the medians of the network maxima (plotted as black lines) lie above the theoretical curves for the network maxima derived on the basis of independence (the red lines). Notionally, this would indicate negative dependence. Cases in which this seems to occur in the present dataset are confined to high return periods only. If negative dependence were to be a real phenomenon, it would correspond to situations where the occurrence of an extreme rainfall at a given location would reduce to below average the chances of occurrence of similarly extreme rainfalls at neighbouring locations. However, there is a good possibility that the apparent negative dependence seen in Figures E.8 to E.21 do not represent real negative dependence but instead arise from sampling effects.

Investigation of cases where the median of the network maxima does exceed the theoretical “independence” values has shown the following. In these cases the networks of gauges are such that the limited availability of different sub-networks of gauges having the right characteristics means that the network maximum selected for different resampled networks often arise from the same gauge and thus the same values arise across the resampled growth curves of network maxima at high return periods. Thus the “median” can be determined from a set of values where very many of the highest values are identical. That the apparent negative dependence is likely to have arisen from sampling effects alone has been confirmed by simulation experiments where simulated annual maximum rainfalls have been generated independently across sites. In such experiments, the same type of occurrence of network maxima plotting a lot higher than the “independence” theory suggests does arise, and to somewhat the same extent, although not always in the same geographical locations as for the real dataset.

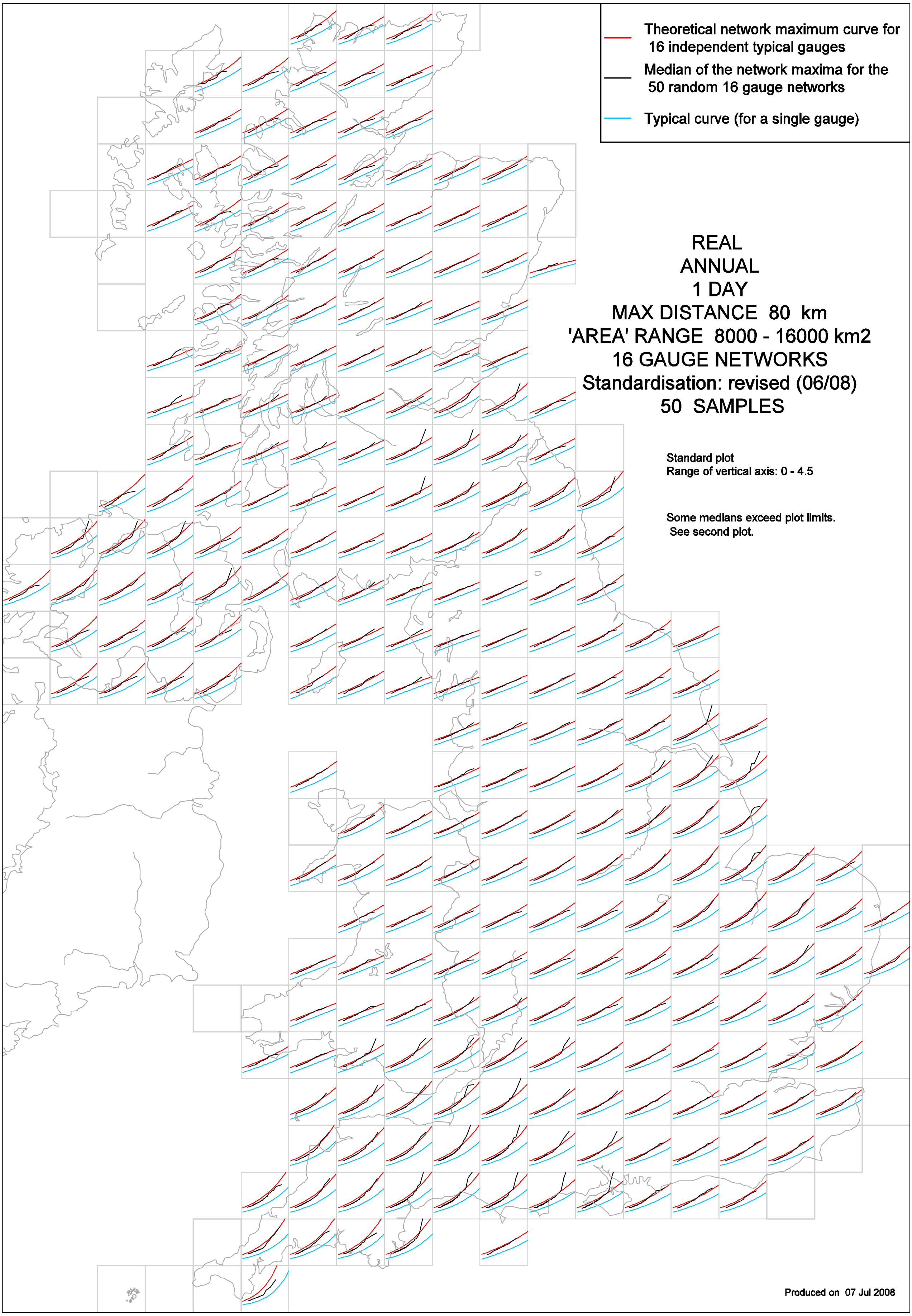


Figure E.8 Networks of 16 gauges

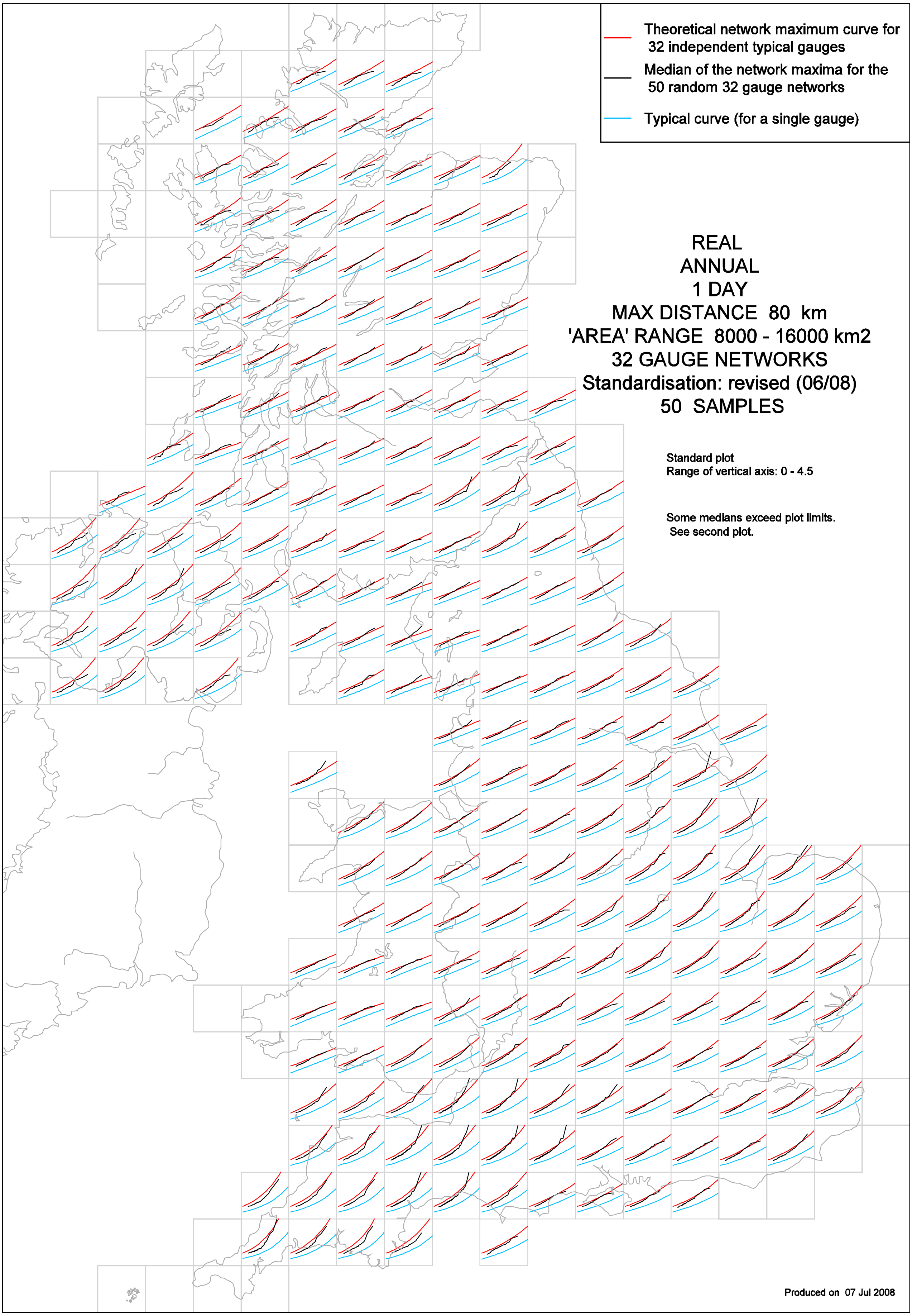


Figure E.9 Networks of 32 gauges

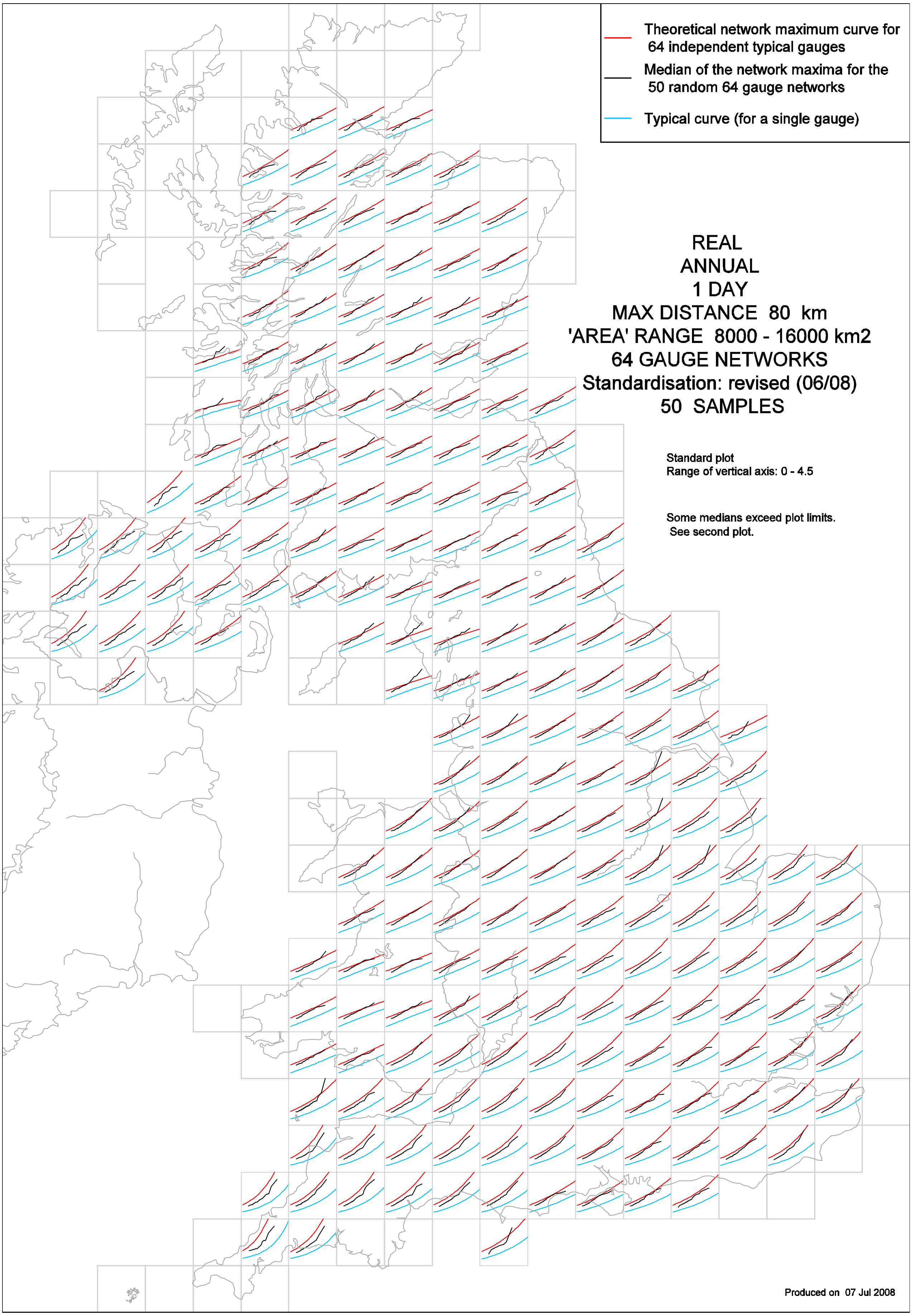


Figure E.10 Networks of 64 gauges

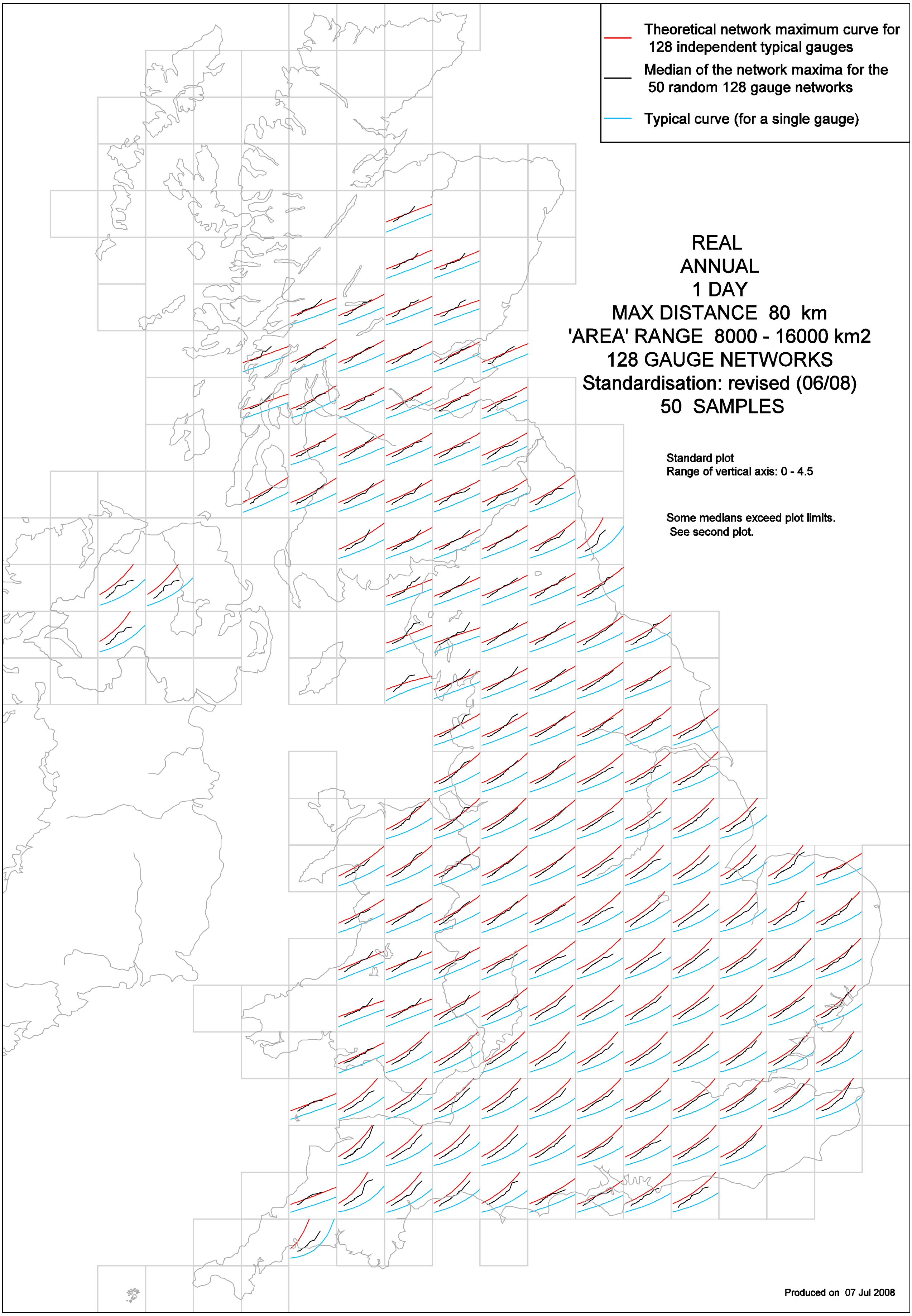


Figure E.11 Networks of 128 gauges

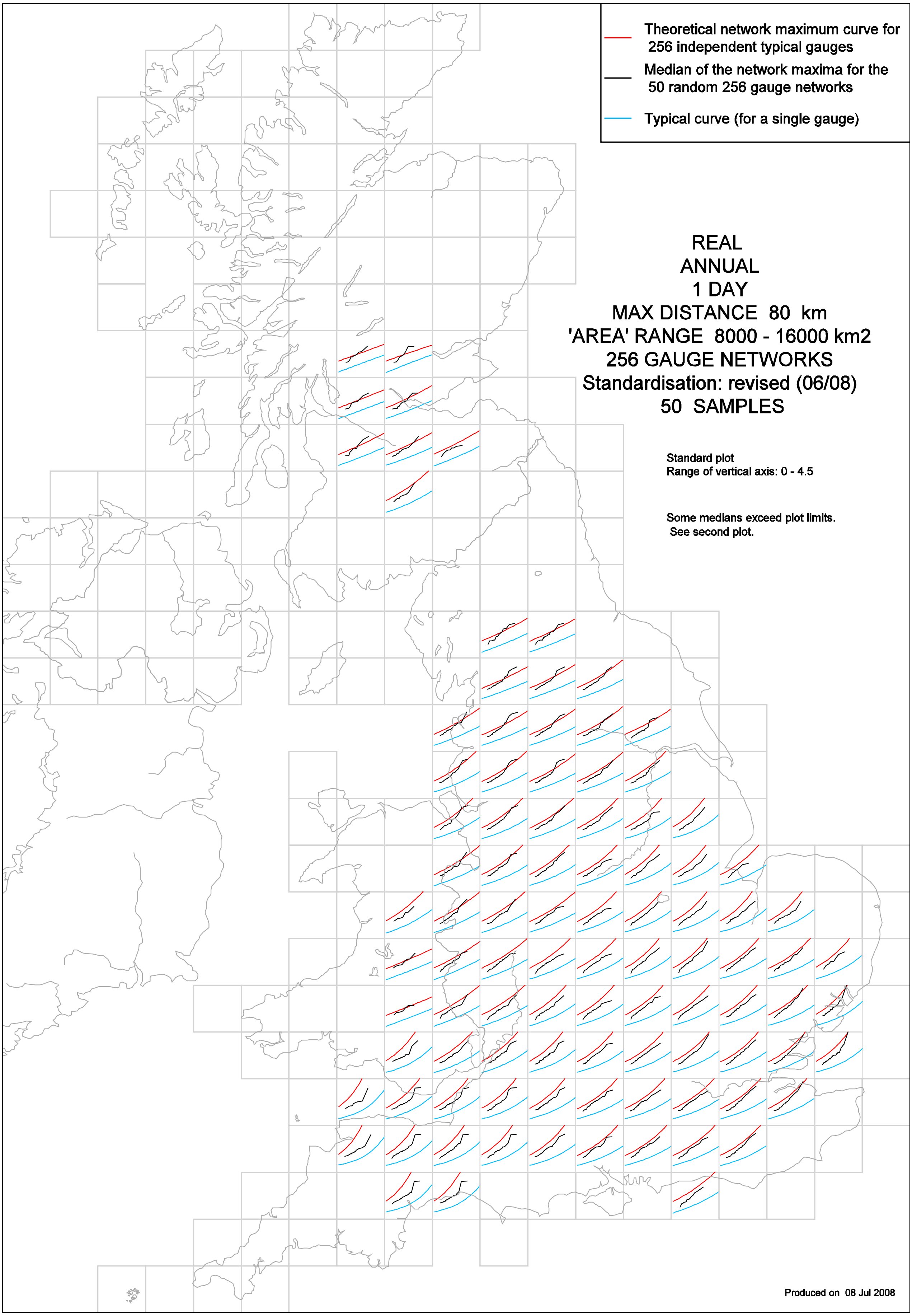


Figure E.12 Networks of 256 gauges

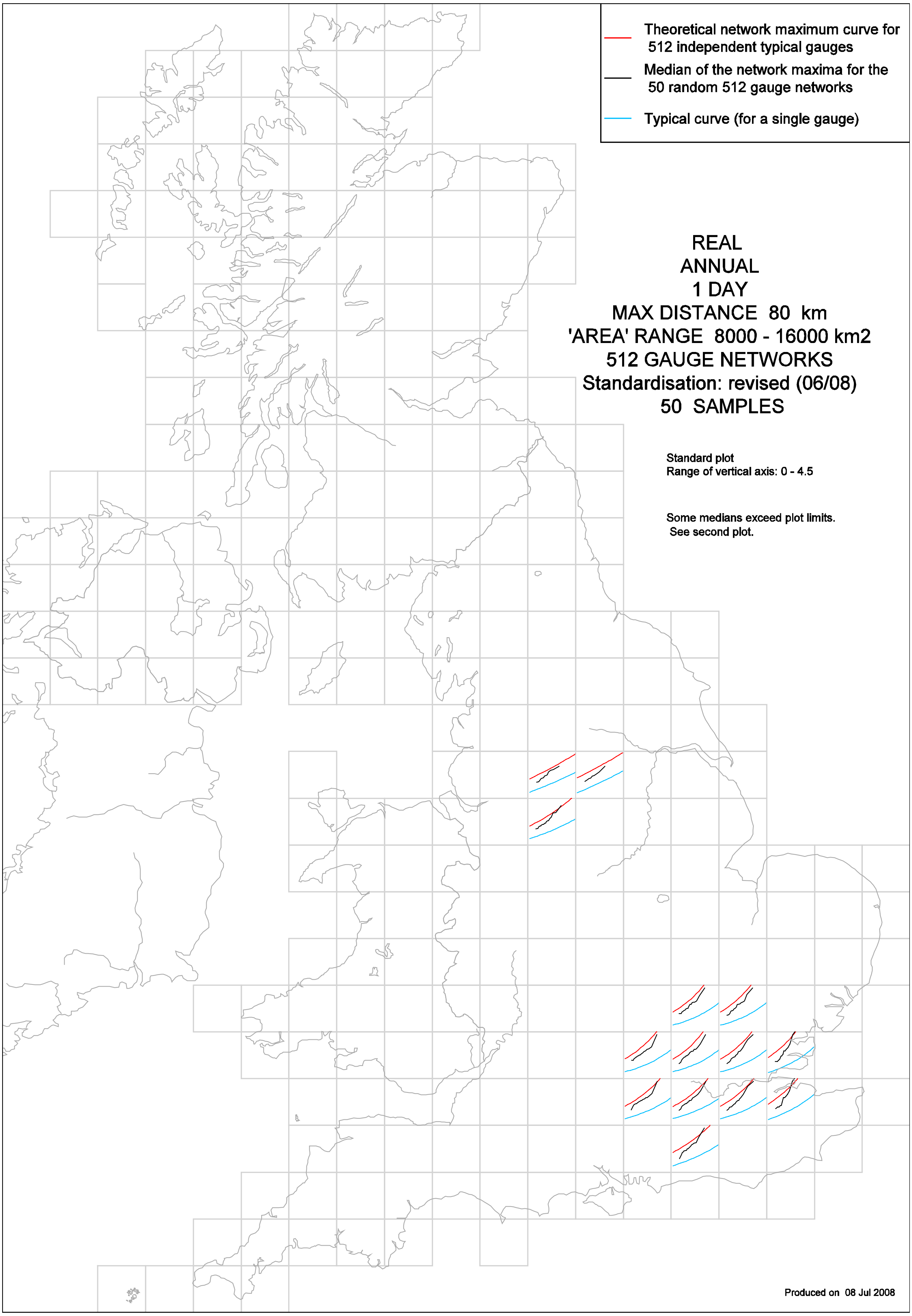


Figure E.13 Networks of 512 gauges

Appendix F Fitting the model for spatial dependence

F.1 Model for spatial dependence

F.1.1 The basic model

This project has developed a new model of spatial dependence in rainfall extremes. Note that this is not a full model for the joint distribution of annual maximum rainfalls at collections of raingauges, but instead specifies $F_{\max}(x)$ as a function of $F(x)$ (for the same value of x, the standardised rainfall), where

- $F(x)$ is the distribution function of (standardised) annual maximum rainfall at a typical site,
- $F_{\max}(x)$ is the distribution function of maximum (standardised) rainfall across a network of raingauges.

The fact that annual maximum rainfalls at nearby raingauges are statistically dependent is reflected in the relationship of $F_{\max}$ to F. The specification of the spatial dependence model relates $F_{\max}$ at a given "x" to F at the same "x". Hence it is sometimes convenient that the specification specifies $F_{\max}$ in terms of F without specifically using "x" in the notation. The number of gauges, denoted by N, plays an explicit part in the specification of the model because there is a need to ensure that the model behaves reasonably in comparison to the simplest case where the rainfalls at all gauges are independent. In the independent case

$$F_{\max}(x) = \{F(x)\}^N .$$

A more complete description of the ideas behind the model is given in Section 6.4.2 and a more direct statement of the model is given here.

For a given value, x, of rainfall, the value of the distribution function, $F(x)$, for a typical gauge is transformed to values on the "Gumbel scale", y, given by

$$y = -\ln\left(-\ln F(x)\right). \qquad \text{(F.1)}$$

The model of complete independence is represented by the corresponding transformation of the distribution function y_N

$$y_N = -\ln\left(-\ln\left\{F(x)^N\right\}\right) = -\ln N - \ln\left(-\ln F(x)\right) = -\ln N + y ,$$

where y is the function of x defined by Equation (F.1). The model for spatial dependence is specified in terms of the transformed value $y_{\max}$ which can later be used to find the distribution function of the network maximum, $F_{\max}(x)$, by inverting the transformation:

$$y_{\max} = -\ln(-\ln F_{\max}(x)). \qquad \text{(F.2)}$$

The model used here determines $y_{\max}$, for a given value x of network-maximum rainfall, as a function of the Gumbel reduced variate y corresponding to the distribution function of single-site rainfall for that same value of x. This function is given by

$$y_{\max}(y) = (-\ln N)H(y;a,b) + y\,, \qquad \text{(F.3)}$$

$$H(y;a,b) = \left\{1 + \exp\left(-\frac{y-a}{b}\right)\right\}^{-1}. \qquad \text{(F.4)}$$

Here $H(y;a,b)$ is the logistic distribution function with parameters a and b.

For completeness, the above model (in terms of the Gumbel reduced variate, y) is equivalent to the following rule for calculating $F_{\max}(x)$ from $F(x)$:

$$F_{\max}(x) = \{F(x)\}^{N^{k(F(x);a,b)}}\,, \qquad \text{(F.5)}$$

where

$$k(F(x);a,b) = \left\{1 + \exp\left(\frac{a}{b}\right)\{-\ln F(x)\}^{1/b}\right\}^{-1}. \qquad \text{(F.6)}$$

Unfortunately, the above relatively simple formulation has to be modified slightly to accommodate the fact that the supposed distribution function constructed in the above way is not always a proper distribution function. That is, there are some values of a and b for which the constructed function $F_{\max}(x)$ is not a one-to-one function. To overcome this potential problem, some constraints are imposed on the parameters to ensure firstly that, if the problem does arise then it happens for values of x considerably lower than the median and thus outside the range of interest here, and secondly that the formulation of the distribution function at Equation (F.3) is appropriately revised to ensure that all distribution functions actually implemented never decrease. This point is returned to in Section F.1.2.

For implementation, the parameters a and b are replaced by somewhat more meaningful parameters that relate more directly to the location of the function $y_{\max}(y)$ between y and $y_N(y)$. In either case, the parameters relate to the strength of dependence within a given network of gauges, in terms of how this affects the distribution of the spatial maximum. Part of the model fitting process entails relating these parameters to the characteristics of the network such as the areal extent, number of gauges, etc..

F.1.2 Modified parameterisation

In order to provide an interpretation of the modified parameterisation being introduced in this section, the meaning of the transformations in Section F.1.1 is first considered. These transformations are implicitly connected to a change of coordinate systems from those used in the usual plots showing results from data analyses. This change of coordinates is schematised in Figures F.1, and F.2.

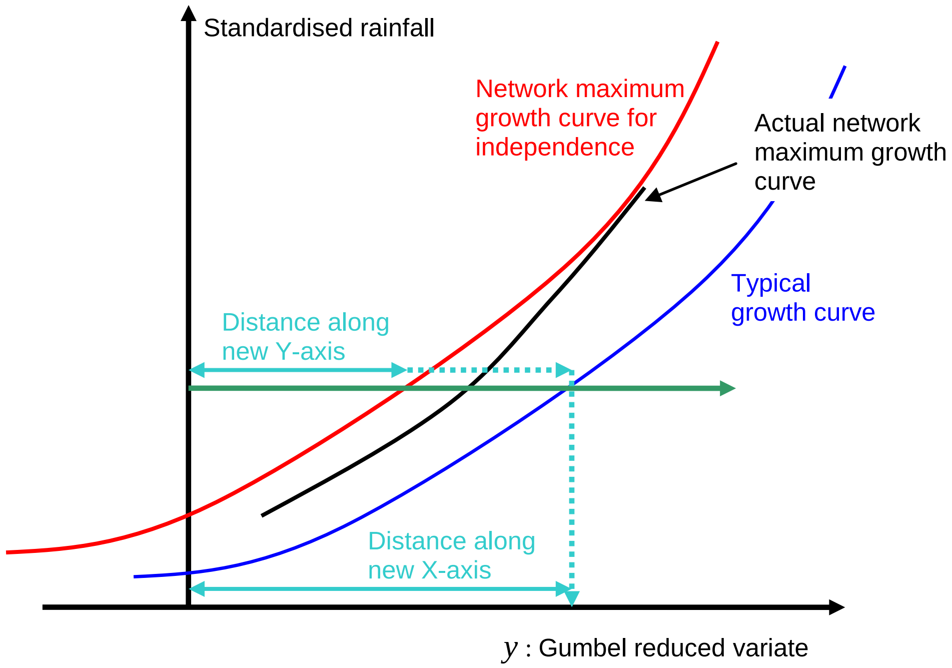


Figure F.1 Change of coordinate system implicit in transformed variables. New Y coordinates (*i.e.* vertical axis coordinates) are taken from the original horizontal axes, while new X coordinates (*i.e.* horizontal axis coordinates) are defined by finding the point on the "typical" growth curve that is at the same vertical location on the original axes.

Figure F.1 relates to how network maximum data are usually plotted, while the result is illustrated in Figure F.2. In addition Figure F.2 shows how the new parameterisation of the model relates to these coordinates. The effect of working with the transformed coordinates is to change the curve representing the distribution of the standardised rainfall at a typical location (the "typical growth curve") in Figure F.1, into a straight line in Figure F.2. This line is labelled "full dependence" as it represents both the distribution for a single raingauge and the distribution for the network maximum under the model that the standardised rainfall at all raingauges is always identical. The basic idea of the revised parameterisation is to use parameters which reflect the relative position of the actual network maximum curve between the "independent" and the "fully dependent" lines.

As indicated in Figure F.2, two parameters γ_1 and γ_2 are defined so that they each measure dependence on a scale from 0 to 1, where a value of "0" means independence and "1" means full dependence. The parameters relate to the distance at which the curve $Y = y_{\max}(y)$ lies between the two curves $Y = y_N(y)$ (independence) and $Y = y$ (full dependence). The relevant distance between the curves according to the model in Equation (F.3) is then $1 - H(y; a, b)$.

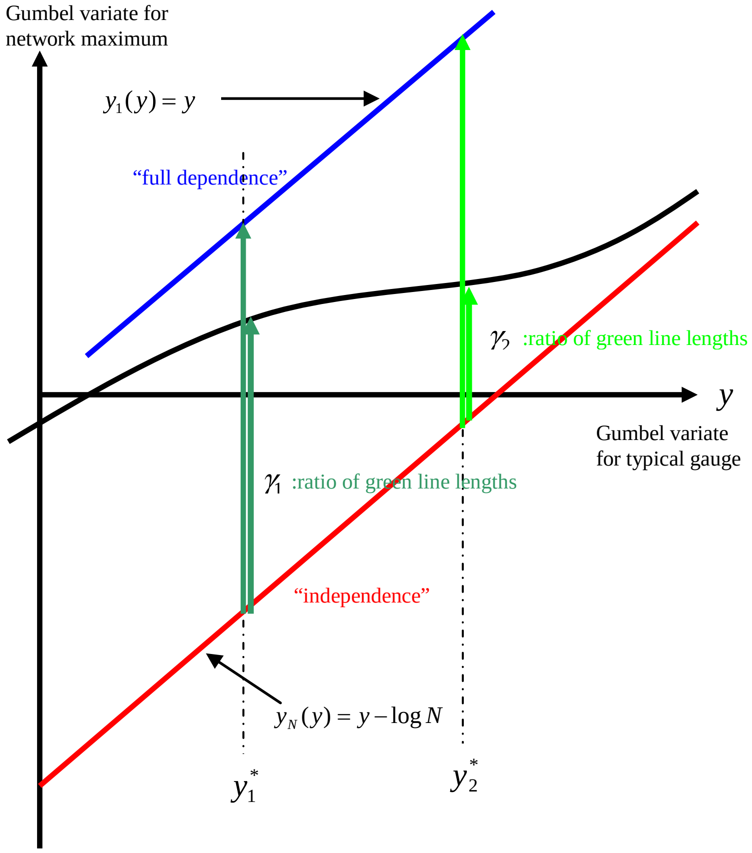


Figure F.2 Growth curves in transformed coordinates, with the parameterisation using γ_1, γ_2 which is introduced in Section F.2.

The overall model-fitting procedure eventually consists of obtaining raw estimates of the relative-location parameters γ_1 and γ_2 for many sizes of networks, and then finding relationships to network size which will allow these relative-location parameters to be predicted. It is considered important that γ_1 and γ_2 should be obtained for values of the Gumbel reduced variate that are relevant to the networks of gauges being considered and for which the rainfall-frequency plots of standardised rainfalls can be expected to provide good evidence even without fitting the specific model introduced here. Unfortunately these values change with the properties of the network being considered, but principally with the number of gauges, at least when the dependence is somewhat limited as is the case here. Figures F.3, F.4 and F.5 illustrate this point.

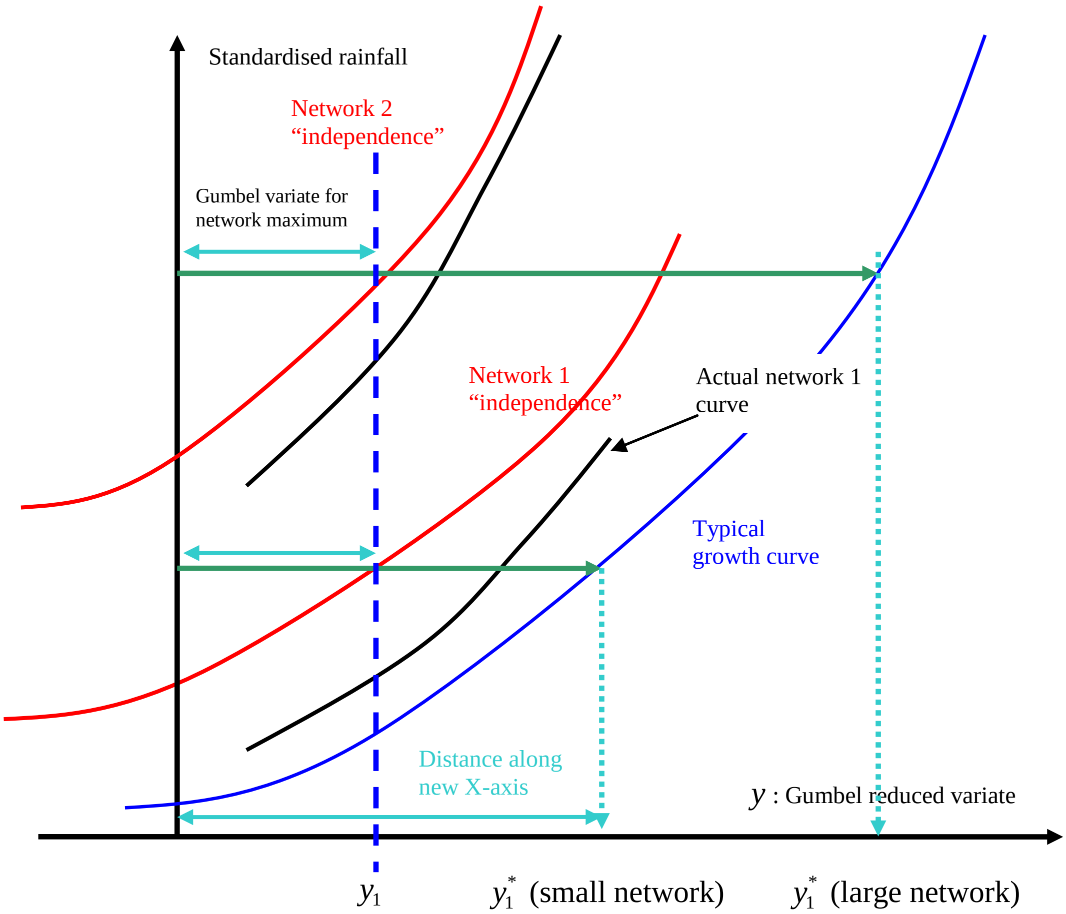


Figure F.3 Change of reference location on typical curve as the network size changes

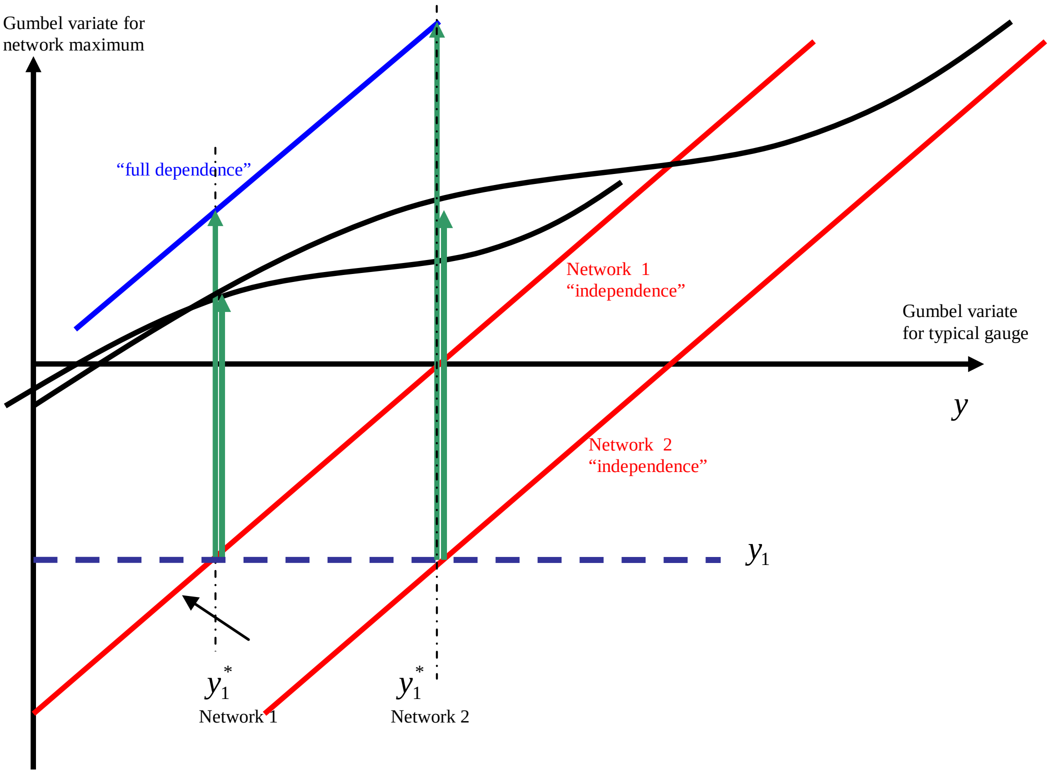


Figure F.4 Location of modified reference points for different networks

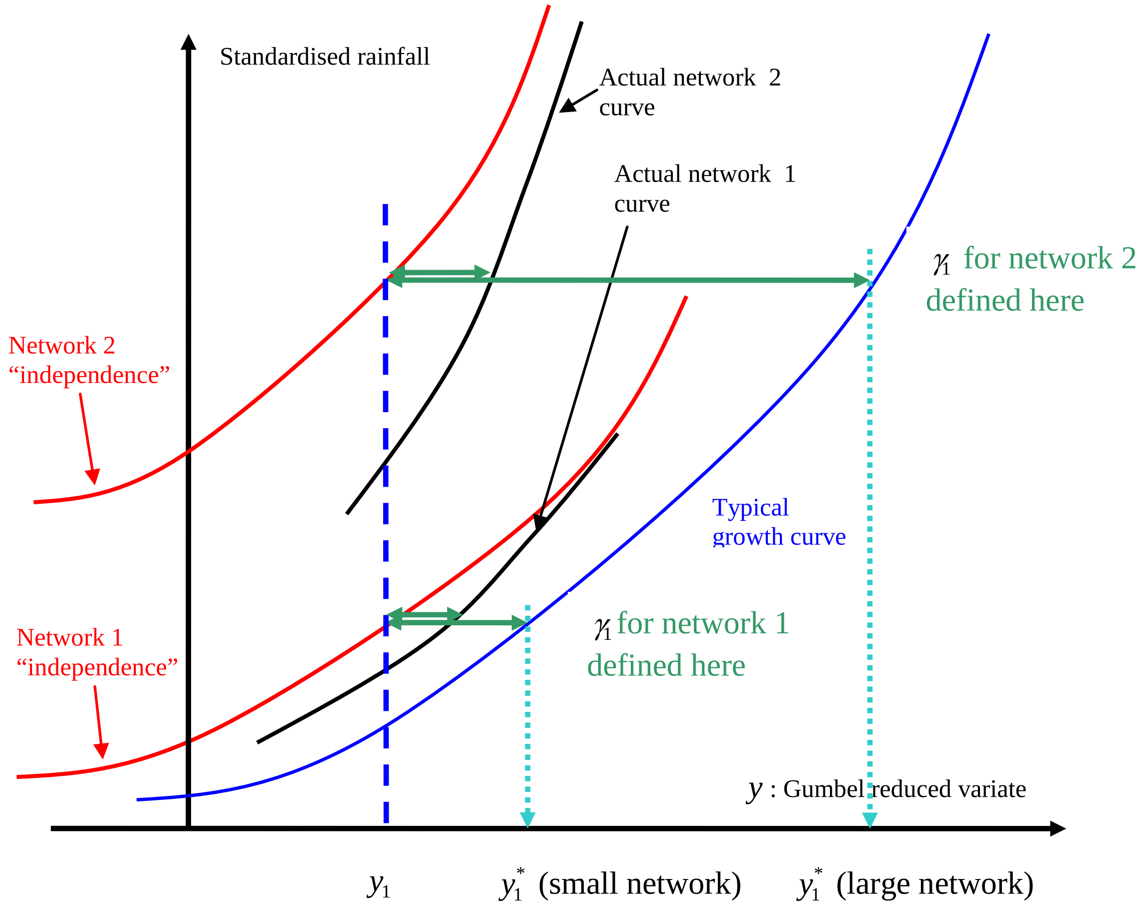


Figure F.5 Comparison of definitions of γ_1 for different network sizes

The relative-location parameters are evaluated at two values of y which are defined as follows. Two initial values y_1, y_2 ($y_1 < y_2$) are chosen and these remain fixed across all data sets. However, for a network of a given size, these values are converted to values y_1^* and y_2^* given by

$$y_1^* = y_1 + \ln N, \quad y_2^* = y_2 + \ln N, \qquad \text{(F.7)}$$

where N is the number of gauges in the network being considered. The effect of this is to ensure that the places at which the relative-location parameters are determined remain aligned with the values of the reduced variate y for which information can be gained from the available data. This is illustrated in Figure F.5. Note that the value $\ln N$ here corresponds directly to the "shift for N independent gauges" in the constant-shift model (Section 6.2 and Appendix E). For the present project the specific choices of $y_1 = 0$ and $y_2 = 4$ have been made.

The Greek character "gamma" is used in the notation for two new parameters γ_1 and γ_2 which are defined to be the values of $1 - H(y; a, b)$ at $y = y_1^*$, and at $y = y_2^*$:

$$\gamma_1 = 1 - H(y_1^*; a, b) = \left\{1 + \exp\left(\frac{y_1^* - a}{b}\right)\right\}^{-1}, \qquad \text{(F.8)}$$

$$\gamma_2 = 1 - H(y_2^*; a, b) = \left\{ 1 + \exp\left(\frac{y_2^* - a}{b} \right) \right\}^{-1}. \qquad \text{(F.9)}$$

Once a model relating γ_1 and γ_2 to the network configuration has been found, it can then be used to determine γ_1 and γ_2 for the networks required within the FORGEX procedure and these can then be converted to values of a, b given by

$$b = \frac{y_2^* - y_1^*}{\ln \frac{\gamma_1}{1-\gamma_1} - \ln \frac{\gamma_2}{1-\gamma_2}} = \frac{y_2 - y_1}{\ln \frac{\gamma_1}{1-\gamma_1} - \ln \frac{\gamma_2}{1-\gamma_2}}, \qquad \text{(F.10)}$$

$$a = \frac{y_2^* \ln \frac{\gamma_1}{1-\gamma_1} - y_1^* \ln \frac{\gamma_2}{1-\gamma_2}}{\ln \frac{\gamma_1}{1-\gamma_1} - \ln \frac{\gamma_2}{1-\gamma_2}} = \frac{y_2 \ln \frac{\gamma_1}{1-\gamma_1} - y_1 \ln \frac{\gamma_2}{1-\gamma_2}}{\ln \frac{\gamma_1}{1-\gamma_1} - \ln \frac{\gamma_2}{1-\gamma_2}} + \ln N, \qquad \text{(F.11)}$$

where the values of y_1^* and y_2^* are determined for the number of gauges, N, in the network being considered.

One reason for changing to the revised parameterisation is that the parameters can be given an intuitive interpretation in that they directly relate to the relative location of the growth curve for network maxima between the curves for the "typical raingauge" and the independence assumption: i.e. they relate directly to the relative location of function $y_{\max}(y)$ between y and $y_N(y)$. More importantly, the overall model-fitting procedure consists of obtaining raw estimates of the relative-location parameters γ_1 and γ_2 for many sizes of networks, and then finding relationships to network size which will allow these relative-location parameters to be predicted. In this sense, this part of the procedure is not too dependent on the specifics of the spatial-dependence model, as expressed in Equations (F.3) and (F.4), provided that modelled curves for the network maxima agree reasonably well with the empirical results for network maxima. However, a stronger reliance on the specifics of the model is made at the stage that it is used within the FORGEX procedure, as outlined in Section F.4.

The potential problem that the distribution function defined by the basic form of the model here, which was mentioned in Section F.1.1, arises because the function $y_{\max}(y)$ given by Equation (F.3) may not be monotonic. In visual terms, the curve for the modelled network maxima might have a region in which it decreases. Such a case is illustrated in Figure F.6, which also indicates the effect of the modification of the basic model.

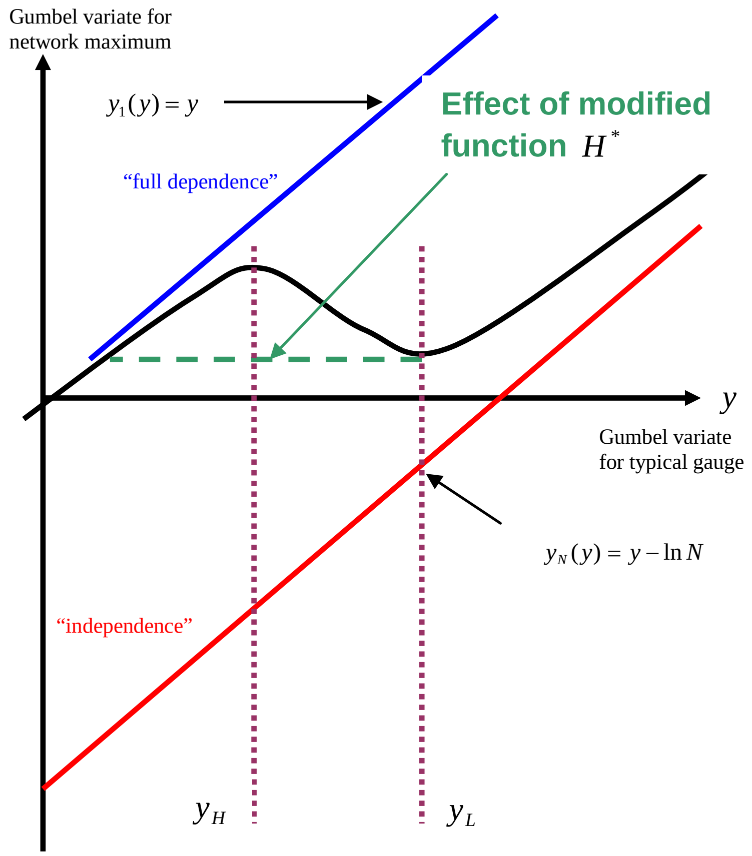


Figure F.6 Modification of basic model to ensure required behaviour.

Mathematically, the problem resolves in the first instance to finding whether the equation

$$1 + (-\ln N)\frac{\partial}{\partial y}H(y;a,b) = 0,$$

has any real roots. This equation is equivalent to a quadratic equation in the quantity

$$z = \exp\left(-\frac{y-a}{b}\right),$$

specifically

$$z^2 + \left(2 - \frac{\ln N}{b}\right)z + 1 = 0.$$

This equation does have distinct real roots if

$$b < \tfrac{1}{4}\ln N,$$

and then the roots z_L and z_H are given by

$$z_L, z_H = \frac{1}{2}\left\{\left(\frac{\ln N}{b} - 2\right) \pm \sqrt{\frac{\ln N}{b}\left(\frac{\ln N}{b} - 4\right)}\right\}$$

The two roots z_L, z_H correspond to values in the *y*-domain given by

$$y_L = a - b\ln z_L, \quad y_H = a - b\ln z_H$$

at which the values of $H(y,a,b)$ are

$$H_L = \left\{1+\exp\left(-\frac{y_L - a}{b}\right)\right\}^{-1} = \{1+z_L\}^{-1},$$

and

$$H_H = \{1+z_H\}^{-1}.$$

The root which is "nearest independence" has the higher value of the two values of H, corresponding to the lower value of z and higher value of y: these values are z_L and y_L.

The revised version H^* of the function H which is used within the spatial dependence model is defined as follows. If there are no real roots, it is equal to H. Otherwise, the value is only changed from H for values of y which are below y_L, and then only over a limited range of values of y. In the range for which a replacement is needed, the function $H^*(y;a,b)$ is defined to be the function which results in a constant value for $\{y+(-\ln N)H^*(y;a,b)\}$. The required constant value here is $\{y_L + (-\ln N)H_L\}$. So the function is replaced by $H^*(y;a,b)$ such that

$$\{y+(-\ln N)H^*(y;a,b)\} = \{y_L + (-\ln N)H_L\}$$

giving

$$H^*(y;a,b) = \frac{y_L - y}{(-\ln N)} + H_L.$$

However, even if $y < y_L$, $H^*(y;a,b)$ only replaces $H(y;a,b)$ if

$$H^*(y;a,b) > H(y;a,b).$$

The effect of the above modification is to repair problem cases. In the standard data-analysis plot showing the frequency distribution of the network maxima in which rainfall values are plotted on the *y*-axis against the Gumbel reduced variate on the *x*-axis, these problem cases would have the modelled distribution function "reversing itself", so that the function has more than one value for some values on the *x*-axis. The modified definition replaces such functions with single-valued functions having a vertical section in them. Since this behaviour may be deemed unrealistic, constraints have been placed on the allowable values of the parameters a and b (or γ_1 and γ_2) to exclude cases where, if the reversal problem arises, the root defining the transition to the modified function is positive: i.e. cases where $y_L > 0$ are excluded.

The model proposed here may be compared with the model of Dales & Reed (1989) by noting that the latter model is a special case of the model here, with the parameters specified by

$$(1-\gamma_1) = \frac{\ln N_e}{\ln N} = a + b\ln AREA + c\ln N + d\log D, \qquad \text{(F.12)}$$

and $\gamma_2 = \gamma_1$. Here N_e is the "equivalent number of independent gauges" in the terminology used by Dales & Reed, and a, b, c and d are the regression coefficients in their model for the ratio of logarithms using the variables $AREA$, number of gauges (N) and duration (D).

F.2. Raw estimates of the dependence parameters

The basis of fitting raw estimates of the dependence parameters is that the proposed model allows the distribution function for network maxima to be treated as a function of the distribution function of single-gauge rainfall, evaluated at the same value of rainfall:

$$F_{\max}(x) = G\{F_T(x); \gamma_1, \gamma_2, N\}, \qquad \text{(F.13)}$$

where γ_1 and γ_2 are the relative-location parameters which need to be estimated, and where N is the number of gauges in the network being considered.

When fitting the model, the values required for $F_T(x)$ are obtained from a GEV distribution fitted as a “typical” distribution for single-gauge rainfall. However the values of x are in this case the network maxima, rather than the rainfall at an individual gauge. Thus, in this formulation the distribution function to be fitted is a two parameter distribution

$$F_{\max}(x) = F_{\max}(x; \gamma_1, \gamma_2, N), \qquad \text{(F.14)}$$

and it is fitted to sets of data consisting of values of network maxima, x.

The basic step of model fitting to find raw estimates of the spatial dependence parameters is done for individual cases, each consisting of selected values of:

- a given network size (number of gauges);
- area covered;
- central location.

The dataset used is the same as that described for the construction of the plots used to explore how spatial dependence varies, examples of which are in Appendix E. Thus, for each case, the following are used:

- the fitted growth curve for typical standardised rainfall for gauges in the neighbourhood;
- values of the network maxima for randomly selected networks of the required characteristics for a number of years.

The sets of network maximum values are combined together over a number of repetitions of the random selection process to form a pooled or combined set of values.

The method selected for fitting the model in Equation (F.14) is based on minimising an Anderson-Darling measure of fit between the modelled distribution and the empirical distribution of the network maxima. This has the advantage of having a basis for fitting which is directly related to a distance between the modelled and empirical distribution functions.

Let the set of values in the combined re-sampled network-maxima dataset for a given case be $\{x_j; j = 1, \cdots, M\}$, where M will vary from case to case. Further let the ordered version of the dataset be $\{x_{(j)}; j = 1, \cdots, M\}$. The usual form for the Anderson-Darling criterion, A_D, is given by

$$A_D = -\frac{2}{M}\left[\sum_{i=1}^{M}\left(i - \tfrac{1}{2}\right)\left\{\ln F(x_{(i)}) + \ln\left(1 - F(x_{(M+1-i)})\right)\right\}\right] - M\,. \qquad \text{(F.15)}$$

For present purposes, this is revised by dropping unnecessary terms, splitting and reversing a summation and recombining to give

$$A_R = -\left[\sum_{i=1}^{M} \left\{ p_{i,M} \ln F(x_{(i)}) + (1 - p_{i,M}) \ln\left(1 - F(x_{(i)})\right) \right\}\right] \qquad \text{(F.16)}$$

where $p_{i,M}$ is a plotting position given by

$$p_{i,M} = \frac{i - \frac{1}{2}}{M}. \qquad \text{(F.17)}$$

While the Anderson-Darling criterion has an established background in statistics as the basis of a test of fit, and while it has also been used elsewhere as an objective function when fitting parameters, it seems worth including the following brief justification that it does represent a pertinent measure of fit for use as an objective function. An individual contribution to the sum in Equation (F.16) is

$$A_{R,i} = -\left\{p_{i,M} \ln F_i + (1 - p_{i,M}) \ln\left(1 - F_i\right)\right\} \qquad \text{(F.18)}$$

where $F_i = F(x_{(i)})$ and where $F(x_{(i)})$ is a function of the parameter values to be fitted. If each F_i were free to take any value then minimising the objective function above would lead to values of F_i which minimise separate objective functions

$$A_{R,i}(F) = -\left\{p_{i,M} \ln F + (1 - p_{i,M}) \ln\left(1 - F\right)\right\}. \qquad \text{(F.19)}$$

These separate objective functions are minimised at

$$F_i = p_{i,M}. \qquad \text{(F.20)}$$

It then follows that choosing parameter values so as to minimise the overall objective function A_R (Equation (F.16)) produces a fit which is a compromise between matching the fitted distribution function values to the plotting positions, as in Equation (F.17), and the constraints implied by insisting that these values arise from a given family of distributions. Note that this argument implies that sets of plotting positions other than those corresponding to the usual Anderson-Darling criterion could be used, but this has not been done here.

The advantages of using the Anderson-Darling criterion, rather than a maximum likelihood procedure for example, are thought to be:

- the fitting procedure can be given an interpretation in terms of the matching of plotting positions (and plotting positions play a role elsewhere in this project);
- the formulation in terms of contributions corresponding to ordered observations would allow, if necessary, a revision of the criterion such that the lowest observations are excluded, while retaining the justification for believing that the fit will be reasonable over the range of the observations that are included.

To summarise the above, the following objective function is used for fitting the spatial dependence model to a single case

$$S(\gamma_1,\gamma_2) = -\left[\sum_{i=1}^{M}\left\{ p_{i,M}\ \ln G\left\{F_T(x_{(i)});\gamma_1,\gamma_2,N\right\} + (1-p_{i,M})\ln\left(1-G\left\{F_T(x_{(i)});\gamma_1,\gamma_2,N\right\}\right)\right\}\right] \tag{F.21}$$

where $F_T(\cdot)$ is the (fixed) GEV distribution for typical standardised rainfall, and where the function G is as above. Specifically

$$G(F;\gamma_1,\gamma_2,N) = F^{N^{k(F;a,b)}}, \tag{F.22}$$

where $k(F;a,b)$ is given by Equation (F.6) and where a and b are defined in terms of γ_1 and γ_2 by Equations (F.10) and (F.11).

The above procedure for obtaining raw estimates of the spatial dependence parameters has been applied to a large set of network configuration cases. In brief, these consisted of all combinations of the following factors, restricted by the ability to find networks with those characteristics (for example there are no networks with large numbers of gauges within small radii for any target location, but this availability varies radically between the hourly and daily durations):

- Durations: from 1 hour to 8 days (11 different durations)
- Radius: radii in kilometres 2,4,8,16,32,64,128,200,300,600,1300
- Number of gauges: 2,4,8,16,32,64,128,256,512,1024,2048
- Central locations: on regular grids covering the country, grid spacing 10km for radii up to 32 km, spacing 20 km for radii 64 km and over.

For each of these target configurations, the following procedure was applied. The network of gauges available within the given radius of the central location was examined to establish firstly whether or not the required configuration could be met at all, but also to establish a range of acceptable sub-network areas that could reasonably be extracted from the records being used. The network area is always defined here in the way established by Dales & Reed and used by the FEH. The range of acceptable areas always has a ratio of 2 to 1 for the upper and lower bounds. The procedure mirrors the Dales & Reed approach of selecting random sub-networks of all the gauges available in a given year, subject to the area being within the specified range. As part of the information extracted from the estimation procedure, the average of all the areas of the selected sub-networks was used to define the “area” associated with the estimated spatial dependence parameters. In addition to this descriptor, a number of others were carried forward as being potentially useful in the later stage of modelling which attempts to relate the spatial dependence parameters to descriptors of the network from which the maximum is extracted. These were:

- the central location, and the average of the locations of gauges;
- the altitude of the central location, and the average of the altitudes of the gauges;
- the value of SAAR at the central location, and the average of the SAAR values for the gauges.

F.3 Fitting a model for the spatial dependence parameters

The procedure outlined in Section F.2 resulted in the sets of raw estimates of the dependence parameters with associated descriptor variables. These were subjected to an initial exploratory analysis with the aim of finding a model in the form of an equation which can later be used (as outlined in Section F.4) to determine values of the spatial dependence parameters appropriate to those networks of gauges which are used within the FORGEX procedure and for which network-maxima are determined for use within the procedure.

The exploratory analysis was undertaken separately for each of the 11 durations, but part of the consideration in making a selection of model structure was the need to ensure a reasonable consistency of behaviour of the modelled spatial dependence parameters across the durations. This led to a decision to restrict the number of descriptors that would be used in the equations being estimated. Drawing conclusions from the exploratory analyses undertaken here is made more difficult because of the underlying basis of the datasets being considered: the values of the raw spatial dependence parameters for individual cases will be closely linked to the values for neighbouring locations simply because they have been determined from overlapping sets of raingauges, and this overlapping effect will be substantial for the larger radii and thus larger areas.

Eventually a decision was made to use equations of the basic form

$$\gamma = a + b\ln(AREA) + c\frac{\ln N}{1+\frac{1}{2}\ln N} + d\,\frac{SAAR}{1000}$$

for both γ_1 and γ_2. This basic form is supplemented by restricting the values to lie between zero and one, and to have $\gamma_2 \le \gamma_1$. The first of these restrictions has been used within the fitting of the model for the spatial dependence parameters that was implemented using a non-linear least squares procedure in which the predicted value is a truncated version of the basic form . Both sets of constraints are included in the values of the spatial dependence parameters which are used in the FORGEX procedure. If the test that $\gamma_2 \le \gamma_1$ fails, the value of γ_2 is reset to that of γ_1.

In the above equation, $SAAR$ refers to the average SAAR across the gauges in the network of N gauges and, once again, $AREA$ is the area of the network based on the Dales & Reed definition in terms of the average inter-gauge distance. The equation includes a term relating to the number of gauges which is modified from its usual simpler form of just having $\ln N$. This was included because values of the coefficient c are sometimes negative and using the simpler form would then mean that values of γ (dependence) would decrease indefinitely with increasing number of gauges which is counter-intuitive. The modified term moderates the influence of the number of gauges in very extreme cases. In practice, including the modified term had a small benefit in the performance of the model at the fitting stage.

Values of the coefficients for later use are given in Tables F.1 and F.2. These also include values for the empirical coefficient of determination (R^2) of the models.

Table F.1 Model for the spatial dependence parameter γ_1

		Coefficients for γ_1			
Duration	R^2	a	b	c	d
1 hour	0.2218	0.172522	-0.013421	-0.044122	0.074768
2 hours	0.2055	0.227983	-0.014943	-0.041989	0.035127
4 hours	0.3546	0.357405	-0.026488	-0.022664	0.000433
6 hours	0.3787	0.411607	-0.027400	-0.021806	-0.029200
12 hours	0.4513	0.540443	-0.033063	-0.047564	-0.050845
18 hours	0.5270	0.614522	-0.039594	-0.039351	-0.053770
24 hours	0.4496	0.599071	-0.031730	-0.069845	-0.076641
1 day	0.7836	0.764177	-0.051923	0.026828	-0.100842
2 days	0.7961	0.789065	-0.054696	0.035308	-0.078894
4 days	0.8216	0.790892	-0.060585	0.060219	-0.051434
8 days	0.8033	0.839129	-0.057941	0.026638	-0.058055

Table F.2 Model for the spatial dependence parameter γ_2

		Coefficients for γ_2			
Duration	R^2	a	b	c	d
1 hour	0.2324	0.055190	-0.005923	-0.076473	0.108828
2 hours	0.1958	0.104052	-0.007057	-0.083696	0.077982
4 hours	0.2113	0.223009	-0.016363	-0.081603	0.040209
6 hours	0.2340	0.252268	-0.016200	-0.077781	0.011422
12 hours	0.2666	0.307816	-0.015863	-0.100175	-0.010657
18 hours	0.3181	0.390480	-0.022551	-0.114791	-0.010932
24 hours	0.2956	0.333007	-0.009053	-0.139122	-0.049676
1 day	0.3731	0.481422	-0.029718	-0.028951	-0.063216
2 days	0.3842	0.521926	-0.031666	-0.038184	-0.054570
4 days	0.4630	0.523486	-0.039878	-0.007107	-0.028527
8 days	0.4161	0.544287	-0.036390	-0.040574	-0.031430

If the coefficient a is taken as a representative measure of strength of dependence, the results in Tables F.1 and F.2 show: increasing dependence with duration and less dependence as measured by γ_2 at its typical return period than measured by γ_1 at its lower typical return period. The coefficient b indicates that dependence decreases with increasing area, as expected. Surprisingly, the coefficient c (for the effect of the number of gauges) is in most cases negative: intuitively, one might expect that “dependence” should increase as the number of gauges increases. However, the relevance of this point is not straightforward because of two considerations:

(i) the return period on the typical curve at which this dependence is measured also varies with the number of gauges, as indicated in Figure F.5;

(ii) the overall effect of the dependence model is not contained in the dependence measure γ itself, but rather in $(1-\gamma)\times\ln N$, which is the left-shift on the Gumbel scale from the "typical" curve to the network maximum curve – what "intuition" requires is that this left-shift should increase with N.

The variation of the coefficient d with duration indicates that, for low durations (up to around 4 or 6 hours) the dependence increases with SAAR, but for larger durations the dependence decreases with SAAR.

F.4 Using the spatial dependence model within FORGEX

The part of the FORGEX procedure that makes use of the spatial dependence model is that which assigns plotting positions to network maxima. For this, all the gauges within a given distance of the central location which have data for a given year are found and the maximum of the standardised annual maxima is used as the network maximum for that given year. For each year, the network maximum has associated with it values of the following quantities:

- the number of gauges available for the year;
- the area (as defined by the Dales and Reed procedure) associated with the actual set of gauges available for the year;
- the average SAAR for the region covered by the network.

These associated values are used to specify the spatial dependence parameters for the network using the model described in Section F.3. This allows the dataset to be reduced to a set of pairs $\{x_{(i)}, s_i\,;\, i=1,\cdots,n\}$, where n is the number of years with at least one gauge in the network, the values $\{x_{(i)}\,;\, i=1,\cdots,n\}$ are the ordered set of network maxima and $\{s_i\,;i=1,\cdots,n\}$ are the corresponding (re-ordered with the network maxima) values of the auxiliary information describing the spatial dependence for each year: specifically,

$$s_j = (\gamma_{1,j}, \gamma_{2,j}, N_j)\,,$$

where $\gamma_{1,j}$ and $\gamma_{2,j}$ are the values of the relative location parameters determined for each year, and N_j is the number of gauges with valid annual maxima in the network in year j.

The method for determining plotting positions which was used in the FEH procedures was found to have problems when used with the non-constant shift model for spatial dependence that is used here. One aspect of these problems was that the sequence of plotting positions produced was not necessarily increasing. The FEH approach was based on treating each plotting position separately and considered the likelihood function for the particular plotting position. A revised procedure has been implemented for this project. This is based on treating all plotting positions jointly and works with the joint likelihood function of these parameters. As with the FEH approach, a modified maximum-likelihood approach to estimation is taken in which a modified likelihood function is defined which has the property of reproducing the standard plotting position formula when applied to models in which there is independence.

One problem with applying a standard approach to defining a likelihood function for the plotting positions is that the points at which the distribution function is evaluated are determined by random quantities which are themselves part of the observed dataset. This is overcome by considering notional fixed points which are either just above or just below the actual observations and the likelihoods associated with the probabilities for these fixed values are determined. The likelihood for points just below and just above an observation are different but can be combined together in a weighted form to define a modified log-likelihood function which then can be used to estimate the probability (which is the plotting position) for the observation. The weighting can be chosen so as to yield a set of plotting positions which coincides with the standard formula.

Consider a set of n fixed points immediately above the n observed values: that is, there is one observation below the first point, one between each pair, and none above the highest point. Specifically, there is an observation, with auxiliary information s_j, which is in the interval between notional points whose probabilities are p_{j-1} and p_j. The likelihood of observing this configuration is

$$G(p_1;s_1)\prod_{j=2}^{n}\left\{G(p_j;s_j)-G(p_{j-1};s_j)\right\}.$$

Consider a set of n fixed points immediately below the n observed points: that is, there is no observation below the first point, one between each pair, and one above the highest point. Specifically, there is an observation, with auxiliary information s_j, which is in the interval between notional points whose probabilities are p_j and p_{j+1}. The likelihood of observing this configuration is

$$\prod_{j=1}^{n-1}\left\{G(p_{j+1};s_j)-G(p_j;s_j)\right\}\left\{1-G(p_n;s_n)\right\}.$$

For the definition of the modified (weighted) log-likelihood function, weights b_j are used on the contributions from “points below” and $1-b_j$ on contributions from “points above”. The definition of the weighted log-likelihood is

$$\begin{aligned}L &= b_1\ln\left\{G(p_1;s_1)\right\}+\sum_{j=2}^{n-1}b_j\ln\left\{G(p_j;s_j)-G(p_{j-1};s_j)\right\}\\ &+b_n\ln\left\{G(p_n;s_n)-G(p_{n-1};s_n)\right\}\\ &+\left(1-b_1\right)\ln\left\{G(p_2;s_1)-G(p_1;s_1)\right\}+\sum_{j=2}^{n-1}\left(1-b_j\right)\ln\left\{G(p_{j+1};s_j)-G(p_j;s_j)\right\}\\ &+\left(1-b_n\right)\ln\left\{1-G(p_n;s_n)\right\}\end{aligned}$$

With obvious conventions for *j*=0 and *j*=*n*+1, this formula can be shortened to the following expression:

$$L = \sum_{j=1}^{n} b_j \ln\{G(p_j; s_j) - G(p_{j-1}; s_j)\} + \sum_{j=1}^{n} (1 - b_j) \ln\{G(p_{j+1}; s_j) - G(p_j; s_j)\}.$$

The weights b are selected in parallel to the approach taken for the FEH, where they were specified so as to reproduce the standard plotting position formulae in the case of a single-gauge network. In this simple case the weighted likelihood is

$$L = \sum_{j=1}^{n} b_j \ln\{p_j - p_{j-1}\} + \sum_{j=1}^{n} (1 - b_j) \ln\{p_{j+1} - p_j\}.$$

For this simple model, the optimal values of $\{p_j\}$ can readily be found by differentiation. This leads to equations for the optimal set of plotting positions p_j relating these to the b_j. The following conclusions can then be drawn. If the required solution is in the form

$$p_k = \frac{k - a}{n + 1 - 2a},$$

then, firstly, b_k should be a linear function of k and, secondly, this function must be given by

$$b_j = \frac{n(1-a) + (2a-1)(j-1)}{n + 1 - 2a}.$$

This compares with the result for the different likelihood function used for the FEH approach,

$$b_j = \frac{na + (1-2a)j}{n + 1 - 2a}.$$

The FEH set of weights goes from approximately a to $(1-a)$, while the set here for the revised procedure does the reverse.

On testing the new joint-likelihood procedure in comparison with the FEH procedure for cases with $\gamma_1 = \gamma_2$ (which corresponds to the model used in the FEH analysis), it was found that the two procedures led to identical or near identical plotting positions for the highest ranked observations, but with marked differences for the lowest ranked observations. These low-ranked observations are not used in the FORGEX methodology.

Appendix G Sets of test sites

A set of gauges with long hourly and daily annual maxima records was retrieved to use for testing the rainfall frequency methodology being developed. The full set comprises 71 sites, based on sites near reservoirs, sites with long rainfall records, a close pair of sites with contrasting SAAR values, and sites to fill in voids in the spatial coverage.

For early analyses, an initial set comprising 34 sites based solely on sites with long rainfall records was used. This set was later expanded to include first one other site, and then a second one, as outlined below. Although being selected on record length only, these early sets include nine reservoir sites.

The text in the main body of the report makes reference to these different test sets by the number of sites that are included in them.

G.1 The set of 34 sites

The original set of 34 sites was selected to include 34 pairs of hourly and daily gauges with long records that were located near each other, preferably on the same site but not being more than 1 km apart. These sites are shown as coloured dots in Figure G.1. In this set all the daily gauges have more than 30 1-day annual maxima. In southern Britain a satisfactory number of hourly gauges could be found that had at least 40 24-hour annual maxima. However, in northern Britain (north of 5000) and Northern Ireland the criterion for hourly data had to be relaxed to sites with at least 20 24-hour annual maxima. The use of 24-hour rather than, for example, 1-hour maxima as a selection criterion was to ensure that gauges with continuous records were selected, as opposed to maxima from tabulations which may not include all durations.

G.2 The sets of 35 and 36 sites

As the analysis proceeded it became clear that it would be beneficial to include Honister Pass in the test set. This site is known particularly for its very high longer-duration rainfalls. It is located in the Cumbrian mountains in northwest England at a comparatively high altitude of 358 m. Its location is shown on the map in Figure G.1 as the southeastern of the two black ‘+’ markers. The daily record for Honister Pass comprises 20 1-day annual maxima, and the hourly record consists of 12 24-hour annual maxima. Hence, the test set comprising 35 sites includes the above 34 sites with long records plus a gauge-pair at Honister Pass which has somewhat shorter records.

Honister Pass has a high standard average annual rainfall (SAAR) of 3510 mm. To ensure the test set includes nearby sites with contrasting SAARs, a gauge-pair at Cornhow Sewage Works, near Loweswater, was included in a test set comprising 36 sites. Cornhow has a SAAR of 1503 mm, and its location is shown in Figure G.1 as the northwestern of the two black ‘+’ markers. The daily record at Cornhow has 30 1-day annual maxima, and the hourly gauge has 25 24-hour annual maxima.

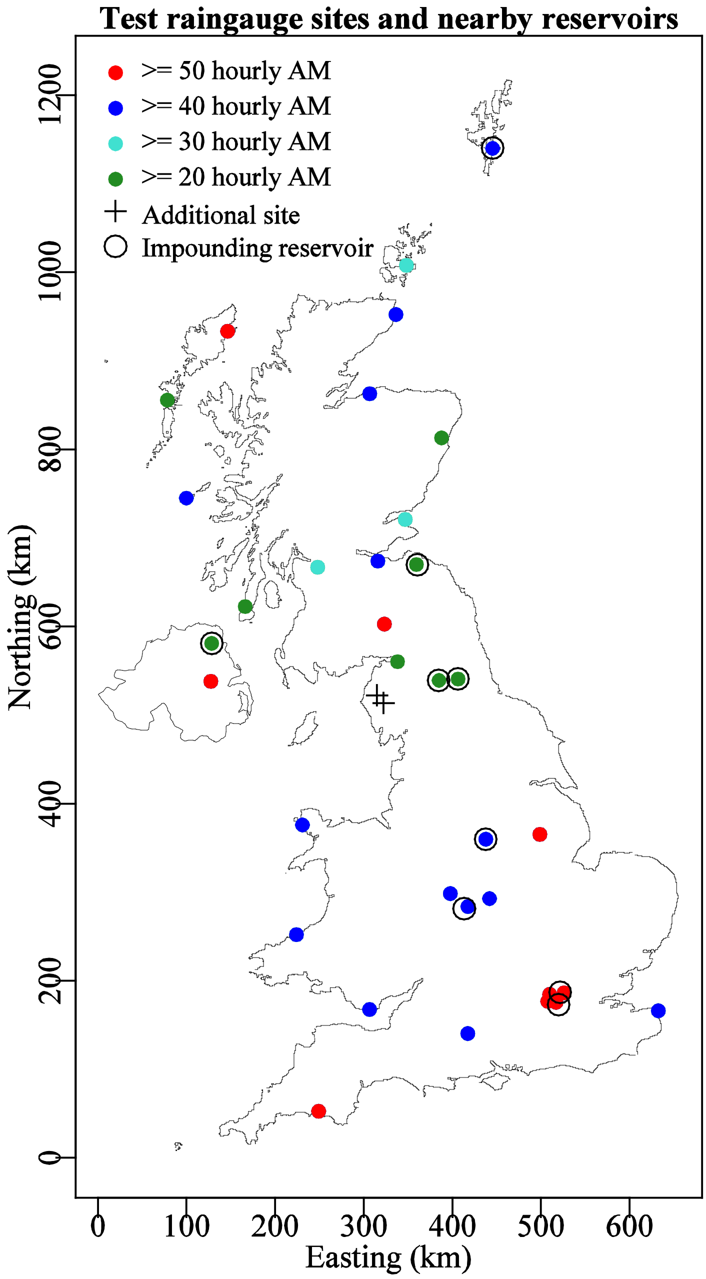


Figure G.1 **Locations of 36 sites in the UK with pairs of hourly and daily gauges with long records. Sites marked with coloured circles were in the first test set of 34 sites. These all have more than 30 1-day annual maxima. The colour of the circles shows the length of the 24-hour annual maxima record at each site (see legend). See text for information on the two additional sites marked '+'.**

G.2 The full set of 71 sites

The full test set comprises 71 sites, and include the sites in the smaller test sets. The full set was selected based on sites near reservoirs, sites with long rainfall records, a few sites with high SAAR, and sites to fill in voids in the spatial coverage, as detailed in Table G.1. In addition to the Honister Pass site, which has a very high SAAR, two other gauges with high SAARs are included. The locations of the sites are shown in Figure G.2.

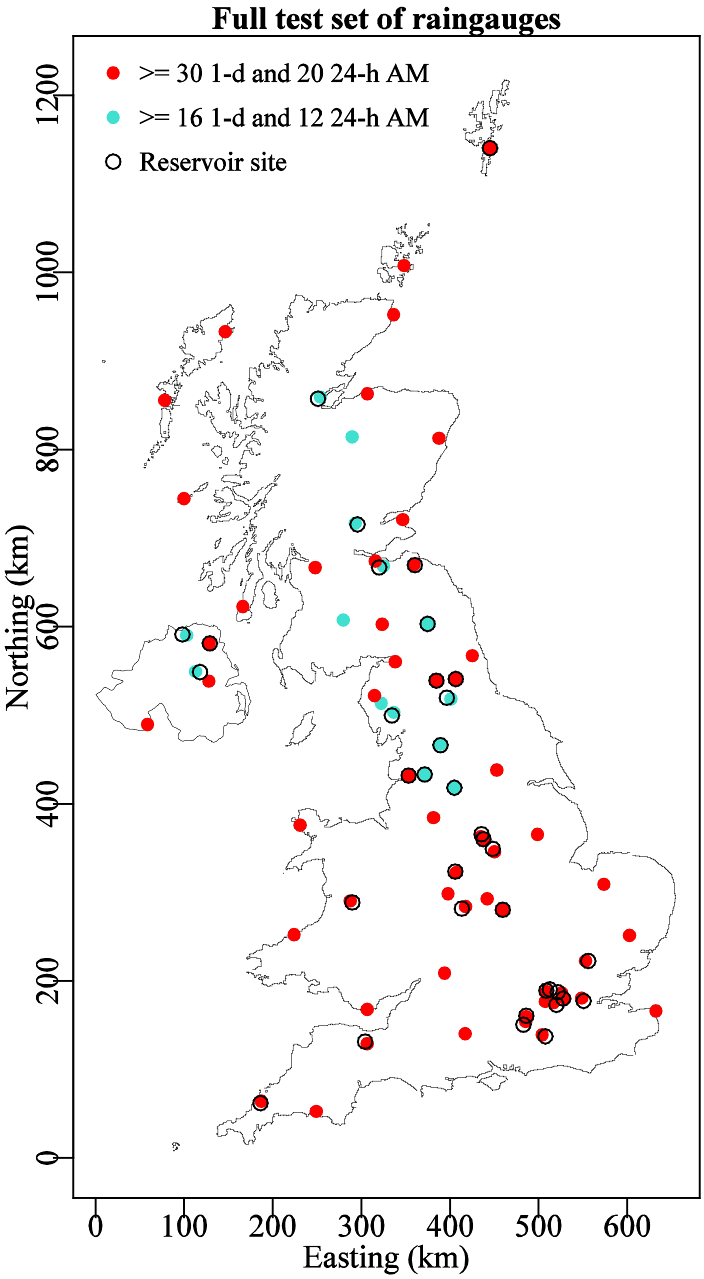


Figure G.2 Locations of the 71 sites in the full test set. Each site has a pair of hourly and daily raingauges with varying record lengths (see legend). Open black circles mark the location of nearby reservoirs.

Table G.1 Details of raingauges and dams in the full test data set. Gauges in sub-sets of the full set are labelled in the column "Original set of 34, 35 or 36". Grid = 0 denotes the GB National Grid system, and grid = -1 denotes the Irish grid.

Near impounding reservoir (R)	Long record (L)	Added for spatial cover (S)	Very high SAAR location (V)	Original set of 34, 35 or 36	Number of daily gauge	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of hourly gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
R	L			34	10763886	Lerwick	4454	11397	0	82	40	1202	10763886	42	1072	Sandy Loch	A
	L			34	767475	Kirkwall	3482	10077	0	26	39	1009	10767475	33			
	L			34	770765	Wick Airport	3365	9522	0	36	56	789	10770765	48			
	L			34	727288	Stornoway Airport	1464	9331	0	15	41	1171	10727288	50			
	L			34	10811394	Kinloss	3068	8628	0	5	40	621	10811394	48			
R					10788068	Dingwall	2538	8593	0	7	22	793	10788069	19	2714	Loch Ussie	B
	L			34	736633	Benbecula Airport	782	8555	0	6	34	1261	10736633	21			
		S			817692	Aviemore	2896	8143	0	228	16	919	10817692	17			
	L			34	10841490	Dyce	3877	8127	0	65	42	790	10841490	26			
	L			34	10719008	Tiree	999	7446	0	9	34	1163	10719008	44			
	L			34	885313	Leuchars	3468	7209	0	10	43	654	10885313	33			
R					881656	Kinkell Bridge	2931	7166	0	20	16	891	881658	12	2142	East Fordoun	B
	L			34	899407	Turnhouse	3159	6739	0	35	39	667	10899407	43			
R	L			34	10903637	Nunraw Abbey	3594	6700	0	197	33	824	10903638	23	471	Thorters	A

Near impounding reservoir (R)	Long record (L)	Added for spatial cover (S)	Very high SAAR location (V)	Original set of 34, 35 or 36	Number of daily gauge	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of hourly gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
R					900176	Fairmilehead W Wks	3248	6683	0	180	42	743	10900175	18	114	Clubbiedean	A
	L			34	660285	Abbotsinch	2480	6667	0	5	32	1037	10660285	32			
	L			34	10675177	Machrihanish	1663	6226	0	10	31	1164	10675177	20			
		S			10621335	Eliock	2797	6074	0	162	41	1320	10621336	17			
R					10010659	Catcleugh Nursery	3750	6031	0	229	37	1098	10660	17	99	Catcleugh	A
	L			34	10610122	Eskdalemuir	3235	6026	0	242	94	1536	10610122	50			
	L				10019355	Jesmond Dene	4253	5672	0	48	30	675	10019356	21			
	L			34	606336	Carlisle	3383	5603	0	28	39	835	10606335	27			
R	L			34	10022163	Tunstall Resr	4064	5407	0	221	109	898	22163	22	485	Tunstall	A
R	L			34	10021228	Burnhope Resr	3850	5391	0	354	44	1258	10021228	23	80	Burnhope	A
	L			36	10594200	Cornhow S Wks	3150	5222	0	98	30	1503	10594201	25			
R					10028185	Lartington Filters	4011	5183	0	220	38	842	10028185	19	260	Hury	A
			V	35	10592463	Honister Pass	3225	5135	0	358	20	3510	10592466	12			
R					10586897	Brathay Hall	3366	5032	0	49	30	1973	586898	15	1716	Tarn Hows	B
R					10073419	Malham Tarn	3894	4671	0	381	44	1492	73422	18	595	Malham Tarn	B

Near impounding reservoir (R)	Long record (L)	Added for spatial cover (S)	Very high SAAR location (V)	Original set of 34, 35 or 36	Number of daily gauge	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of hourly gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
	L				64421	Church Fenton	4528	4380	0	8	38	608	10064421	23			
R					10575383	Great Harwood, Kebb Farm	3722	4327	0	204	43	1219	575384	15	152	Dean Clough Lower	A
R	L				576634	Preston, Moor Park	3537	4311	0	33	42	1004	10576634	25	2973	Highgate Park FSR	B
R					77835	Ringstone Resr	4050	4178	0	310	43	1318	77836	16	403	Ringstone	A
	L				564419	Ringway	3814	3844	0	69	30	808	10564419	55			
	L			34	532207	Valley	2309	3758	0	10	36	844	10532207	44			
	L			34	142001	Waddington	4988	3653	0	68	44	601	10142001	50			
R	L				109084	Ashover No 2	4349	3629	0	178	35	858	10109084	24	1490	Press No.3	B
R	L			34	109141	Ogston Resr	4380	3598	0	102	39	791	10109141	40	367	Ogston	A
R	L				117626	Nottingham, Watnall	4503	3457	0	117	34	707	10117626	33	1024	Moorgreen	A
R	L				93536	Blithfield Resr	4071	3226	0	83	41	705	10093536	30	909	Blithfield	A
	L				10193359	Marham	5737	3091	0	21	32	610	10193359	25			
	L			34	94320	Willenhall S Wks No 2	3979	2983	0	119	41	690	10094320	40			
	L			34	98210	Hinckley S Wks	4420	2927	0	99	37	637	10098210	40			
R	L				421140	Dolydd	2874	2904	0	297	31	1876	10421140	25	117	Clywedog	A

Near impounding reservoir (R)	Long record (L)	Added for spatial cover (S)	Very high SAAR location (V)	Original set of 34, 35 or 36	Number of daily gauge	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of hourly gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
R	L			34	10096892	Elmdon	4176	2839	0	96	48	699	10096892	45	1056	Olton	A
R	L				447787	Stanford Resr	4596	2804	0	112	38	651	10447787	22	1522	Stanford	B
	L			34	517546	Aberporth	2241	2521	0	133	55	851	10517546	46			
	L				221992	Wattisham	6026	2514	0	89	41	568	10221992	25			
R	L				243350	Stansted	5531	2226	0	101	47	622	10243350	23	2182	Easton Farm	B
	L				461467	Miserden Park	3939	2088	0	232	44	877	10461468	22			
R	L				279502	Ruislip, Manor Farm Bowling Green	5090	1877	0	45	34	658	279502	21	2812	George Vth Storage Reservoir	A
R	L			34	246690	Hampstead	5262	1863	0	137	93	683	10246690	67	1063	Brent	A
R	L			34	247344	Northolt	5092	1850	0	40	40	616	10247344	54	1664	Ruislip Lido	A
R	L				290007	Cross Ness S Wks	5487	1806	0	8	92	529	10290007	25	1340	Hall Place FRR	A
R	L				246263	St James's Park	5298	1800	0	5	35	612	10246262	21	2970	Serpentine	A
	L			34	247536	Heathrow	5077	1767	0	25	39	597	10247536	55			
R	L			34	287049	Kew	5171	1757	0	5	110	591	10287049	95	2073	Pen Ponds Upper Lake, Richmond	A
	L			34	10491860	Rhoose	3066	1677	0	65	37	930	10491860	41			
	L			34	301114	Manston	6324	1661	0	49	38	569	10301095	40			

Near impounding reservoir (R)	Long record (L)	Added for spatial cover (S)	Very high SAAR location (V)	Original set of 34, 35 or 36	Number of daily gauge	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of hourly gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
R	L				10271490	Camberley S Wks	4860	1595	0	60	39	656	10271491	24	1143	Sandhurst, Lower Lake	B
R	L				10271432	South Farnborough	4856	1541	0	65	51	671	10271418	24	912	Bourley Military No.2	B
	L			34	10336376	Boscombe Down	4172	1403	0	126	44	705	10336376	45			
R	L				10282289	Cranleigh S Wks	5041	1392	0	47	43	765	10282290	24	1180	Vachery Pond	A
R	L				402073	Wiveliscombe, Maundown W Wks	3065	1291	0	198	32	1100	402074	30	111	Clatworthy	A
R	L				10383476	St Mawgan	1872	641	0	103	40	1004	10383477	32	383	Porth	B
	L			34	368487	Plymouth, Mountbatten	2492	527	0	50	31	983	10368484	76			
R					962647	Coleraine, Cutts	2853	4303	-1	3	67	1009	10962647	15	2030	Dunalis	NA
	L			34	963676	Altnahinch Filters	3115	4238	-1	213	39	1418	10963676	23	15	Altnahinch	NA
R					959461	Toomebridge	2988	3905	-1	15	65	861	10959461	17	-1	Artoges	NA
	L			34	955817	Aldergrove	3147	3809	-1	63	34	867	10955817	57			
	L				8002437	Clones	2500	3263	-1	89	55	928	8000074	30			

Appendix H A possible alternative distribution for the DDF model

This appendix outlines a possible alternative to the underlying distribution used in the DDF model described in Section 8.4. Specifically, the Gamma distribution is used as a basic component of the model because it has the special property that totals of random quantities from a member of a family of distributions also belong to the same family. This then gives a basis for relating the parameters of the distributions of total rainfall across different durations. There are few families of distributions having this property. Section 8.4 contains mention of “a continuous version of the Binomial distribution” and the purpose of this appendix is simply to record an outline of this possibility.

The usual Binomial distribution has a distribution function which is often specified in the following form. Here n is the sample size, p is the probability of success, and A is the random variable which has the binomial distribution. The upper tail probability is given by

$$\Pr(A \geq a) = \sum_{i=a}^{n} \binom{n}{i} p^i (1-p)^{n-i} = I_p(a, n-a+1),$$

where I is the incomplete Beta function defined for general (not necessarily integer) values of the arguments by

$$I_p(a,b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \int_0^p t^{a-1}(1-t)^{b-1}\,\mathrm{d}t.$$

A rearrangement of this is

$$\Pr(A < a) = \sum_{i=0}^{a-1} \binom{n}{i} p^i (1-p)^{n-i} = 1 - I_p(a, n-a+1) = I_{1-p}(n-a+1, a).$$

The basic form of the proposed continuous Binomial distribution has its distribution function defined for a random variable X by

$$\Pr(X \leq x) = I_{1-p}(Q-x, x) = 1 - I_p(x, Q-x), \qquad (0 \leq x \leq Q),$$

where Q is a real valued shape parameter, which is the upper bound, and p is a “location” parameter $(0 \leq p \leq 1)$. An extended form of the distribution has an extra scale parameter c:

$$\Pr(X \leq x) = I_{1-p}\left(\frac{Q-x}{c}, \frac{x}{c}\right) = 1 - I_p\left(\frac{x}{c}, \frac{Q-x}{c}\right) \qquad (0 \leq x \leq Q).$$

The precise properties of this distribution are largely unknown. By construction, the density function should behave similarly to the probability mass function of the Binomial distribution. Thus, in an approximate sense, it should be single peaked and skewed to the right for $p < \frac{1}{2}$ and skewed to the left for $p > \frac{1}{2}$, at least if p is not too close to either 0 or 1.

For implementation of the computations necessary for this project, in order to retain numerical accuracy in the calculations, it seems best to work in terms of the logarithms of $\Pr(X \leq x)$ and this may mean that the first of the alternative formulae given above is most useful, given that a pre-existing routine for evaluating the incomplete beta function can be suitably modified.

The reason why the Binomial distribution is possibly relevant to the distribution of total rainfall over various durations is that the distribution of totals of Binomial random variables with the same shape parameter also has a Binomial distribution (with a shape parameter which is simply related to the original). It is unknown but unlikely that this property holds exactly for the above continuous version of the Binomial distribution. However, the general behaviour of the distributions as the shape parameter varies should be suitable. As discussed in Section 8, a major consideration was that the frequency curves for different durations within the DDF model should not cross. This property will hold for a model constructed in the same way as in Section 8, if it makes use of the continuous version the Binomial distribution described above.

Appendix I Some background to L-moments

I.1 Introduction

The use of L-moments as descriptive statistics is presently widespread in hydrological applications involving extreme values, particularly since they play a prominent role in the FEH flood estimation procedures (Robson & Reed, 1999). Their use in the FEH followed the publication, by Hosking & Wallis (1997), of a systematic approach to the pooling of information across sites (regionalisation) which was based on L-moments. A presentation of the mathematical basis of, and the properties of, L-moments had been given earlier in a formal statistical context by Hosking (1990). Some later related work has also been published by Hosking (1992, 2006). Recent appearances of L-moments in the statistical literature include the book by Hand & Nagaraja (2003, Section 9.9) and papers by Serfling & Xiao (2007), Delicado & Goria (2008), Alkasasbeh & Raqab (2009) and Jones (2004, 2009). Favourable comparisons of L-moments with ordinary moments have been reported by Royston (1992) and Ulrych *et al.* (2000). Add-ons for computer packages to enable the implementation of L-moments are available for “R”, “Stata” and “Matlab”.

The use of the terminology “L-moments” is by Hosking (1990) to relate to the pre-existing terminology “L-statistics” which applies to linear combinations of order statistics. Thus L-moments are special types of L-statistics, and in both cases the “L” emphasises that the quantities are linear functions of the order statistics. However, note that L-moment ratios do not have this property.

The description of L-moments in the following subsections relies on the works cited above, with explicit references usually omitted for readability.

I.2 Definition

Population values

Suppose that the set of values $\{X_1,\ldots,X_n\}$ is a sample of n independent and identically distributed random variables. When the sample is sorted into increasing order the notation $X_{j:n}$ is used for the j'th largest value. The set of values $\{X_{j:n};\, j=1,\ldots,n\}$ is the set of order statistics. In the following, samples of differing sizes n are considered and these are all assumed to relate to the sample underlying population.

The population value of the r'th L-moment is denoted by λ_r and the value exists (is finite) provided that a single value from the population has a finite mean. The first few population L-moments are defined in terms of expectations of combinations or the order statistics as follows:

$$\lambda_1 = \mathrm{E}(X) = \mathrm{E}(X_{1:1}),$$

$$\lambda_2 = \tfrac{1}{2}\mathrm{E}(X_{2:2} - X_{1:2}),$$

$$\lambda_3 = \tfrac{1}{3}\mathrm{E}(X_{3:3} - 2X_{2:3} + X_{1:3}),$$
$$\lambda_4 = \tfrac{1}{4}\mathrm{E}(X_{4:4} - 3X_{3:4} + 3X_{2:4} - X_{1:4}).$$

In this report, L-moments up to order 4 are used. A number of alternative expressions for the L-moments are available in the literature already cited, of which the following are important: expressions for λ_r in terms either of $\{\mathrm{E}(X_{1;j});\, j=1,\ldots,r\}$, or of $\{\mathrm{E}(X_{j;j});\, j=1,\ldots,r\}$; expressions in terms of integrals of the quantile function $x(p)$ in combination with polynomials in p; expressions in terms of "probability weighted moments".

Given the definition of the L-moments, L-moment ratios are defined, and given descriptive and shortened names as follows:

$\tau = \lambda_2 / \lambda_1$: L-CV, L-CVAR, L-moment coefficient of variation

$\tau_3 = \lambda_3 / \lambda_2$: L-skewness, L-Skew

$\tau_4 = \lambda_4 / \lambda_2$: L-kurtosis, L-Kurt.

These names have been generally adopted because these L-moment ratios measure aspects of the shape of probability distribution that correspond in a general sense to the established terms "coefficient of variation", "skewness" and "kurtosis". In addition, "L-scale" is used to denote the ordinary L-moment λ_2, and this report has used "L-CVMED" and "lcmed" to denote a version of τ (L-CV) in which λ_2 is scaled by the median instead of the mean.

Various properties of L-moment ratios are available in the literature of which the following provide guides to the sizes of sample values:

(i) if $X \geq 0$, then $0 < \tau < 1$;
(ii) $|\tau_r| < 1$ for $r = 3,4,\ldots$;
(iii) $\tfrac{1}{4}(5\tau_3^2 - 1) < \tau_4 < 1$.

The last inequality is used in this report to provide the "overall lower bound" curves in the plots in Section 4.2.

Values of L-moments and L-moment ratios for some simple distributions are given in the following table.

Distribution	λ_1	λ_2	τ_3	τ_4
Uniform on (α, β)	$\tfrac{1}{2}(\alpha+\beta)$	$\tfrac{1}{6}(\beta-\alpha)$	0	0
Exponential, scale α	α	$\tfrac{1}{2}\alpha$	$\tfrac{1}{3}$	$\tfrac{1}{6}$
Gumbel u, α	$u + \gamma\alpha$	$\alpha \log 2$	0.1699	0.1504
Logistic, scale α	0	α	0	$\tfrac{1}{6}$
Laplace, scale α	0	$\tfrac{3}{4}\alpha$	0	0.2361
Normal (μ, σ^2)	μ	$\pi^{-\frac{1}{2}}\sigma$	0	0.1226

Sample estimates

Given a sample of data, estimates of the L-moments of the corresponding population are typically obtained without making parametric assumptions about the form of the distribution. This project has used what are called the "unbiased estimators" in the literature. These have good properties of invariance in comparison to alternatives which have mainly been derived through the correspondence of L-moments to probability weighted moments: there was once a fashion for estimation of probability weighted moments using simplified weighting schemes called "plotting-position estimators", since "plotting positions" were used in formulating the weights.

There are no simple and direct general formulae defining the sample L-moment estimates for general orders, although the route via probability weighted moments using the "unbiased" estimates of these may be simplest. However, all expressions are equivalent to defining the estimate l_r of the r th L-moment to be the U-statistic based on samples of size r which corresponds directly to the definitions of the population quantities. For an ordered sample, $x_{1:n} \le x_{2:n} \le \cdots \le x_{n:n}$, the lowest order estimates would be equivalent to

$$l_1 = n^{-1}\sum_i x_{i:n} \text{ ,}$$

$$l_2 = \binom{n}{2}^{-1} \tfrac{1}{2}\sum_{i>j}\sum \left(x_{i:n} - x_{j:n}\right),$$

$$l_3 = \binom{n}{3}^{-1} \tfrac{1}{3}\sum \sum_{i>j>k} \sum \left(x_{i:n} - 2x_{j:n} + x_{k:n}\right).$$

Sample values of the L-moment ratios are defined by

$$t = l_2 / l_1, \qquad t_3 = l_3 / l_2, \qquad t_4 = l_4 / l_2,$$

and these are the sample L-CV, sample L-skewness and sample L-kurtosis, respectively.

This report does not always distinguish notationally between the sample values and population values for the L-moments and L-moment ratios. Note that the inequalities satisfied by the population values are not always strictly obeyed by the sample values.

I.3 Usefulness

L-moments and L-moment ratios have been proposed as being useful in two contexts. Firstly they are as measures of the shape of distributions, providing numerical measures which can be compared across distributions (either sample data or populations) and which are available without fitting particular distributions. It is arguable that the flood estimation procedures of the FEH, which involve the averaging of the sample L-moment ratios across sites within a group, are effectively averaging the shapes of the sample distributions rather than averaging estimates of parameters. Secondly, they can be used to derive estimates of the parameters of distributions based on sample data in an approach which is directly parallel to the method of moments. As an adjunct to this, tests for the fit of a family of distributions to sample data can be based on L-moments.

As measures of distributional shape, L-moments are thought to be preferable to conventional moments on three grounds. Firstly, that the sample estimates for orders over 1 are less sensitive to outliers in the case of L-moments than conventional moments, because the latter involve squares and higher powers of the values. Secondly, because the range of possible sample values accords well with the population values for L-moments, whereas the ranges of sample values for the conventional moment-ratios (such as skewness) are limited by functions of the sample size. This means, for example, that if the true skewness is moderately large, say 3, then the sample size would have to be at least 12 before there was any chance at all of the sample skewness being that high. Thirdly, the power of a certain test of normality (the Shapiro-Wilk test) against a number of alternative distributions has been found (Hosking, 1992) to be more closely related to the population L-moment ratios than to the conventional moment ratios.

Two considerations are relevant with respect to estimation using L-moments. The first relates to the convenience of using the estimator, either in having the estimate given by a closed-form expression or in having a simple computational procedure compared with an iterative one. Speed of computation can be particularly important when undertaking extensive statistical analyses such as in the present project. Estimation using L-moments shares with probability weighted moments a number of cases of distributions for which L-moment estimates are available in simple form whereas those for the conventional method of moments are not, and for which the maximum likelihood approach would require an iterative optimisation-search or root-finding procedure. The second consideration relates to the accuracy of the estimation procedure. Various studies have indicated that L-moment estimation is better in terms of mean square error for estimating population quantiles than the either the method of moments or maximum likelihood, at least for distributions relevant to extreme value analyses and for sample sizes up to about 100 (which would be a large sample in the context of practical analyses of annual maxima). However, important problems do arise with the use of L-moments for estimation, of which the following are examples:

(i) In some instances, solutions to the set of equations derived from a straightforward application of the approach may not exist, or there may be several solutions – but this does not arise for the GEV distribution used in this project.

(ii) Distributions fitted by the approach may be contradicted by the data to which they have been fitted. In particular, if a GEV distribution is fitted, there may be values in the data used for fitting which are either above the upper bound of the fitted distribution or below the lower bound. In the present project, a modified version of the straightforward L-moment estimate has been used to prevent this happening.

Appendix J Reassessment of discretisation conversion factors

J.1 Introduction

Consider a one-year record from an hourly raingauge. The highest 24-hour total for all the 24-hour periods starting at 0900 will be less than or equal to the highest 24-hour total for any starting hour. Thus the annual maximum for a daily-read gauge will be less than or equal to the 24-hour annual maximum at that location.

In the terminology of the FEH DDF model, an annual maximum for 24 hour (1 day) total rainfall, derived from data for daily-read gauges (*i.e.* from 1 day resolution data) is known as a *fixed* duration value, while a corresponding value derived from 1 hour resolution data is also known as a *fixed* duration value. In the latter case the designation ‘fixed’ seems inappropriate as a number of overlapping totals are involved in the maximisation step: hence *semi-sliding* is used instead in this report, given that each total is limited to starting on clock hours, or at multiples of the underlying data resolution. The FEH used ‘sliding duration’ to denote annual maxima that would be obtained if it were possible to consider totals starting at any time: this type of annual maximum is called a ‘*fully-sliding*’ duration maximum in this report. In the FEH, based on research by Dwyer and Reed (1995), the difference between the annual maxima statistics from fully-sliding and semi-sliding periods for 1-hour resolution data was treated as negligible for durations of 12 hours or more.

Both the FEH and the new DDF model of this project are fitted to data corresponding to fully-sliding durations. These data values are derived from fixed and semi-sliding duration annual maxima by applying a *discretisation conversion factor* appropriate to the duration being considered and to the resolution of the underlying dataset.

J.2 Initial revision of discretisation conversion factors

The discretisation conversion factors used for the work described in this report derive partly from those used in the FEH, with values being updated for a subset of the durations, based on some new empirical analyses. These analyses have used the improved 1 hour resolution rainfall dataset available to this project to reassess the factors for converting 1, 2, 4 and 8-day annual maxima statistics from fixed and semi-sliding to fully-sliding. In particular, the 1 hour resolution dataset is used to derive values for both:

(i) the fixed-duration 1-day and semi-sliding duration 2, 4 and 8-day annual maxima (corresponding to what would be derived from 1-day resolution data), and

(ii) the fully-sliding duration 1, 2, 4 and 8-day annual maxima, as approximated by the semi-sliding duration values based on 1 hour resolution data.

While analyses were also done for other cases, the fixed-duration 1-day and semi-sliding duration 2, 4 and 8-day rainfalls in (i) were computed for the 0900 to 0900 day to correspond to the standard day for daily-read gauges. Some interesting patterns of variation within the day for other possible starting times were found but are not described here as they correspond directly with those found in the improved analysis reported later (Section J.3).

The values obtained in (i) and (ii) were used to derive discretisation conversion factors by taking the ratio of the two values obtained for any one year and then forming the arithmetic mean of these, first across all years, and then across all suitable 1 hour raingauges.

The analysis used all hourly raingauges with at least nine years of data, and the results are shown in Table J.1. This table shows the discretisation conversion factors for daily durations actually applied in this project (in the column headed "New") in comparison with those used in the FSR and FEH studies and those published in a recent study for Ireland (Fitzgerald, 2007). Whilst there is generally good agreement between the three sets of figures, the FEH 48-hour value differs somewhat from the others. The use of the new value for this case results in a decrease in the fully-sliding 48 hour duration rainfall values compared with what would have been obtained with the FEH factor.

Table J.1 Fixed and semi-sliding to fully-sliding discretisation conversion factors for daily durations derived from 1-day resolution

Conversion		New	FSR	FEH	Irish
from duration	**to duration (fully-sliding)**				
Fixed 1-day	24-hours	1.146	1.11	1.16	1.15
Semi-sliding 2-day	48-hours	1.072	1.06	1.11	1.08
Semi-sliding 4-day	96-hours	1.043	1.03	1.05	1.04
Semi-sliding 8-day	192-hours	1.025	1.015	1.01	1.04

"New" indicates the revised factors used for the results in this report
"Irish" are values for the Irish Republic (Fitzgerald, 2007)

J.3 Improved analysis of conversion factors

J.3.1 Introduction

This section reports an extended analysis of the discretisation conversion problem that was completed too late for the improved factors obtained to be used in the results described in this report. It is felt that this work is of enough interest to be included here, and replaces work with a similar coverage from an earlier draft. The factors found are only slightly different from those actually used in the results reported elsewhere, so these would not be misleading. However the recommendation is that any subsequent use of the procedures described in the main report should make use of the improved factors detailed in this part of this Appendix, subject to any further re-analysis.

In order to be precise about the analyses undertaken, the following terminology is defined.

- *res-1d annual maxima.* Annual maxima calculated from a record of daily rainfall totals. (1-day resolution data corresponds to 24 hour periods each starting at 0900). For 1-day duration totals this gives fixed-duration maxima, while for durations of 2 or more days, this gives semi-sliding duration maxima. Note that the FEH used the term 'fixed duration' maxima for both cases.

- *res-1h annual maxima*. Annual maxima calculated from a record of hourly rainfall totals (*i.e*. the 1-hour resolution data). For 1-hour duration totals this gives fixed-duration maxima, while for durations of 2 or more hours, this gives semi-sliding duration maxima. A fixed-duration 2-hour rainfall would be derived from data at a 2-hour resolution.

- *res-xh annual maxima*. Annual maxima calculated from a record of rainfall totals with a resolution of x-hours (constructed as an intermediate dataset from the 1-hour resolution data).

- *res-0h annual maxima.* Annual maxima that would be obtained from a continuous record: that is, a record with a time resolution of 0-hours. The term "*true annual maxima*" is usually avoided because the "true value" (zero resolution data) is never known but can only be estimated. These are the ideal values usually required as the target for extreme rainfall estimation. In the main data analysis for estimating extreme rainfalls they are estimated from the *res-1d* or *res-1h* case using a *discretisation conversion factor*. The *res-0h annual maxima* are the fully-sliding duration maxima referred to elsewhere in this report, while the FEH referred to these as the 'sliding duration' maxima.

- *Discretisation conversion factor.* In theory this is the ratio between the *res-0h annual maxima* and the *res-1d* (or *res-1h*, as applicable) annual maxima for a particular duration. The procedure for estimating these factors uses an average ratio between the (estimated) *res-0h annual maxima* and the *res-1d* (or *res-1h*, as applicable) annual maxima for a particular duration.

The two different basic resolutions of data available for this project allow sets of data for two groups of durations to be derived: specifically *res-1h* maxima for 1, 2, 4, 6, 12, 18 and 24 hours, and *res-1d* maxima for 24, 48, 96 and 192 hours (1, 2, 4 and 8 days). In practice, it is usually the statistics of the unknown *res-0h* (fully-sliding) maxima that are required, as for most applications the practical consequences of heavy rainfall would not be related to time-intervals delimited by clock hours or calendar days. The approach taken in this project, as in the FEH, has been to convert values calculated from 1-hour and 1-day resolution data to fully-sliding duration values at the end of the FORGEX stage of the analysis by applying the *discretisation conversion factors*. The rainfall amount in the DDF model is therefore the value that relates to continuous data.

For a one-year record from an hourly raingauge, the maximum 24-hour total for all the 24-hour periods starting at 0900 (equivalent to data from a daily raingauge, i.e. the 24-hour *res-1d* maximum) will be less than or equal to the maximum 24-hour total for any starting hour (the 24-hour *res-1h* maximum). Likewise the 24-hour *res-1h* maximum will be less than or equal to the *res-0h* 24-hour maximum, which would be obtained were the data continuous.

J.3.2 Discretisation conversion factors for daily resolution data

Dwyer and Reed (1995) estimated the *res-1d* 24-hour discretisation conversion factor to be 1.16; they also presented factors for other durations. The approach adopted here is not the same as that used by Dwyer and Reed (1995), who estimated values of the discretisation conversion factor from a small number of long records. In the present study, average values have been calculated using data from all individual hourly gauges (*i.e.* gauges from different sources are not concatenated) that have at least nine years of data, amounting to 829 raingauges. This is considered to better represent the data that have been used to create the new DDF model than using only a few gauges. In the following description, ‘average ratio’ refers to the geometric mean of the ratio unless stated otherwise.

Section 8.2 includes the fact that the new DDF model developed for this project is fitted to FORGEX results for return periods of two years and higher. The use of the conversion factor, both within the step of fitting the DDF model and in general usage, is that it is applied to convert a (fixed or semi-sliding duration) rainfall amount having a given return period to a fully-sliding duration rainfall amount of the same return period. While it is easiest to apply a single conversion factor across all return periods, there is no reason why conversion factors should be constant. However, use of a varying factor would open the possibility that a set of rainfalls that was monotonically increasing with increasing return period would no longer be increasing after conversion.

Given the above, a study has been made of how the empirical conversion factors vary with return period. The 1-hour resolution data allows the direct calculation of the average ratio between the 24-hour *res-1h* annual maximum and the 24-hour *res-1d* annual maximum (the latter is computed from hourly data by using a start time of 0900 for consistency with daily-read gauges). This ratio is close to the *res-0h* 24-hour discretisation factor. Figure J.1 shows the variation of the ratio with the Gumbel reduced variate, *y* (the 2 year return period has a *y* value of 0.367). In this diagram, each point plotted represents an average across a set of underlying points, where these are grouped according to the *y*-values into 10 sets (*i.e.* into *y*-deciles). The underlying points represent values pooled across all raingauges, where each raingauge contributes *n* points if it has *n* years of data: the ratio associated with the *j*’th highest *y*-value is computed from the *j*’th highest res-1h annual maximum and the *j*’th highest res-1d annual maximum. The *y* value for such a point is calculated from *j* and *n* using the Gringorten formula as explained in Section 7.2. Figure J.1 clearly shows that, with very minor exceptions, the ratio declines with return period. However, there is a possibility of non-consistent values being created using non-constant conversion factors. Because of this and also because of the point noted above, that the factors are only used for return periods of 2 years or more, it was decided to use the average of the ratios across only those cases attributed a return period of two years and above. Table J.2 contrasts the ratios obtained in this way with those obtained by averaging across all of the data.

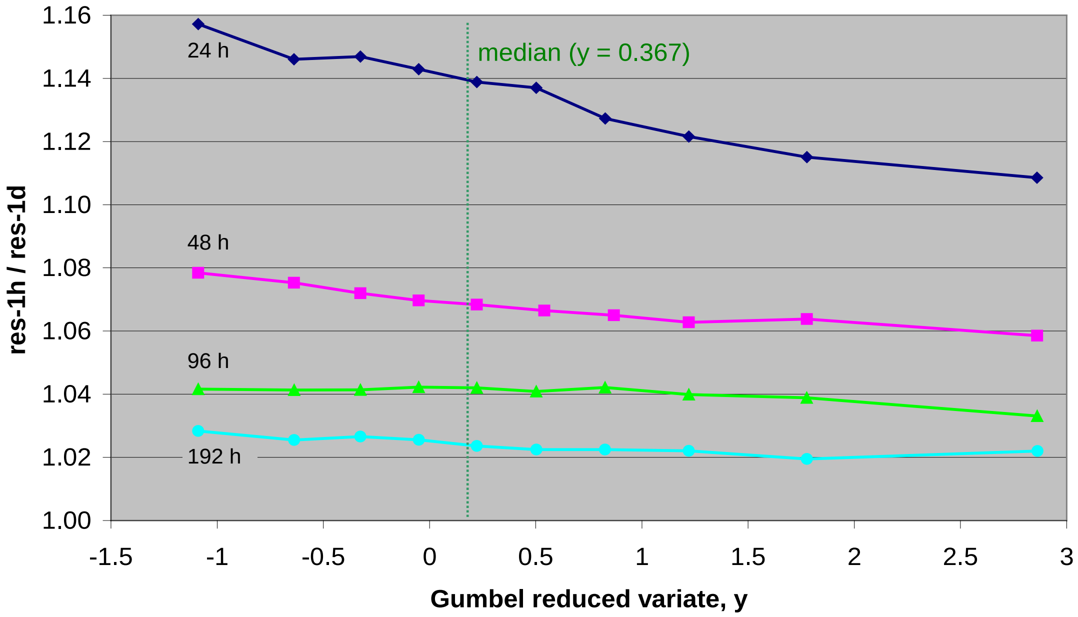


Figure J.1 Variation with return period of the average ratio of 1-hour resolution annual maxima to 1-day resolution annual maxima

Table J.2 The average ratios for different durations of annual maxima calculated from 1-hour resolution and from 1-day resolution data annual maxima. The effect of only averaging across cases with a return period of at least two years is shown.

	Average ratio	
Duration (h)	for all data	for only those cases having a return period of at least 2 years
24	1.134	1.121
48	1.068	1.063
96	1.040	1.039
192	1.024	1.022

By aggregating the hourly data, ratios can also be determined for other resolutions such as 2, 3, 4, 6, 8 and 12 hours (i.e. ratios between *res-1*d and *res-2h* annual maxima, between *res-1d and res-3h* annual maxima, and so on). The relationship between these ratios can be used to estimate the ratio between *res-1d* and the unknown *res-0h* annual maxima (i.e. that which would have been obtained from continuous data). The top line in Figure J.2 is the straight-line fit to resolutions 1, 2, 3, 4 and 6 hours for the 24-hour duration. Its intercept with the vertical axis (1.1259) is taken to be the value applicable to continuous (*res-0h*) data. The other three lines show the results of the same analysis for rainfalls totalled over durations of 48, 96 and 192 hours. These results are given, to 3 decimal places, in the penultimate column of Table J.3. Note that these differ slightly from the factors applied in this project (Section J.2), which were derived by taking the average gauge values of *res-1h*/*res-1d* for all values, using the arithmetic mean. The latest values are recommended for use in the national implementation of the new DDF model. Also shown in Table J.3 are the FEH and FSR values, and those published in a recent study for Ireland (Fitzgerald, 2007). Whilst at first sight, the FSR figures appear low, they are in fact quite consistent with the new results as they were derived for a return period of 5 years (equivalent to y = 1.5 on Figure J.1).

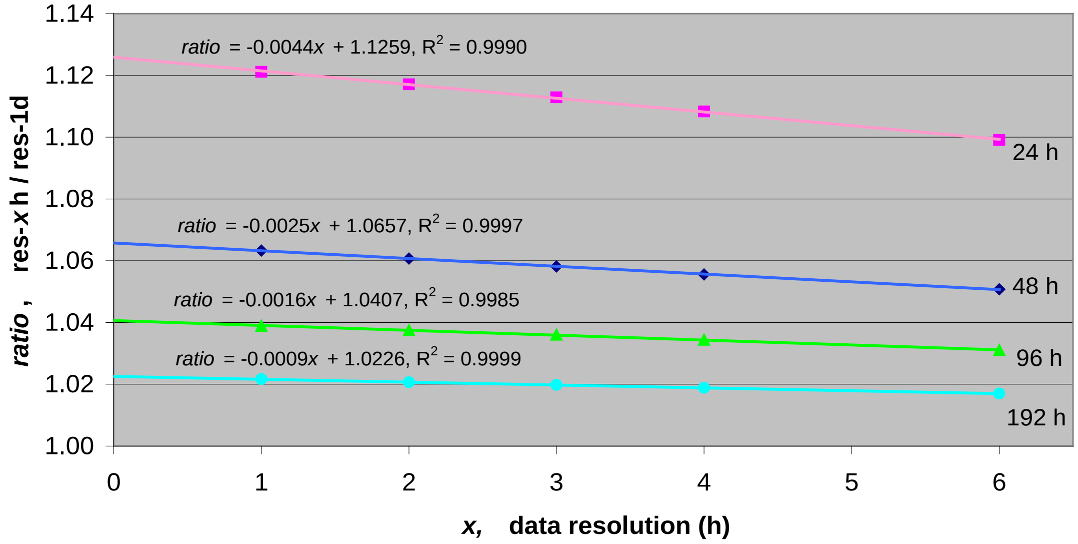


Figure J.2 Variation with data resolution (x) of the average ratio of x-hour resolution annual maxima to 1-day resolution annual maxima (up to x = 6 hours). Lines are least-squares best fits to the plotted points.

Table J.3 Discretisation conversion factors for 1-day resolution data

Duration (h)	FSR	FEH	Revised values, as applied in this project	Recommended values, from Figure J.2	Irish (Fitzgerald, 2007)
24	1.11	1.16	1.146	1.126	1.15
48	1.06	1.11	1.072	1.066	1.08
96	1.03	1.05	1.043	1.041	1.04
192	1.015	1.01	1.025	1.023	1.04

It is interesting to note that, with the exception of the longest duration, the linear relationship between the ratio and resolution does not apply to the full range of resolutions (Figure J.3). This can be explained by postulating hypothetical average storm profiles, but this is beyond the scope or requirements of the current project.

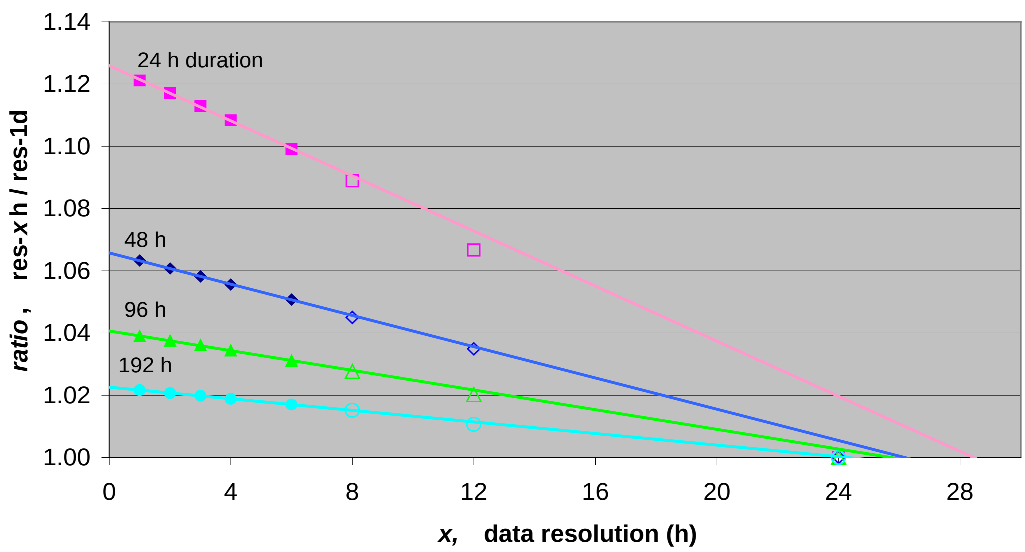


Figure J.3 Variation with data resolution (x) of the average ratio of x-hour resolution annual maxima to 1-day resolution annual maxima (up to x = 24 hours: the ratio is always one for x = 24). Lines are least-squares best fits to the solid points (*i.e.* up to 6 hours).

J.3.3 Discretisation conversion factors for hourly resolution data

Figures J.2 and J.3, which were constructed mainly for the purposes of assessing the discretisation conversion factors for annual maxima derived from 1-day resolution data, suggest that a reasonably linear relationship exists between resolution and duration, for resolutions which are small compared with the duration being considered (say up to a quarter of the duration). This linear relationship is used to extrapolate to a resolution of zero to find the *res-0h* result. A similar analysis has been undertaken, focussing on the sub-daily durations, where there is some concern whether the few resolutions for which it is possible to derive results will enable a linear extrapolation to zero to be justified. The results are shown in Figures J.4, J.5 and J.6 for durations of 12, 8 and 6 hours respectively. While Figure J.4 (12 hours) shows a good linear fit to the lowest 3 resolutions, and thus a linear extrapolation to zero is justified in this case, in other cases (Figures J.5 and J.6) the justification for extrapolation is less strong.

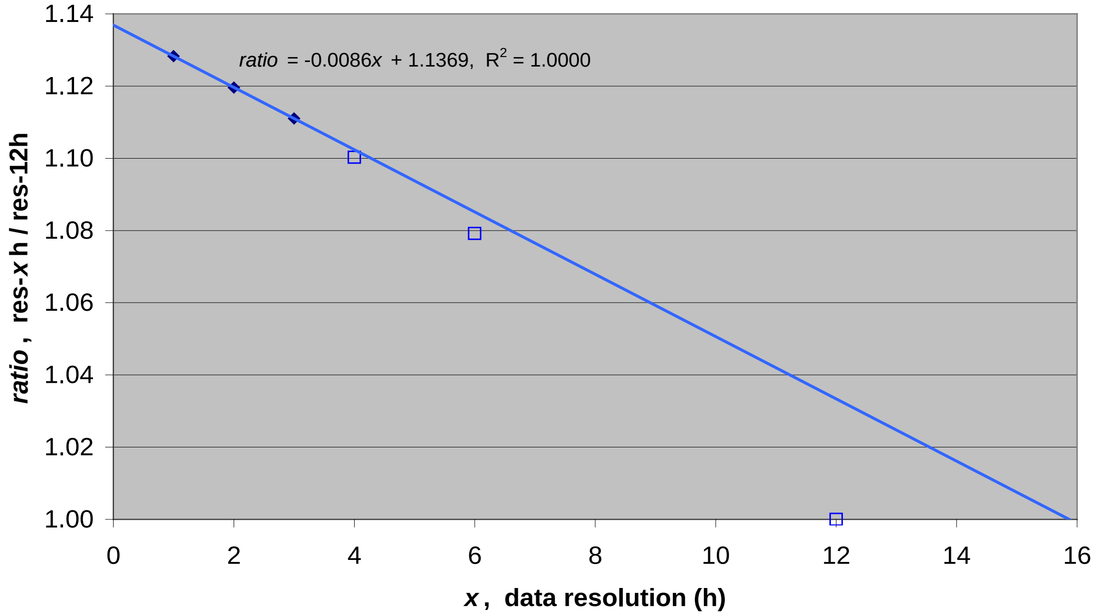


Figure J.4 Variation with data resolution (x) of the average ratio of x-hour resolution values to 12-hour resolution values for 12 hour duration annual maxima. Line is the least-squares best fit to the solid points.

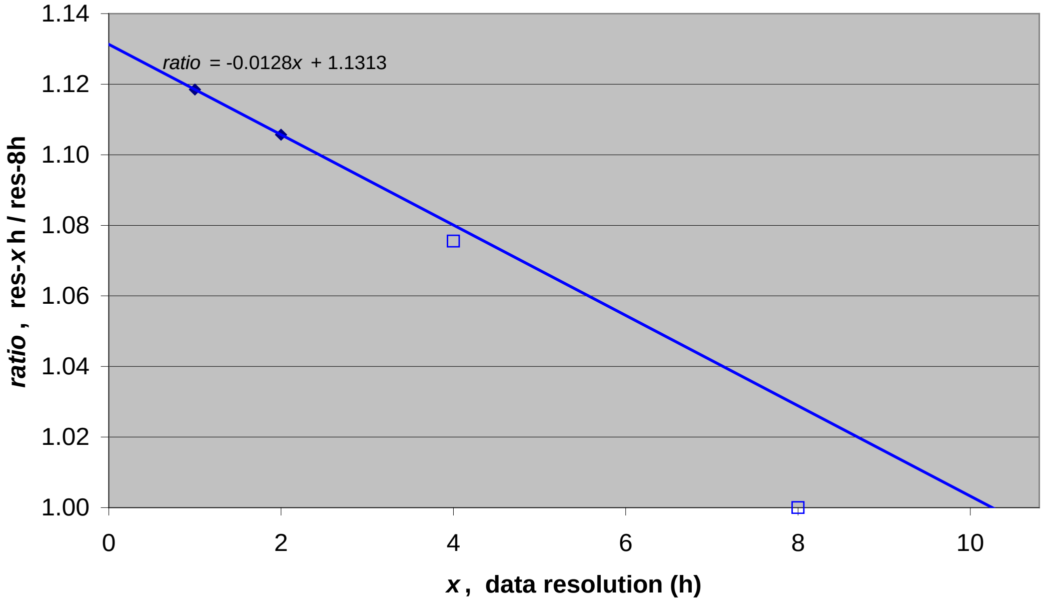


Figure J.5 Variation with data resolution (x) of the average ratio of x-hour resolution values to 8-hour resolution values for 8 hour duration annual maxima. Line is the least-squares best fit to the solid points.

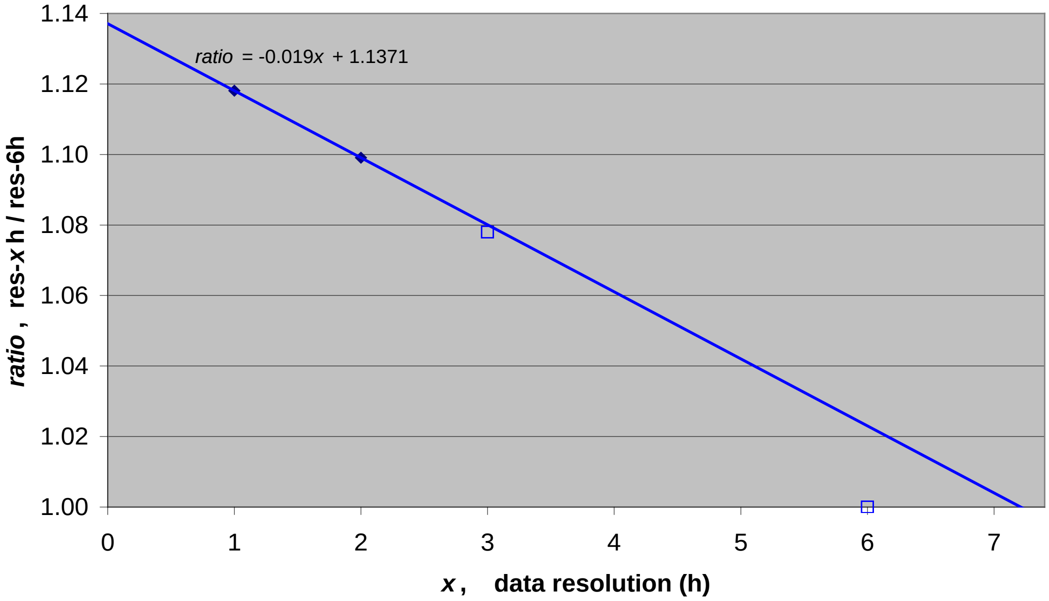


Figure J.6 Variation with data resolution (x) of the average ratio of x-hour resolution values to 6-hour resolution values for 6 hour duration annual maxima. Line is the least-squares best fit to the solid points.

The discretisation conversion factor for a given duration is derived as being equal to the ratio of the projected *res-0h* value to the fitted *res-1h*, where the *res-0h* value corresponds to the required resolution and the *res-1h* corresponds to the value that would be obtained from 1-hour resolution data. For the 24-hour duration, the straight line equation gives a factor of 1.1259/(1.1259-0.0044) = 1.004, using the coefficients quoted on Figure J.2. Similarly, values of 1.008, 1.011 and 1.017 are found for the durations of 12, 8 and 6 hours respectively.

The FEH, following Dwyer and Reed (1995), uses a discretisation conversion factor of 1.00 for durations of 12 hours and above when applied to annual maxima derived from 1-hour resolution data. Whilst the factor obtained here for 24 hours is in agreement with the FEH figure to two decimal places, the new result of 1.008 implies that 1.00 is too low at the 12-hour duration.
It is interesting to note that the new factor of 1.017 for the 6 hour duration lies midway between the FSR value of 1.015 and the FEH's 1.019. A summary of the discretisation conversion factors for 1-hour resolution data is given in Table J.4.

For durations lower than 6 hours, an analysis of the same type as above would require a base resolution of 15 minutes of finer. This is necessary in order to examine how the relationship with resolution behaves in order to justify an extrapolation to a zero resolution result. If it is not possible to obtain a sufficiently extensive dataset before the implementation project, it is recommended that values mid-way between the FSR and FEH values should be used, on the grounds of the reductions demonstrated in Table J.2 and the above analysis for the 6-hour duration. Table J.5 summarises the overall position if this suggestion is adopted, allowing comparison of all the different sets of conversion factors.

Table J.4 Discretisation conversion factors for 1-hour resolution data

Duration (h)	FSR	FEH	Recomputed values
1	1.15	1.16	-
2	1.06	1.08	-
4	-	1.03	-
6	1.015	1.019*	1.017
8	-	1.01	1.011
12	-	1.00	1.008
18	-	1.00	1.005
24	-	1.00	1.004

*by interpolation across several values

Table J.5 Discretisation conversion factors used in the FSR, FEH and the current study, and those recommended for future applications.

		Discretisation conversion factors			
Duration (h)	Data Resolution	FSR	FEH	Current	Recommended for future work
1	1 hour	1.15	1.16	1.16	1.155
2	1 hour	1.06	1.08	1.08	1.070
4	1 hour	-	1.03	1.03	1.035
6	1 hour	1.015	1.019*	1.019	1.017
8	1 hour	-	1.01	1.01	1.011
12	1 hour	-	1.00	1.00	1.008
18	1 hour	-	1.00	1.00	1.005
24	1 hour	-	1.00	1.00	1.004
24	1 day	1.11	1.16	1.146	1.126
48	1 day	1.06	1.11	1.072	1.066
96	1 day	1.03	1.05	1.043	1.041
192	1 day	1.015	1.01	1.025	1.023

* by interpolation across several values

J.3.4 Investigation into diurnal variations in the discretisation conversion factors for daily resolution data

The analysis in Section J.3.2 was based on 24-hour periods starting at 0900 for consistency with data from daily-read raingauges. It is of interest to note how this ratio is affected by the start time of the 24-hour period. By conducting the computations for all 24 possible starting hours the results shown in Figure J.7

were obtained. Note that for ease of computation a slightly simpler analysis was in fact applied, and then the results were scaled to give agreement with the 0900 results obtained in Section J.3.2. There is clearly a cyclical variation, which in the case of the 24-hour duration has a non-trivial amplitude. The implication of the 24-hour results is that on average, annual maxima from 24-hours starting at 1200 are about two per cent higher than those from 24-hours starting at 2300.

Investigations were conducted into how this pattern varied with northing, easting, continentality (using distance from Calais), SAAR and record length. The strongest relationship was with northing, which is the case shown in Figure J.8, in which the 24-hour data are split at a northing of 4000 (just north of the north coast of Wales). Note that the grid references of Northern Ireland gauges were first converted to the equivalent location on the GB grid. Figure J.8 shows the average 0900 value in the north to be 1.7% higher than that in the south. However, Figure J.9 shows that there is considerable variation in the 0900 values computed for the individual hourly raingauges and, because of this, no attempt has been made to incorporate a relationship with northing into the model.

J.3.5 Further investigations to be made

The introduction of the ‘fixed, semi-sliding and fully-sliding’ terminology in this project has identified a potential gap in knowledge about conversion factors. The conversions available from fixed and semi-sliding duration annual maxima to fully-sliding duration annual maxima match the requirements linked to current data availability. A problem is apparent for the reverse conversion step, in which fully-sliding duration annual maxima can be converted back to only those same fixed and semi-sliding durations: that is, for the same underlying resolutions. For example, a 6-hour fully-sliding duration rainfall can be converted to a 6-hour semi-sliding rainfall corresponding to a resolution of 1-hour, but this may not always be what is required. However, it would be sufficient for checking a DDF-derived rainfall against values from direct data analysis based on the present underlying resolution. Some other possible requirements for extreme rainfalls have been indicated in Section 3.6 and, if these were considered important enough, new sets of conversion factors might be devised.

If a parallel analysis to that for annual maxima is to be undertaken for seasonal maxima, this would require evaluation of discretisation conversion factors for these cases. Even if factors for summer and winter were the same (although there is no real reason to expect this), these would not necessarily be the same as the values presently available for use with annual maxima.

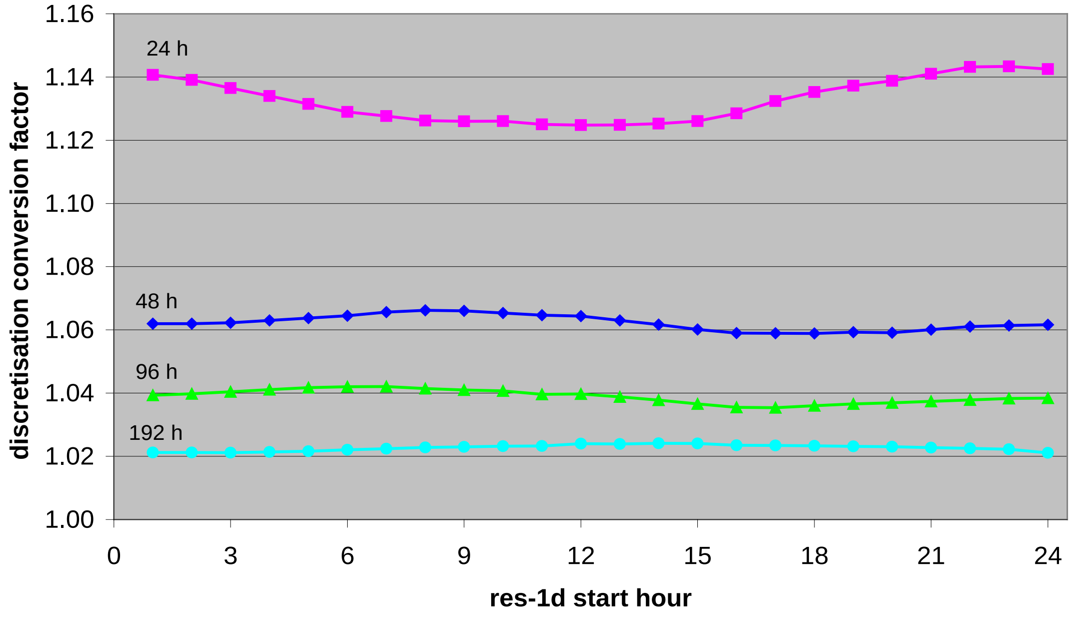


Figure J.7 Diurnal variation in the res-1d discretisation conversion factors

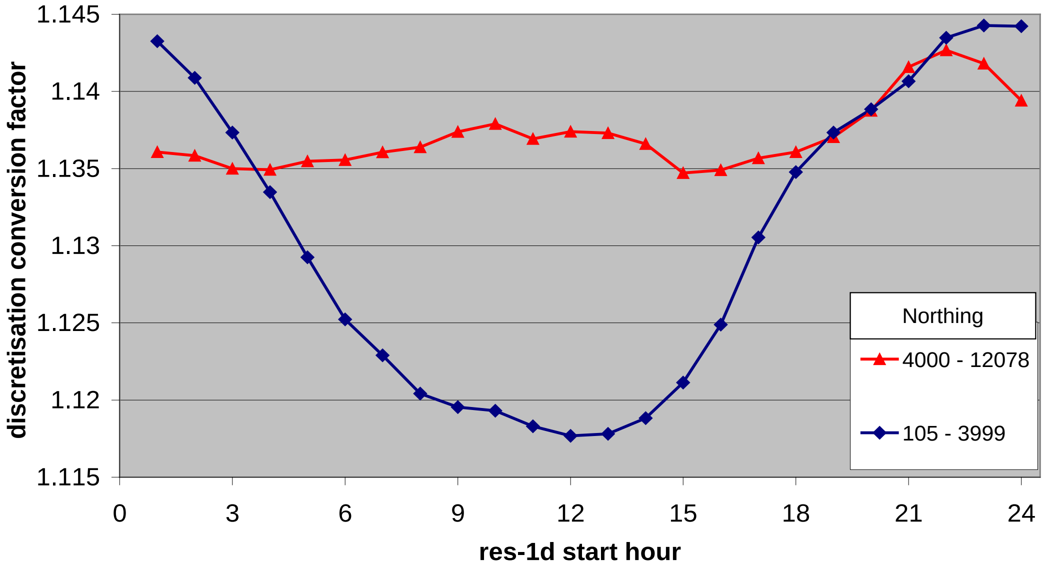


Figure J.8 North-south comparison of the diurnal variation in the 24-hour res-1d discretisation conversion factor

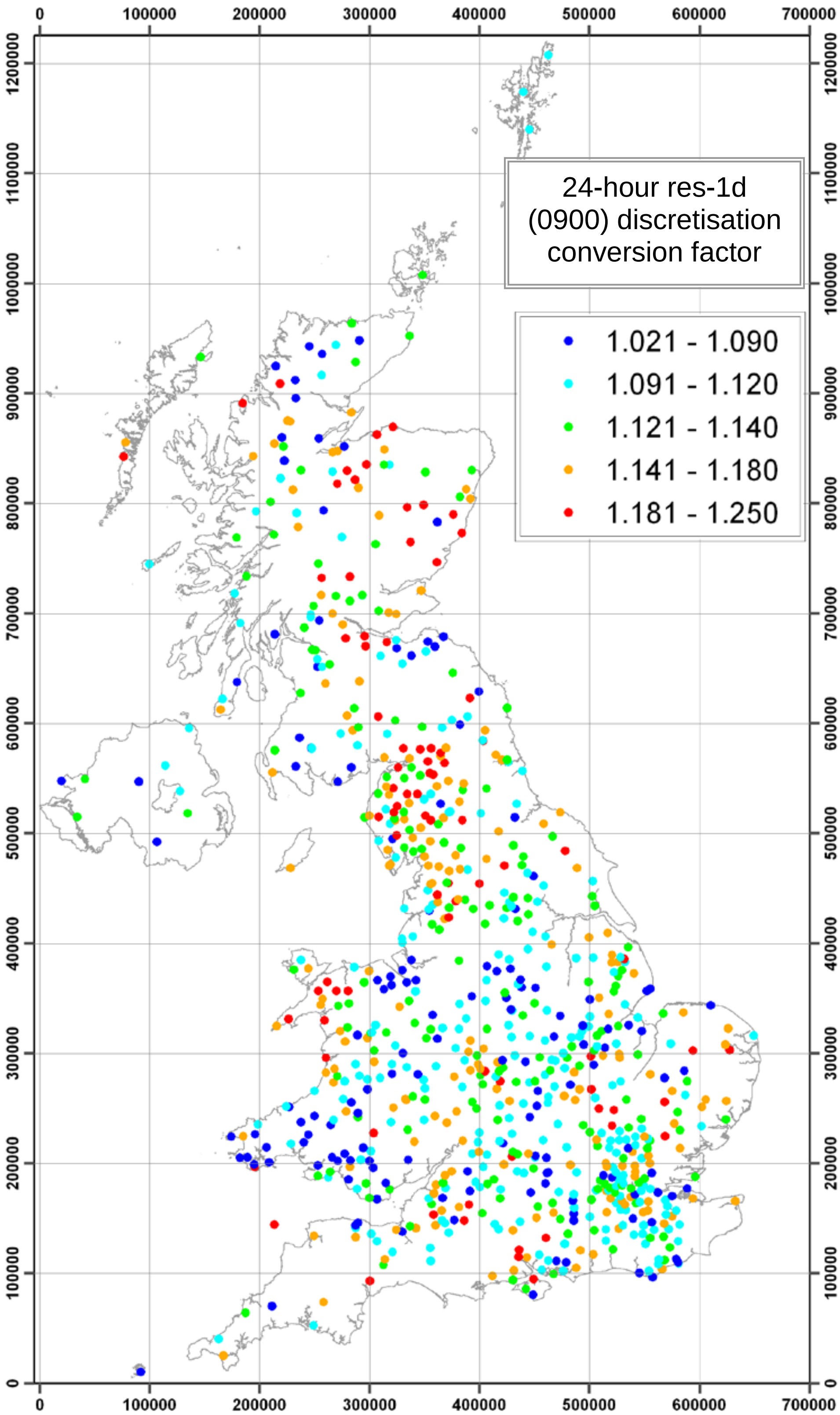


Figure J.9 24-hour res-1d (0900) discretisation conversion factors computed at all hourly raingauges with at least nine years of data

Appendix K Results maps

This Appendix comprises maps showing the ratio of the rainfall estimates from the new DDF model with those from the FEH DDF model and the FSR procedures at the locations of the 71 test gauges. The maps show the results for every combination of the following durations and return periods.

Durations

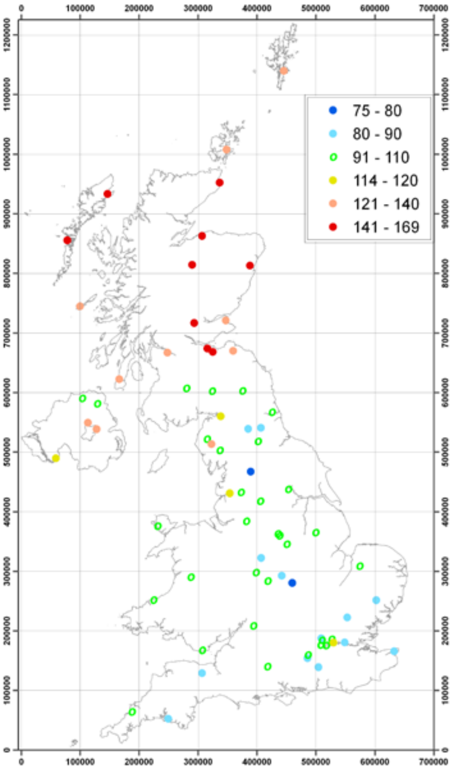
- 1 hour
- 2 hours
- 6 hours
- 24 hours
- 192 hours

Return periods

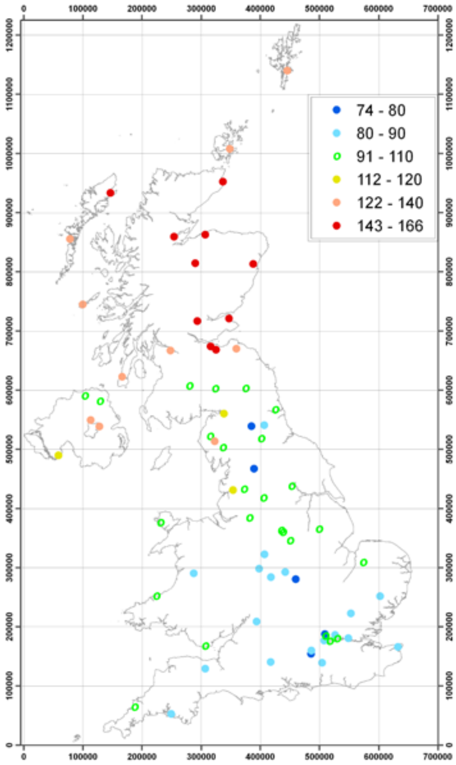
- 100 years
- 200 years
- 1,000 years
- 10,000 years

Full details are provided in Section 9.2.

New as % of FEH for 1 hour 100 year



New as % of FEH for 1 hour 200 year



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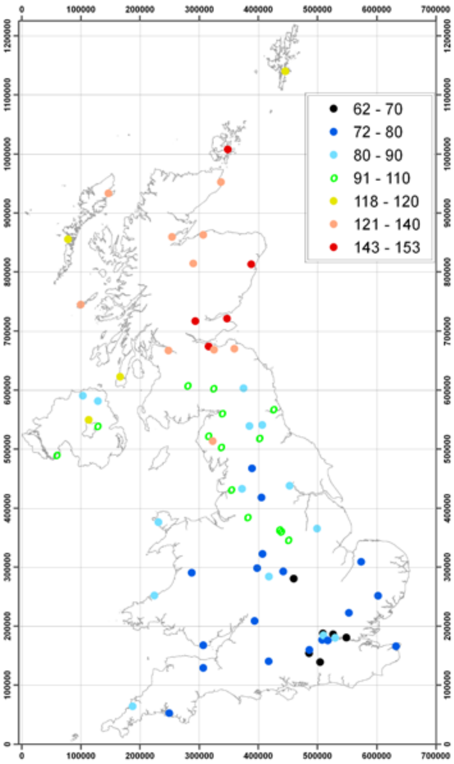

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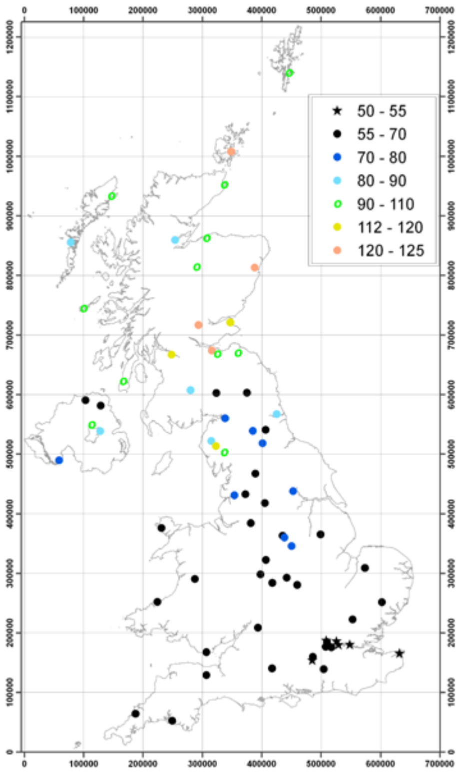

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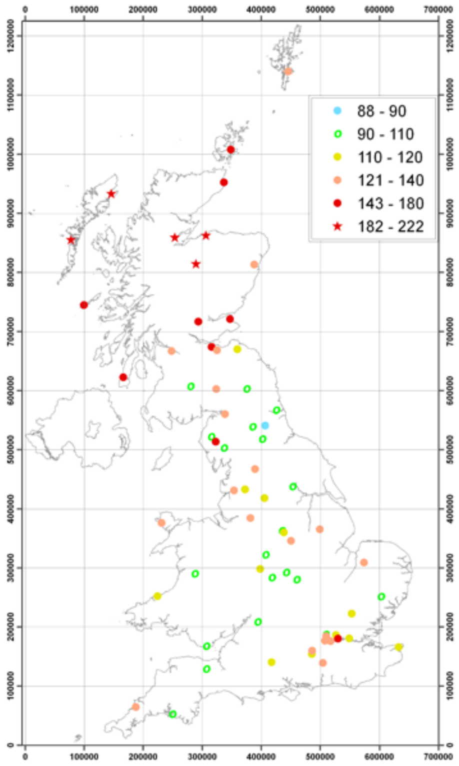

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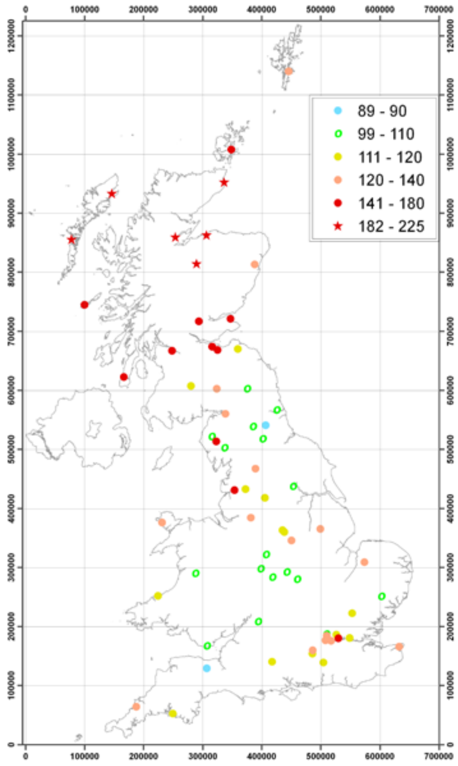

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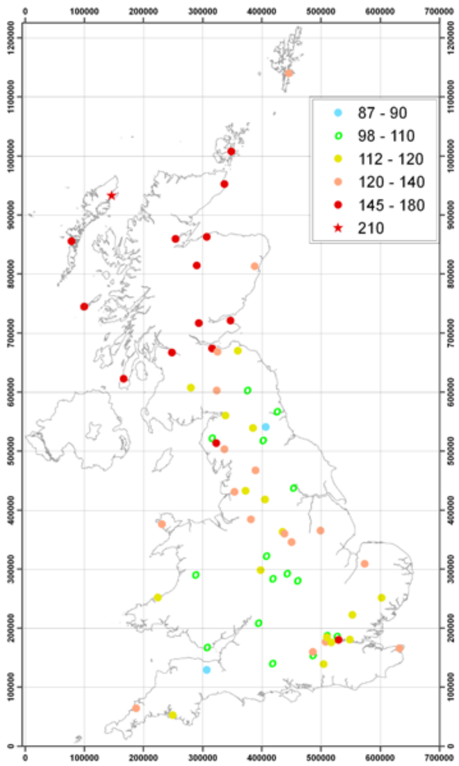

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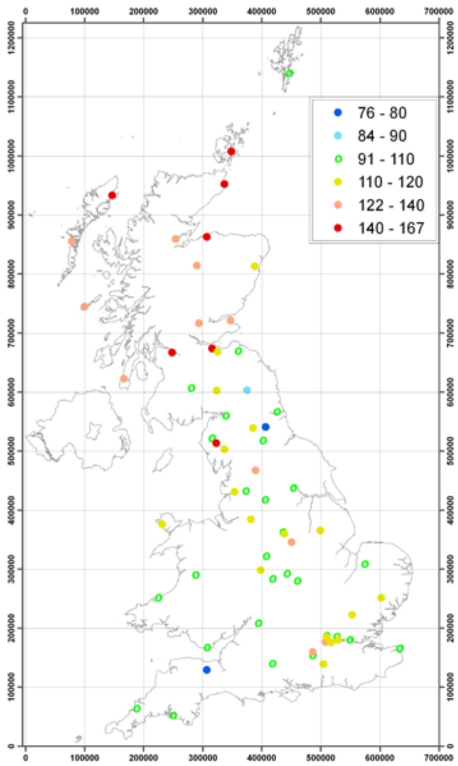

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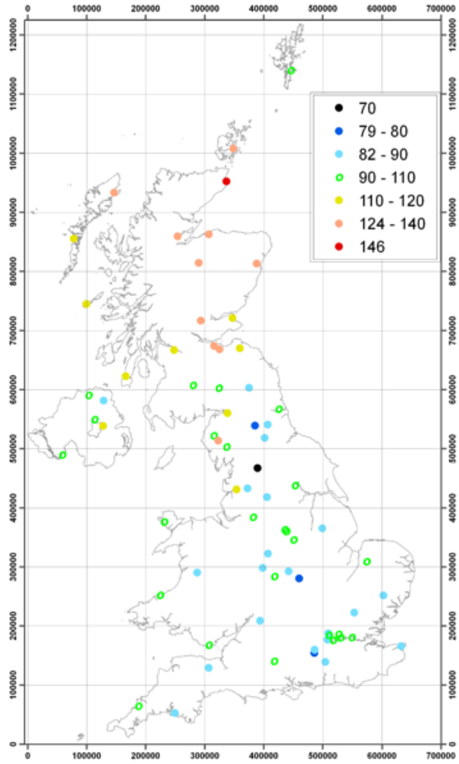

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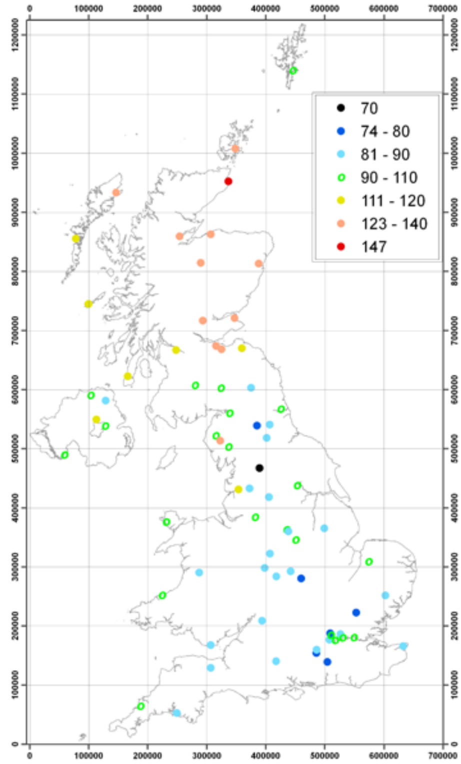

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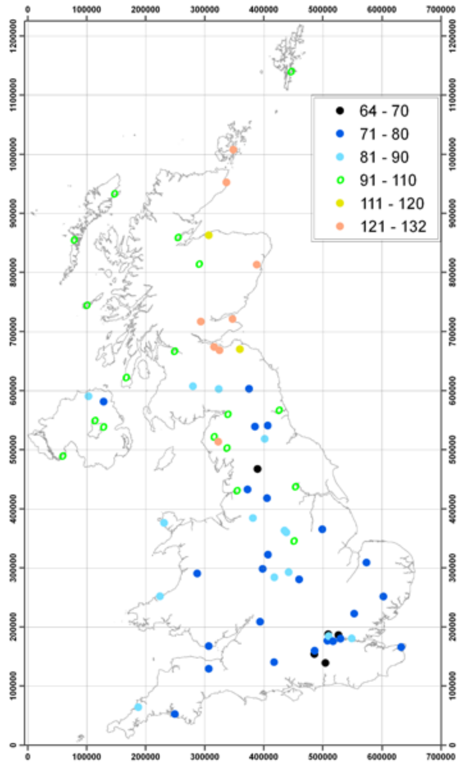

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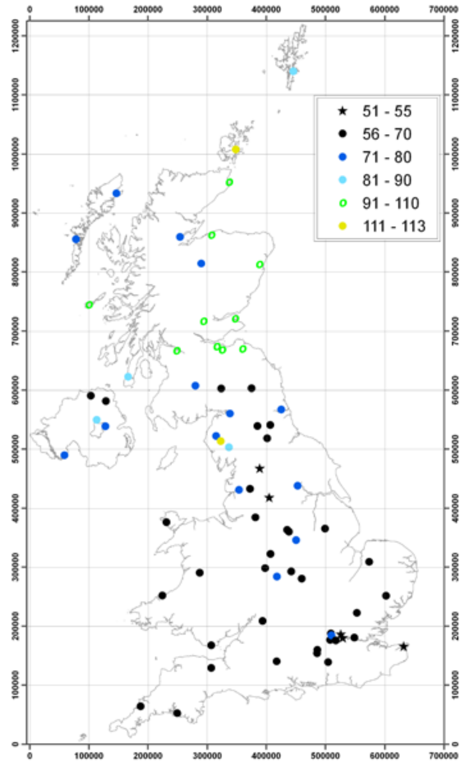

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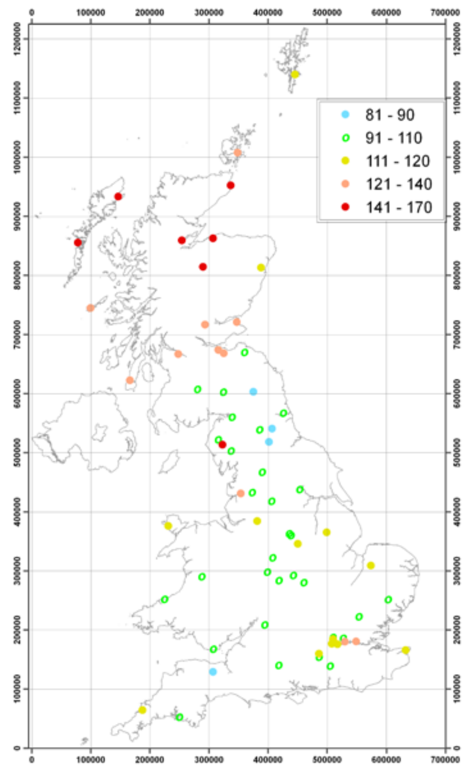

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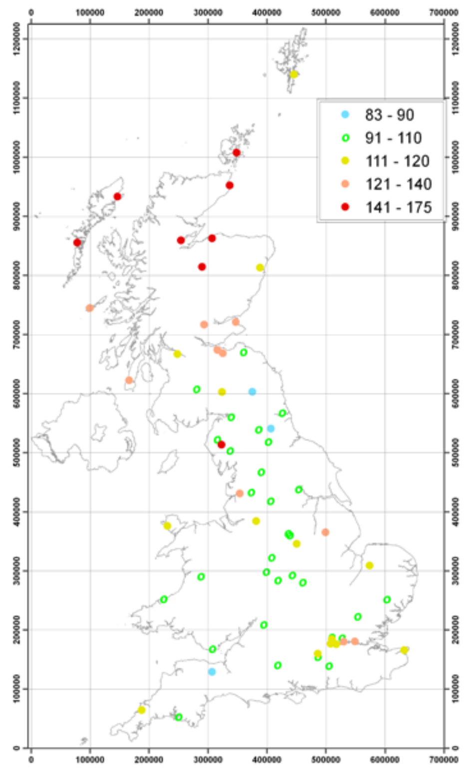

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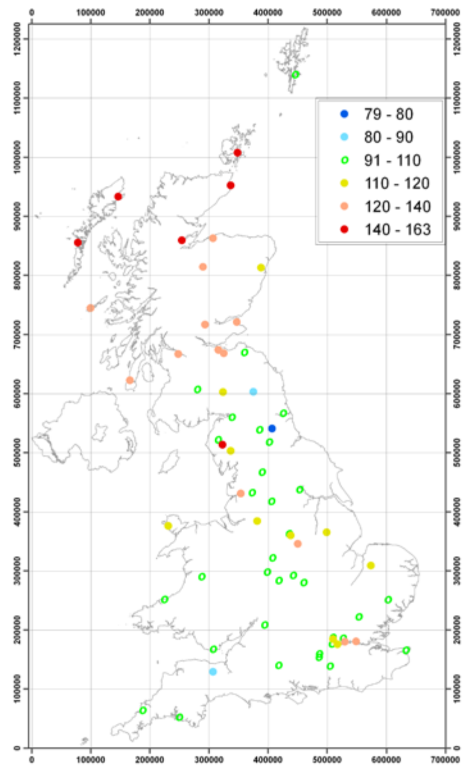

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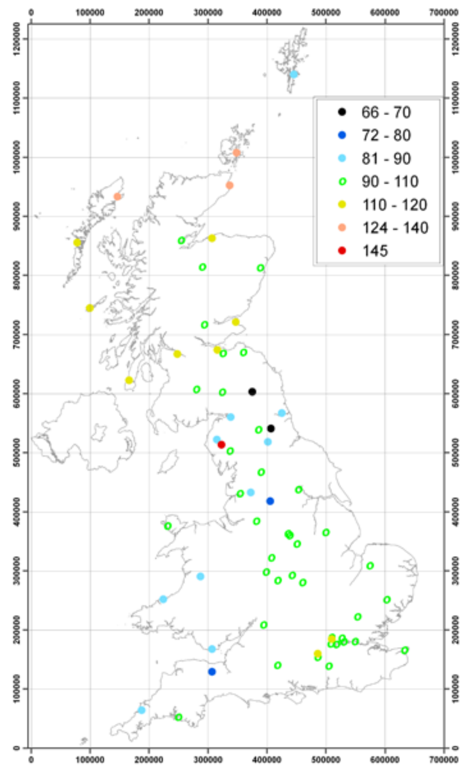

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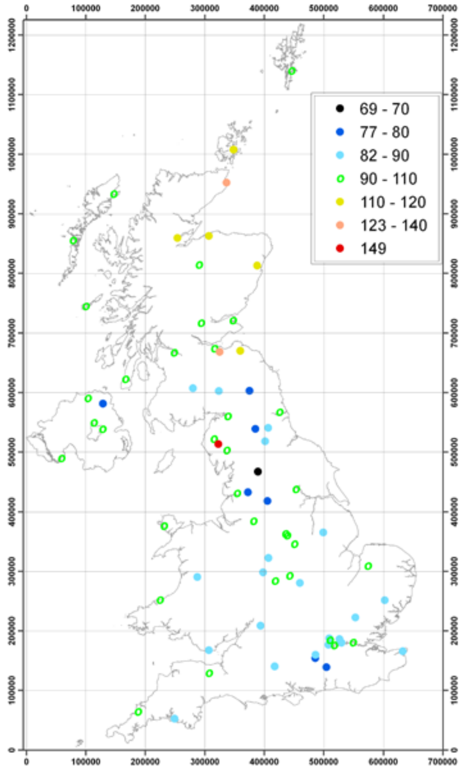

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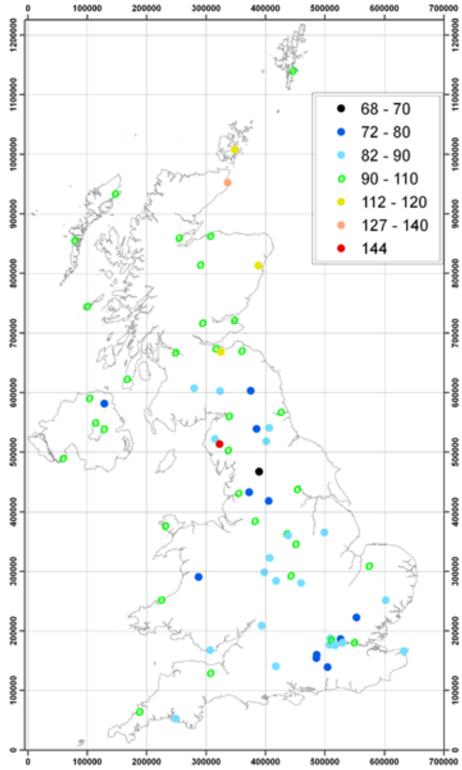

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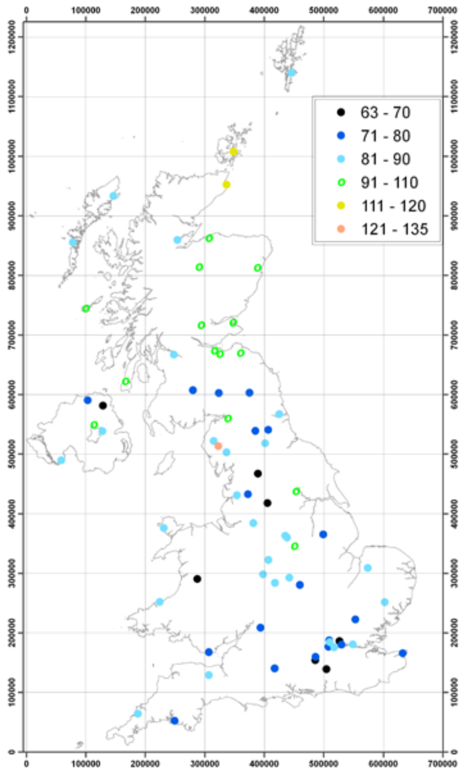

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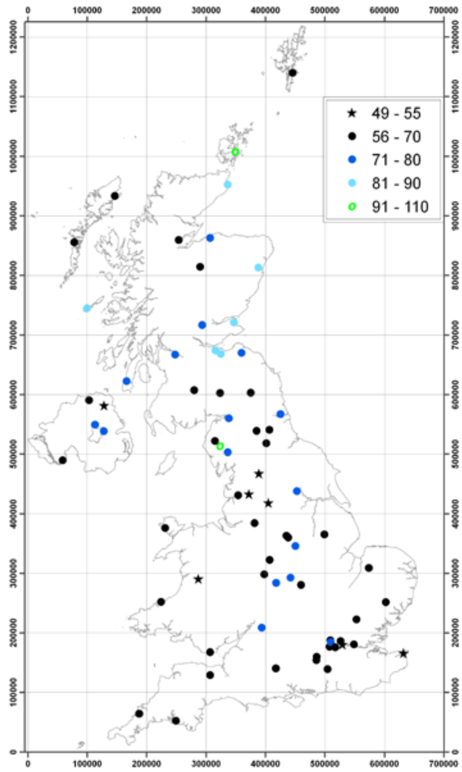

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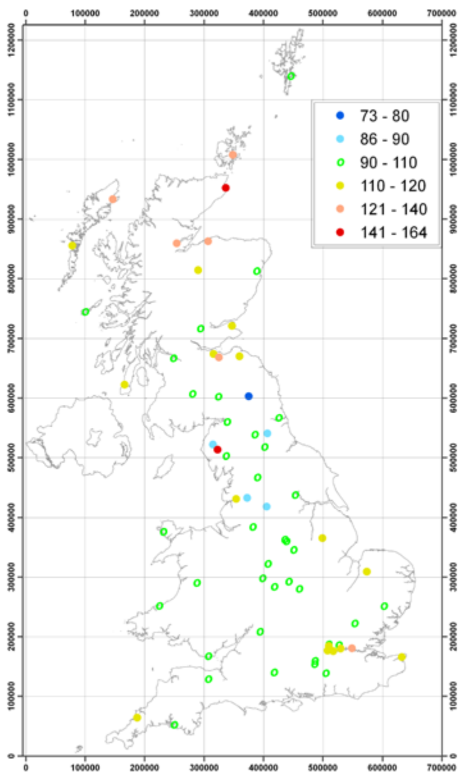

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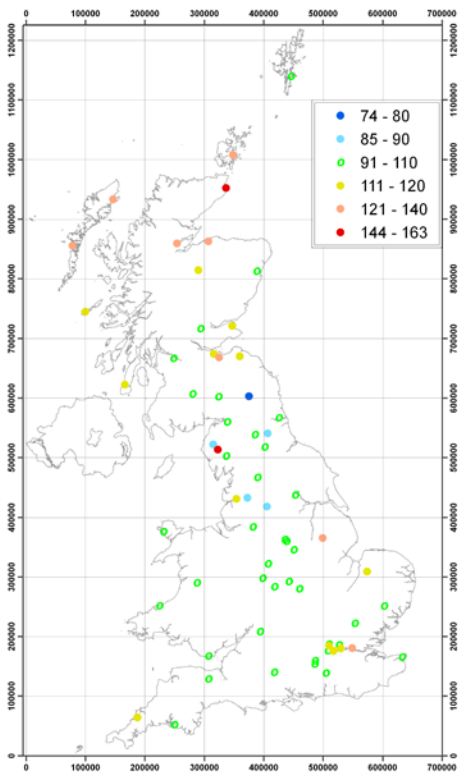

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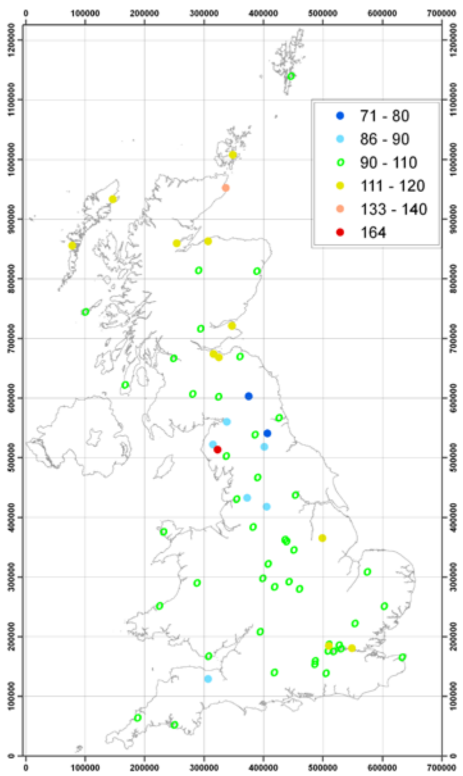

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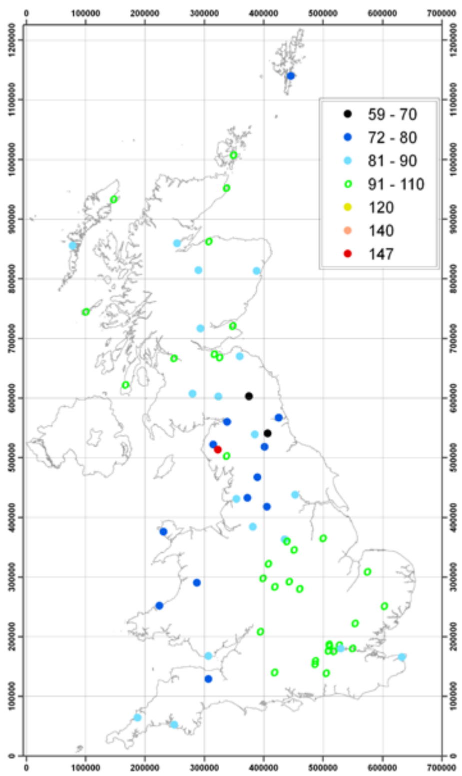
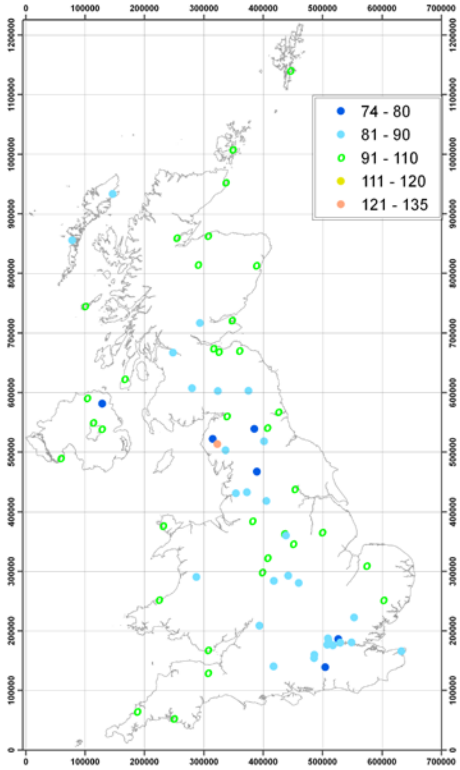


New as % of FEH for 24 hour 100 year



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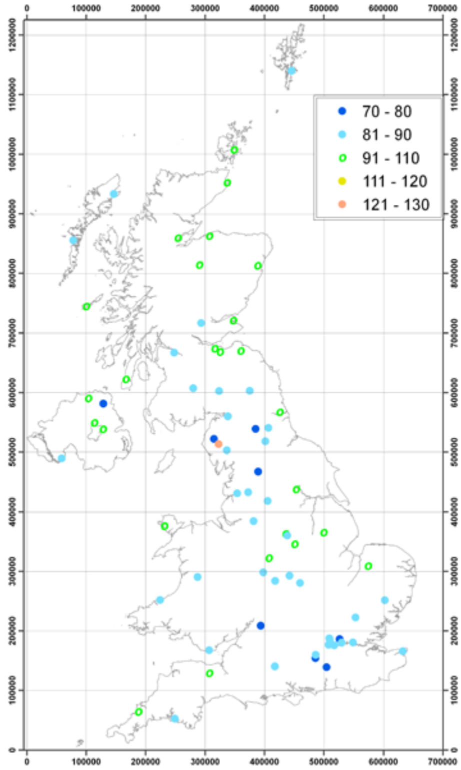

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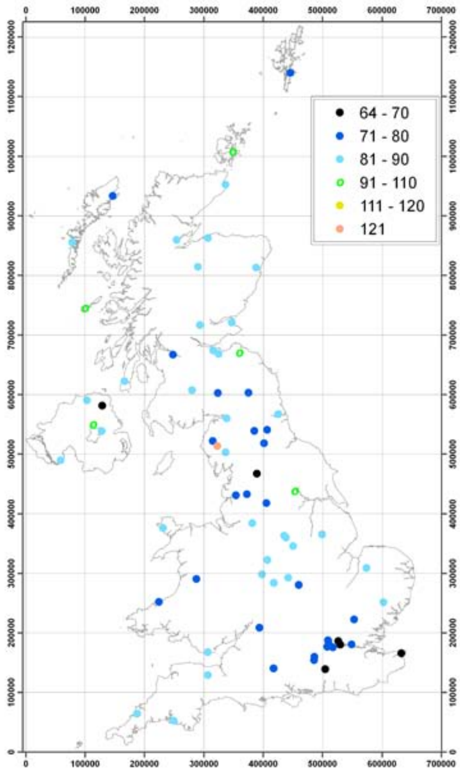

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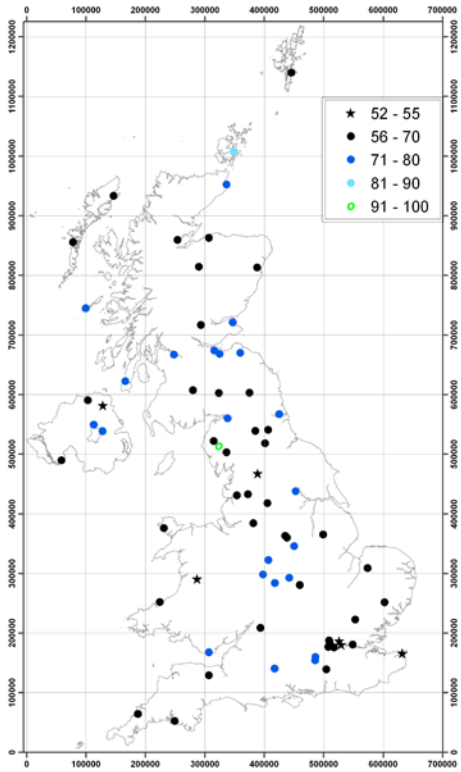

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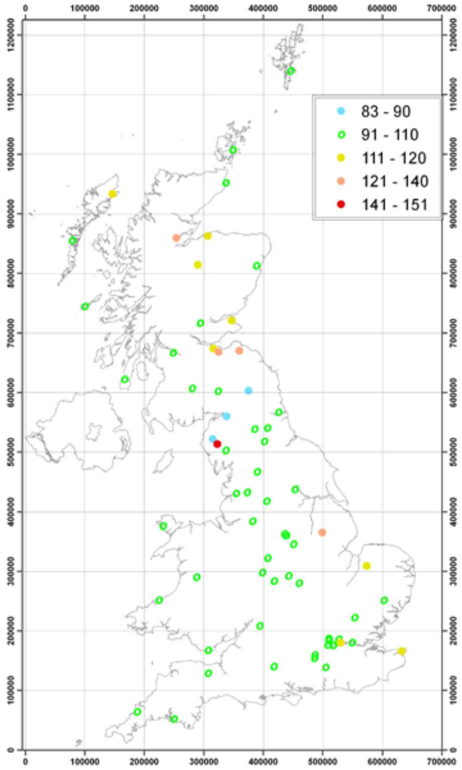

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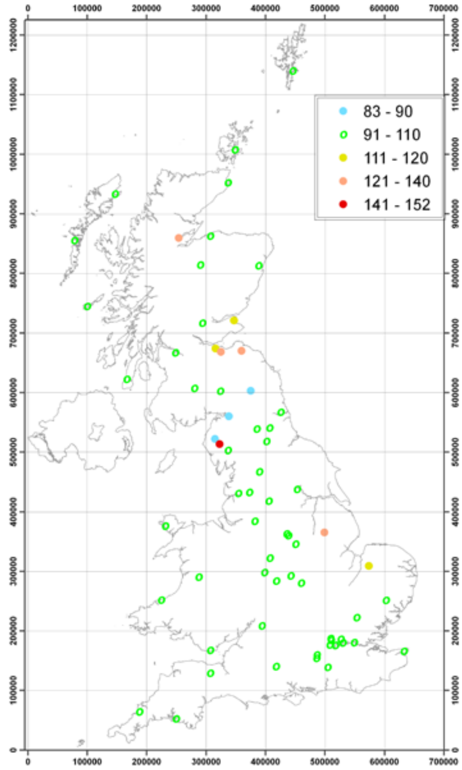

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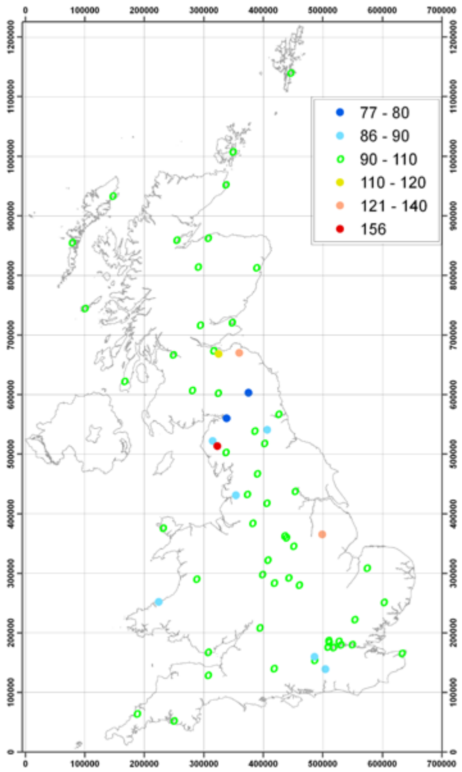

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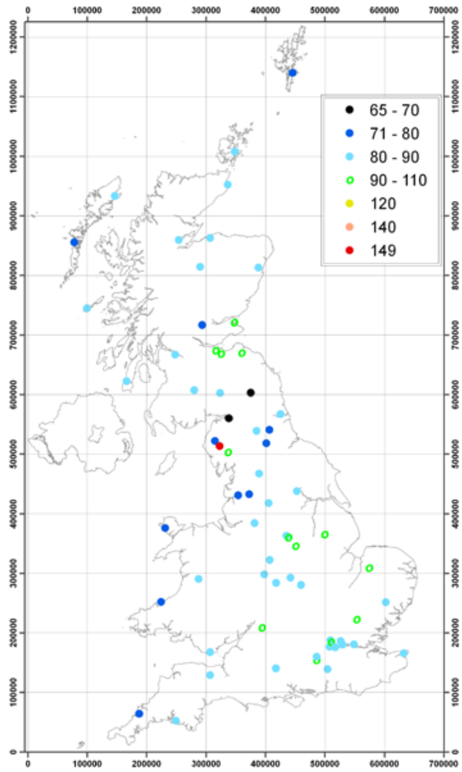

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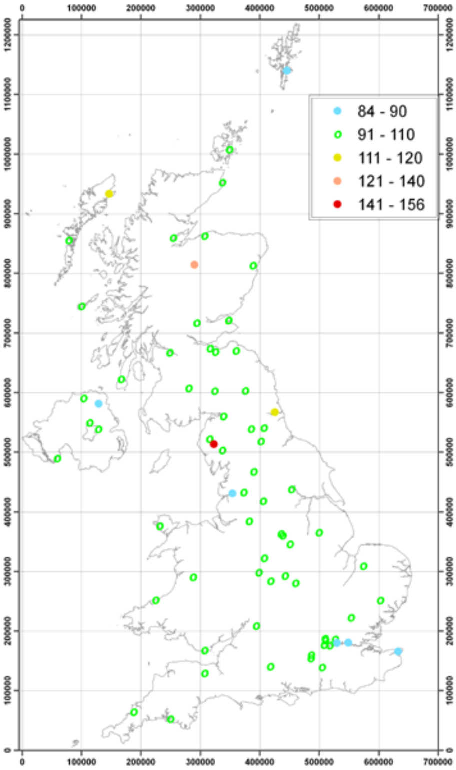

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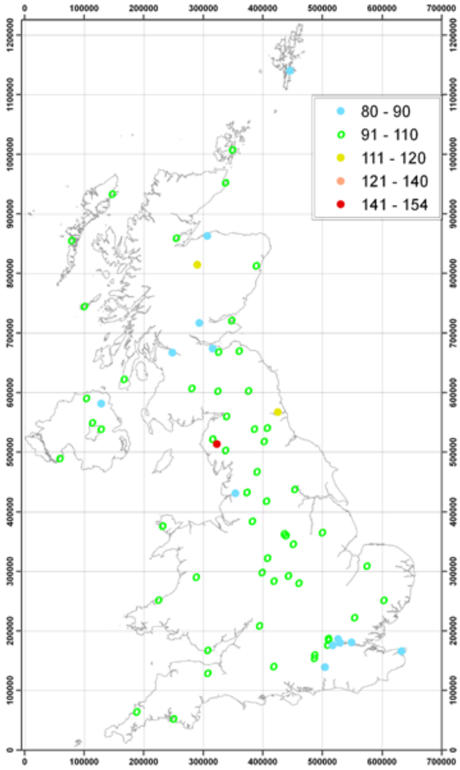

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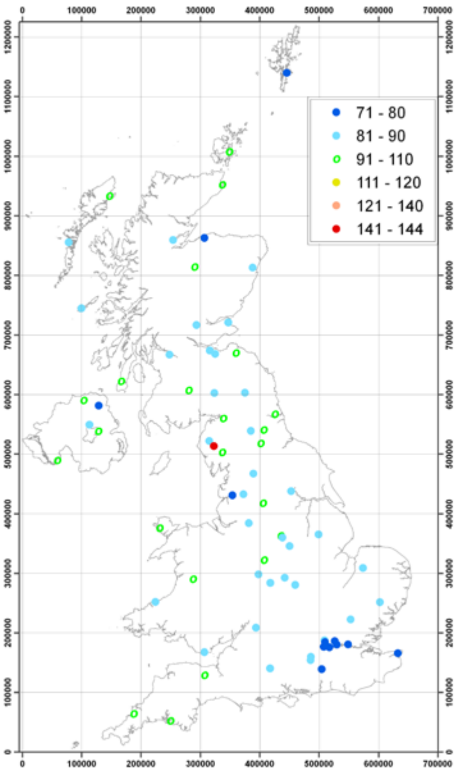

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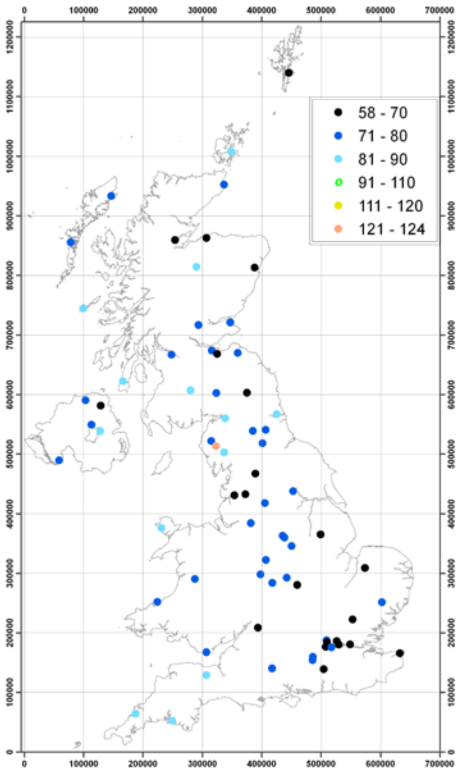

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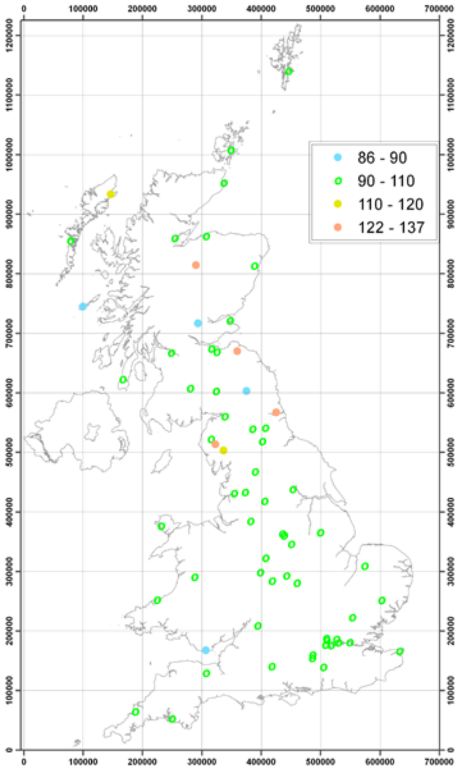

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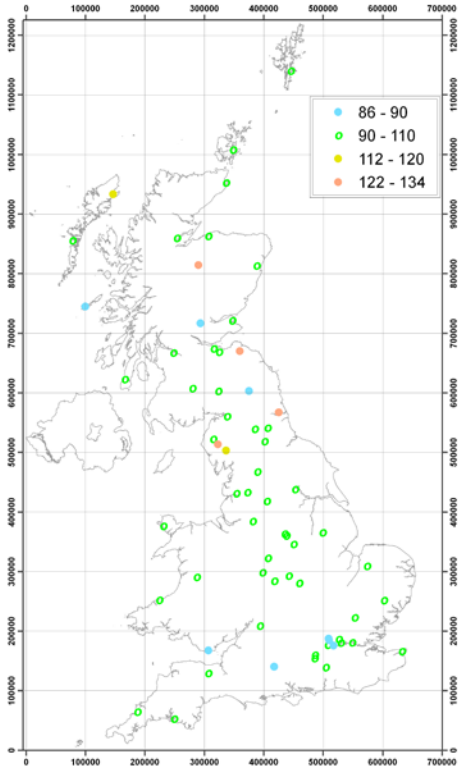

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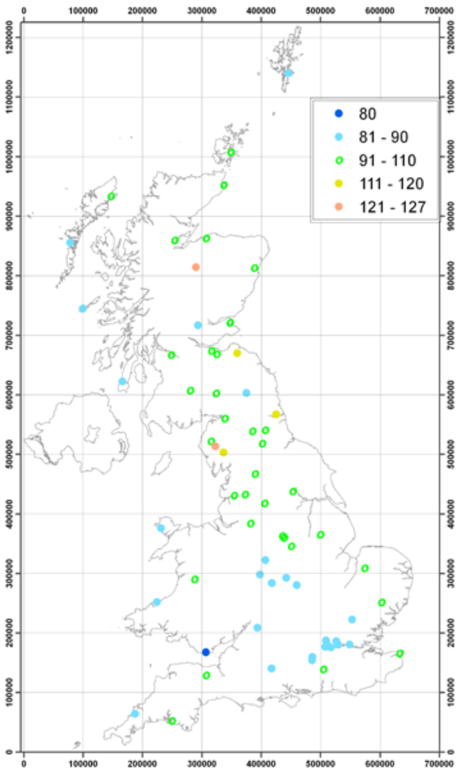

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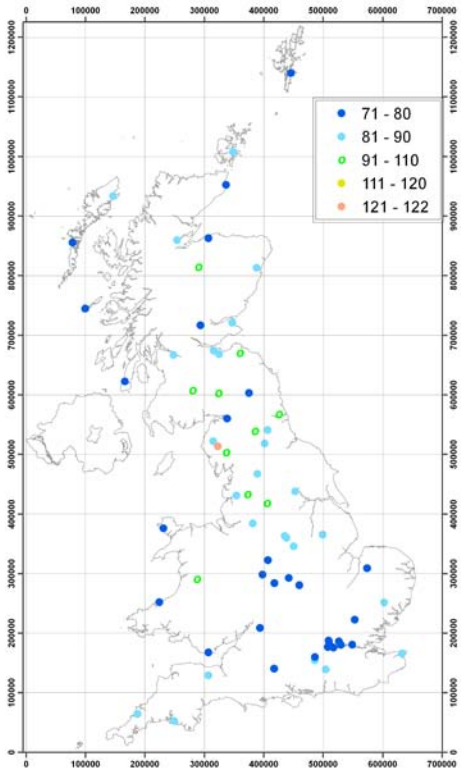

Appendix L Probability distribution of the largest observed return period

This appendix outlines a justification for the formula in Section 9.3.2 which is used to define the acceptance region for a test of model fit based on the highest return period observed for historical extreme rainfall events.

Here the problem is to assess the distribution of the largest return period observed across a set of M instances on which return periods are or might be determined, assuming that events for the different instances are statistically independent. The return period R for any one instance is related to the probability point P of the actual outcome within its distribution (where these distributions may be different for different instances), by

$$R = 1/(1-P).$$

The largest return period $R_{\max}$ is related to the corresponding probability point $P_{\max}$ (the non-exceedance probability) by

$$R_{\max} = 1/(1-P_{\max}).$$

The distribution of $P_{\max}$ is given by

$$\Pr(P_{\max} < p) = p^M ,$$

based on

$$P_{\max} = \max_{i=1,..,M}\{P_i\},$$

where the quantities P_i are independent random variables each having $\Pr(P_i < p) = p$.

A significance test based on the largest observed return period can be constructed by finding the values r corresponding to selected values of the probability α for which

$$\Pr(R_{\max} < r) = \alpha.$$

This is equivalent to solving

$$\Pr(1/(1-P_{\max}) < r) = \Pr(P_{\max} < 1-r^{-1}) = \alpha,$$

which reduces to

$$\left(1-r^{-1}\right)^M = \alpha,$$

and then to

$$r = \frac{1}{1-\alpha^{1/M}}\,.$$

For large M ,

$$\begin{aligned} r &= \frac{1}{1-\alpha^{1/M}} = \left\{1-\exp\left(\frac{\ln\alpha}{M}\right)\right\}^{-1} = \left\{-\frac{\ln\alpha}{M} - \tfrac{1}{2}\left(\frac{\ln\alpha}{M}\right)^2 + \cdots\right\}^{-1}, \\ &= \left[\left(\frac{-\ln\alpha}{M}\right)\left\{1-\tfrac{1}{2}\left(\frac{-\ln\alpha}{M}\right)+\cdots\right\}\right]^{-1}, \\ &\approx \frac{M}{-\ln\alpha}\left\{1+\tfrac{1}{2}\left(\frac{-\ln\alpha}{M}\right)\right\} = \frac{M}{-\ln\alpha}+\tfrac{1}{2}. \end{aligned}$$

For the purposes of this project the second term here is usually irrelevant.

Appendix M Return period of near-PMP rainfall

M.1 Introduction

By definition, the probable maximum precipitation (PMP) is assumed to be the physical upper limit to the amount of precipitation that can fall over a specified area in a given time. The technique of estimating PMP currently used by engineers in the UK is set out in the Flood Studies Report (FSR) published in 1975. The development of a new approach to flood statistics published in the Flood Estimation Handbook (FEH) in 1999 did not update this procedure, but was limited to rainfalls with a return period of up to 2000 years. Although not in accord with the FEH recommendations, the FEH procedure has subsequently been applied to even rarer rainfalls. Studies which have done this (e.g. MacDonald and Scott, 2001) have found that, if rainfalls with very low probability of exceedance are derived using the statistical approach in the FEH, these are larger than FSR's PMP values. However, the FSR's PMP values have also been exceeded in some observed storms: for example the 1989 Halifax storm rainfall totals may have exceeded the FSR PMP for the area yet had an estimated return period of around 1 in 6000 years according to the FEH results (Dempsey and Dent, 2009).

Of course, the PMP values produced for the Flood Studies Report are only estimates, and these might be revised, either based on the same underlying methodology or on some new approach targeted on specifying an upper bound to the amount of rainfall. However, while PMP plays a formal role in current design procedures, developments of these procedures along the lines of cost-benefit analyses would require rainfalls to be estimated for sets of extremely low occurrence probabilities. Thus there may be no explicit role for "PMP", although the use of bounded distributions of rainfall is not precluded. If this transition is made, there would naturally be an interest in knowing the probabilities assigned by the new methodology to previously-used values of PMP. In addition, it would be useful if a probability of occurrence can be assigned to PMP values within the conceptual framework in which those values are determined: this might be used as a guide to selecting a design probability in cases where a rainfall amount would be determined to have that probability of exceedance.

The FEH procedure for determining rainfall frequency (Faulkner, 1999) is one example of how a probability of excedance can be assessed for any rainfall amount, and this could be applied to PMP values. The improvement of procedure is the subject of the present report. A rather different approach is described in Section M.2, in which a resampling approach to past rainfall events, on the basis a transposing observed storms in space, is combined with a statistical model. This again leads to an approach that can assign a probability of exceedance to any rainfall amount: Section M.2 reports some previously published results of applying this to separately determined PMP values. Section M.3 outlines a conceptual model which might be used initially to assign a PMP value, while Sections M.4 and M.5 go on to ascribe a return period for PMP-like events using this framework, for moderately-side areas and large areas respectively. In particular, Section M.4 evaluates the frequencies of occurrence of the orographic and convergence processes to derive the return period for a very severe storm, while Section M.5 compares this analysis with observations of the occurrence of Mesoscale Convective Systems (MCS) (Browning and Hill, 1996), which have been associated with the occurrence of severe flooding such as that which occurred at Lynmouth in 1952 (Collier and Hardaker, 1996). It is assumed that severe storms lasting 10-24 hours are MCSs, i.e. storms producing both stratiform and convective rainfall. Figures M.1 and M.2 show satellite and radar images of a MCS that occurred on 10 May 2006. In fact a MCS has a particular dynamic structure, and it may be that storms of this duration may be more frontal in origin albeit containing significant convective rainfall. A further recent example which produced heavy rainfall in the Oxford area on 22 July 2006 was described by Webb and Pike (2007). The calculations in Sections M.4 and M.5 might therefore be valid for both meteorological types. Note that the July 2007 storm events in Hampshire, Gloucestershire, Worcestershire and Oxfordshire did have a structure involving stratiform and convective rainfall. The calculations in these sections assume representative fixed values of various parameters

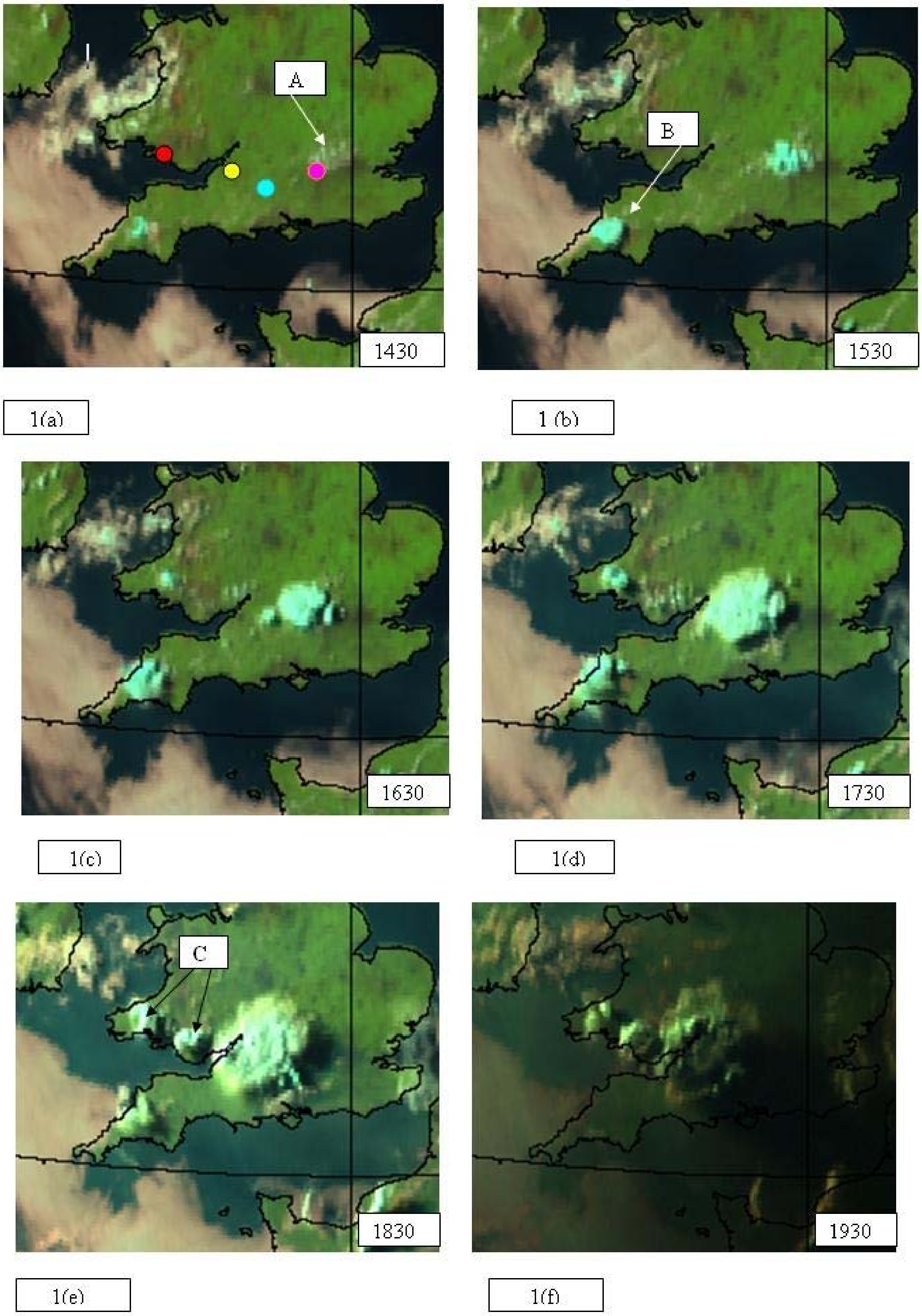

Figure M.1 Meteosat 8 false colour cloud images showing the development of an MCS over southern England on 10 May 2006. Times are in UTC, and the coloured circles represent the locations of selected places: yellow Bristol; magenta Reading; cyan Larkhill; red Swansea. (From Young, 2007)

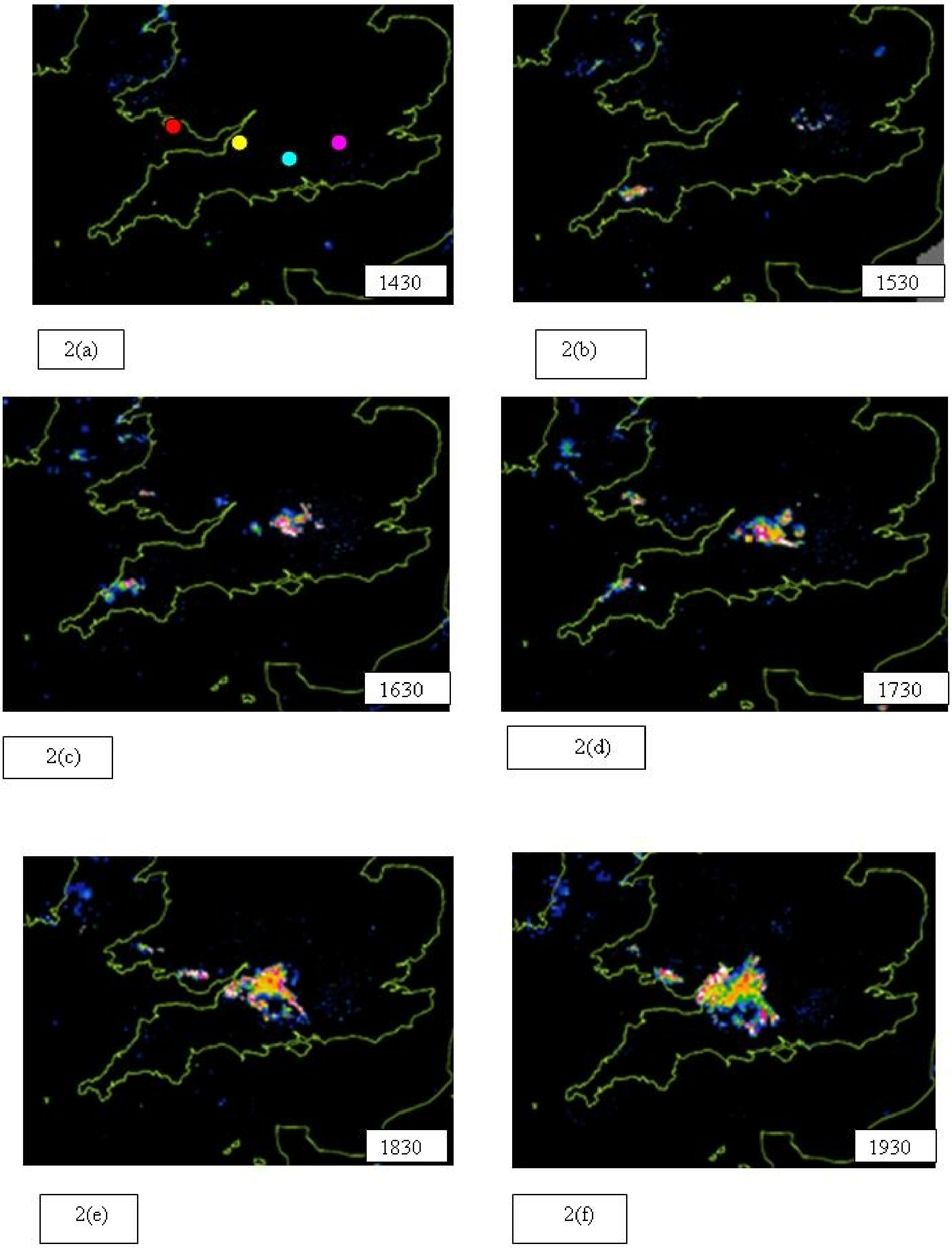

Figure M.2 One km resolution radar network images for 10 May 2006 with the times corresponding to the images in Figure M.1. Colours represent rainfall rates: blue less than 1 mm/h; green greater than 1mm/h; orange greater than 4 mm/h; white greater than 32 mm/h. (From Young, 2007).

M.2 Storm transposition approach

Fountaine and Potter (1989) investigated the estimation of probabilities of extreme rainfalls by adopting the stochastic storm transposition approach outlined by Alexander (1963), and developed by the US Committee on Techniques for Estimating Probabilities of Extreme Floods (1988). A summary of the analysis is also given by Austin *et al* (1995). The context of these earlier studies was to estimate extreme catchment-average rainfalls.

Let R_{max} be a random variable representing the annual largest value of catchment-average rainfall of duration D occurring on a catchment of interest in 1 year. The aim is to estimate the probability of occurrence of intervals in which R_{max} exceeds r: that is, to find $p_{max}(r)$, where $p_{max}(r) = P(R_{max} \geq r)$. Assumptions are made that the catchment lies within a homogeneous region and that records of the spatial profiles of past storms are available on which to base the analysis. The assumption of spatial homogeneity is used to suggest an analysis based on assuming that a given recorded storm might equally well have occurred centred on any location within the homogeneous region. However, the requirements of this spatial homogeneity assumption are, in practice, loosened by modifying the spatial transposition of observed storms to allow adjustments to be made for differences in moisture potential across the region (Fountaine and Potter, 1989, p1563).

A further assumption is made that storm events occur as a Poisson process in time. It follows that $p_{max}(r)$ is related to the similar function for storm-rainfalls, $p_{storm}(r)$, by

$$p_{\max}(r) = 1 - \exp\{-\lambda p_{storm}(r)\},$$

where $p_{storm}(r) = P(R_{storm} \geq r)$. Here R_{storm} is a random variable representing, for any storm which is counted as affecting the homogeneous region, the largest catchment average rainfall in a duration D for the selected catchment. The quantity λ denotes the rate of occurrence (storms per year) of storms which affect the homogeneous region.

The above formula is used in practice by constructing estimates as follows:

$$\hat{\lambda} = \frac{m}{N},$$

$$\hat{p}_{storm}(r) = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{C}\sum_{c=1}^{C} b_{cj}(r),$$

where N is the length of record (years) during which data are available for significant storms that have occurred in the homogeneous region containing the catchment of interest and where m is the number of such storms. The letter j is used to index the storms available in the record while c is used to index the transposed storm centres of which there are C in total for each storm event: these are assumed to be uniformly spread over the homogeneous region (otherwise a simple weighting can be applied). Finally $b_{cj}(r)$ is an indicator variable such that $b_{cj}(r)= 1$ if the largest duration-D average catchment rainfall equals or exceeds r when calculated from the version of storm j which has been transposed to centre c, and $b_{cj}(r)= 0$ otherwise.

For storm *j*, the quantity

$$\bar{b}_{j\bullet}(r) = \frac{1}{C}\sum_{c=1}^{C} b_{cj}(r)$$

is effectively the fraction of the homogeneous region at which the storm can be centred so as to give a catchment area rainfall of duration *D* which exceeds *r*. Further,

$$\bar{b}_{\bullet\bullet}(r) = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{C}\sum_{c=1}^{C} b_{cj}(r) = \frac{1}{m}\sum_{j=1}^{m}\bar{b}_{j\bullet}(r)$$

is the average of such fractions. When applied to point rainfalls rather than to catchment area rainfalls, the quantity $\bar{b}_{\bullet\bullet}(r)$ is the average fraction of the homogeneous region for which storms have a duration-D rainfall at the target point which exceeds *r*.

A simplification used by the Yankee Atomic Electric Company is reported by Fountaine and Potter (1989) in which the rate of exceedance of the threshold *r* is small. Here

$$\hat{p}_{\max}(r) = 1 - \exp\left\{-\hat{\lambda}\hat{p}_{storm}(r)\right\} = 1 - \exp\left\{-\frac{m}{N}\bar{b}_{\bullet\bullet}(r)\right\}$$

$$\approx \frac{m}{N}\bar{b}_{\bullet\bullet}(r).$$

To summarise, data from observed events are combined with a probabilistic model to produce estimates of the probability that rainfall at a point or over a catchment will exceed any given amount *r*. The probabilistic model entails the assumptions that future storms will be limited to the range of storms that have occurred in the observed record, but that spatially transposed versions of the storms can occur with equal probability anywhere in the region, and that such storms will occur as a Poisson process.

Both the exact formula and its approximation were applied by Fountaine and Potter (1989) to a catchment of 220 miles^2 (569.8 km^2) in central Wisconsin, USA. An exceedance probability range for rainfall from 11 inches to 13 inches was found to be 3×10^{-5} to 4×10^{-5} (about 1 in 3×10^4 years).

The storm transposition technique remains rather subjective and further work needs to be undertaken. Newton (1980) notes that the probability of a storm producing the PMP over a particular catchment of the Tennessee Valley in the USA has been taken as 1 in 10^8 years, with a probability of 1 in 10^6 years defining the upper confidence limit. However, considering a storm antecedent to a storm-producing PMP, given that the total rainfall for the storm sequence should not exceed PMP for that duration, reduced this exceedance probability to about 1 in 6×10^5 years with a probability of 1 in 2×10^4 years defining the upper confidence limit.

M.3 A conceptual mechanism for explaining large rainfall events

The simple model of a convective storm used here is that of Collier and Hardaker (1996), although it is considered from a different viewpoint. It is considered applicable for rainfall events having a duration of up to 24 hours. The model assumes that the physical processes mainly responsible for extreme convective rainfalls are associated with forced ascent over orography, local surface heating (thermals) and mesoscale convergence. No allowance is made for the contribution to storm development of latent heating due to the condensation of cloud droplets into rain water. This could increase the severity of a storm through increased vertical velocity, although not significantly during the initial stages of development. Further, treatment of the local heating due to solar radiation is simplified by evaluating it as the maximum monthly mean value from sunrise to the early afternoon without cloud being present. Clearly, as cloud forms, the amount of solar heating is reduced, but the present work assumes that no cloud forms initially before a storm. This assumption is discussed in Section M.4. The Storm Model has also been applied in other countries (Hardaker, 1996). The use here is not to estimate rainfall amounts, but rather to identify combinations of conditions that will lead to the most extreme rainfalls.

The Storm Model described by Collier and Hardaker (1996) is based upon estimating the likely value of maximum surface heating producing an increase in temperature (ΔT) from the climatologically minimum temperature which leads to convection. It comprises three components:

- solar heating
- orographic uplift expressed in terms of the air temperature increase that would have been required to produce an equivalent buoyancy
- uplift resulting from convergence, expressed in terms of the air temperature increase that would have been required to produce an equivalent buoyancy.

This is expressed as:

$$\Delta T = T_{\max} - T_{\min} = \frac{G}{C_p \zeta H} + \frac{V^2 h T_{\min}}{g d^2} + \frac{w V T_{\min}}{g L}, \qquad \text{(M.1)}$$

where the three components are represented respectively by the three terms of the equation, and where the parameters are as defined in Collier and Hardaker (1996): T_{max} = the maximum temperature (degrees Kelvin), T_{min} = the observed minimum temperature before convection takes place, G = monthly value of available heat from sunrise to early afternoon, H = height to which solar heating is effective, approximately the surface boundary layer depth, ζ = air density, C_p = specific heat of dry air, V = horizontal wind speed, g = acceleration due to gravity, d = characteristic horizontal width of orography (orographic width), h = height of orography, L = characteristic length scale of the mesoscale convergence and w = vertical velocity.

Heavy rainfalls can be estimated by calculating the maximum dew-point temperature from the mean daily minimum temperature and the mean daily maximum temperature derived by adding ΔT to the minimum temperature. Thus the occurrence of rainfalls close to PMP is directly related to the parameter values used in Equation (M.1). Examination of the equation reveals that the parameters fall into three categories, namely constants (g, ζ at given temperature and pressure, C_p, H and G, for given latitude and time of the year), catchment characteristics (h and d) and meteorological variables (V, T_{min}, w and L).

It is proposed to estimate the return period of rainfalls close to PMP by examining the probability of occurrence of extreme values of the terms in Equation (M.1). Of these variables, the environmental temperature will be taken as fixed and determined by the time of the year under consideration (note that the ratio G/H does not vary greatly over the summer months (Table M.1)). Also, it is not thought likely that extreme values of T_{min} contribute substantially to the occurrence of PMP-sized events. When considering severe thunderstorms, predominately a summer phenomenon, the problem is reduced to examining the frequency of occurrence of the maximum values of convergence and orographic uplift. This is approached by analysing the frequency of observed extreme events and allowing for the likelihood of the storm direction being close to that of the steepest orographic gradient in a catchment.

Table M.1 Monthly values of available heat from sunrise to early afternoon in England (*G*), and the height (*H*) to which solar heating is effective, approximately the surface boundary layer depth (columns 1-3: after Gold (1933), from Petterssen (1956))

Month	G (cal cm^{-2})	H (km)	G/H (cal cm$^{-3}\times10^5$)
January	40	0.56	71
February	70	0.76	92
March	100	0.91	110
April	140	1.07	131
May	175	1.19	147
June	180	1.22	148
July	165	1.16	142
August	150	1.10	136
September	115	0.98	117
October	80	0.82	98
November	40	0.56	71
December	30	0.49	61

M.4 Return period analysis for major thunderstorms in the UK

The following analysis estimates the likelihood of occurrence of the combination of conditions necessary for rainfall approaching PMP for durations of around 10 hours over areas of around 200 km^2. Storms having durations of 10 hours are taken as they are regarded as those which might have particular significance for the safety of medium to large reservoirs (see Austin et al, 1995).

Collier and Lilley (1994) found that, on average, about thirteen severe thunderstorms lasting five hours or more occur somewhere in the UK (mainly England and Wales) each year. Analyses of radar and other data indicate such storms can contain areas of convergence over an area of around 200 km^2. Taking the area of England and Wales as 151,168 km^2, and assuming that such storms do not overlap or move, then, the average number of such storms per year occurring at any individual location = (13 × 200)/151168 = 1/58 = 0.017.

For any individual 200 km^2 catchment, for PMP it would be necessary for the storm centroid to coincide with the catchment centroid and for the storm and catchment to be the same shape. Here we allow the storm centroid to lie within the central 10% of the catchment area and we assume a probability of 1 in 4 of the storm and catchment having a reasonably similar shape, a combined probability of 1/40 or 0.025.

For PMP, the wind direction should be in the direction of maximum orographic gradient in order to maximise uplift. In this analysis we have chosen to use the range of wind directions that gives rise to a wind strength in the direction of maximum orographic gradient that is at least 90% of its strength were it to be exactly in the direction of maximum orographic gradient. This is a range of +/- 25.8 degrees (since cos(25.8) = 0.9). Making no assumptions about prevailing wind directions or orographic gradient directions, the probability of winds being within this range is 2×25.8/360 = 1/7.0, or 0.14. Note that the orographic term of Equation (M.1) is important in the majority of catchments, not just those with high elevations, as it contains the ratio h/d^2. For example, the topographic effect of Hampstead Hill is thought to have contributed to the onset of the 1972 Hampstead storm (Bailey *et al.*, 1981).

Further, for PMP, we need to have a value of surface heating that is close to the maximum climatological value. How frequent is it that there is no cloud before a storm forms, and the surface heating is a maximum? In fact such a situation is quite rare. Studies of the development of boundary layer thermals and associated cloud is an area of current research. Figure M.3 shows an example of thermals observed with a vertically pointing Doppler lidar. Convective cloud is shown to form before the thermals penetrate the boundary layer top marked by a temperature inversion and a heavy shower results. This inversion acts as a lid holding back the convective development. Hence the surface heating is reduced when the cloud forms. Here we assume that the necessary conditions, with thermals penetrating the inversion and then leading to major ascent of the air to the top of the troposphere, will have occurred for 1 in 10 of the storm events. This is not an unreasonable assumption as the atmosphere for major storms will be potentially very unstable above the inversion. In other situations convection

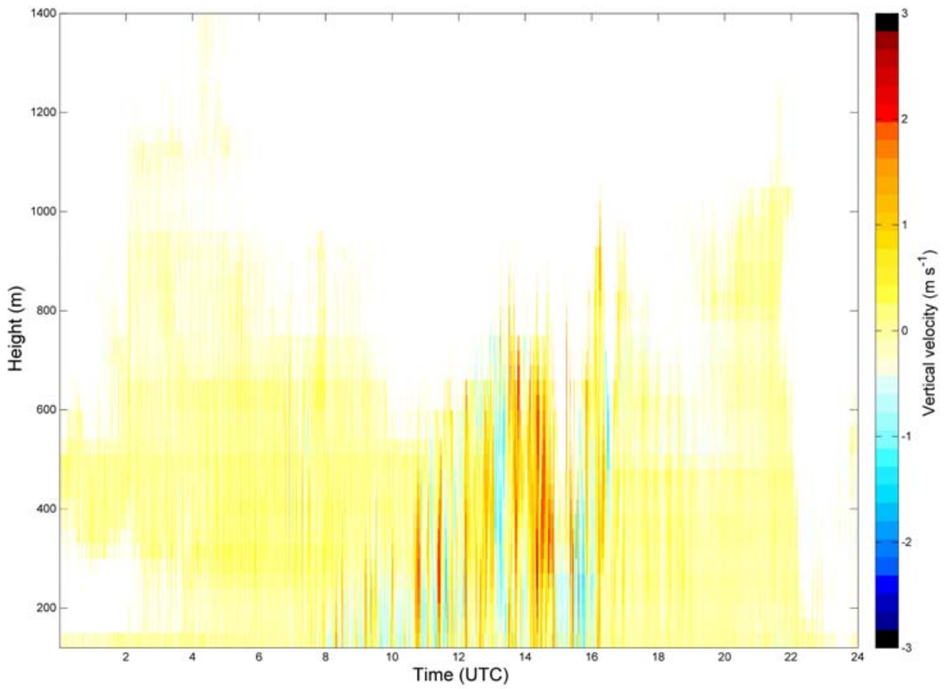

Figure M.3 The development of thermals at Achern, Germany as observed using the Salford 1.5 micron Doppler lidar on 15 July 2007. The vertical velocity (m/s) of atmospheric aerosol is shown. Thermals grow over a period of 8 minutes reaching the top of the boundary layer located at a height of about 800 m, which they do not penetrate initially. At about 1600 UTC the thermals penetrate the inversion at the top of the boundary layer which has acted as a lid.

could occur but might not penetrate to the top of the troposphere and therefore would not lead to such severe events.

Bringing the above four conditions together gives the average number of PMP events per year (of around 10 hours duration), for an individual 200 km^2 catchment in England and Wales = 0.017 × 0.025 × 0.14 × 0.1 = 0.000006, *i.e.* 1 in 1.7×10^5 years.

For smaller catchments subject to the same storm, it could be argued that the return period would be similar, because whilst the chance of the catchment lying under the storm increases, if – as is likely – the storm rainfall is not spatially uniform, PMP will only occur if the catchment lies under the most intense part of the storm. PMP for larger catchments may be associated with different weather conditions, as discussed later.

If this mechanism is relevant to PMP at individual points, the assessment of return period of PMP for a point depends on the spatial variation of rainfall within the storm relative to the most intense point within the storm. For example, if 5% of the storm area experienced a rainfall at or very close to the storm maximum, the average number of PMP events per year for a point would be $0.017 \times 0.05 \times 0.1 = 0.000085$, i.e. 1 in 1.2×10^4 years.

M.5 Return period analysis for Mesoscale Convective Systems (MCS) in the England and Wales

Mescoscale Convective Systems may be defined as continuous cloud systems of thunderstorms associated with an area of precipitation 100 km or more in horizontal extent in at least one direction (Houze, 1993).

Browning and Hill (1984) discuss the dynamical structure of MCSs. Young (2007) describes an MCS on the 10 May 2006 which brought severe weather to central southern England. Figures M.1 and M.2 show satellite and radar

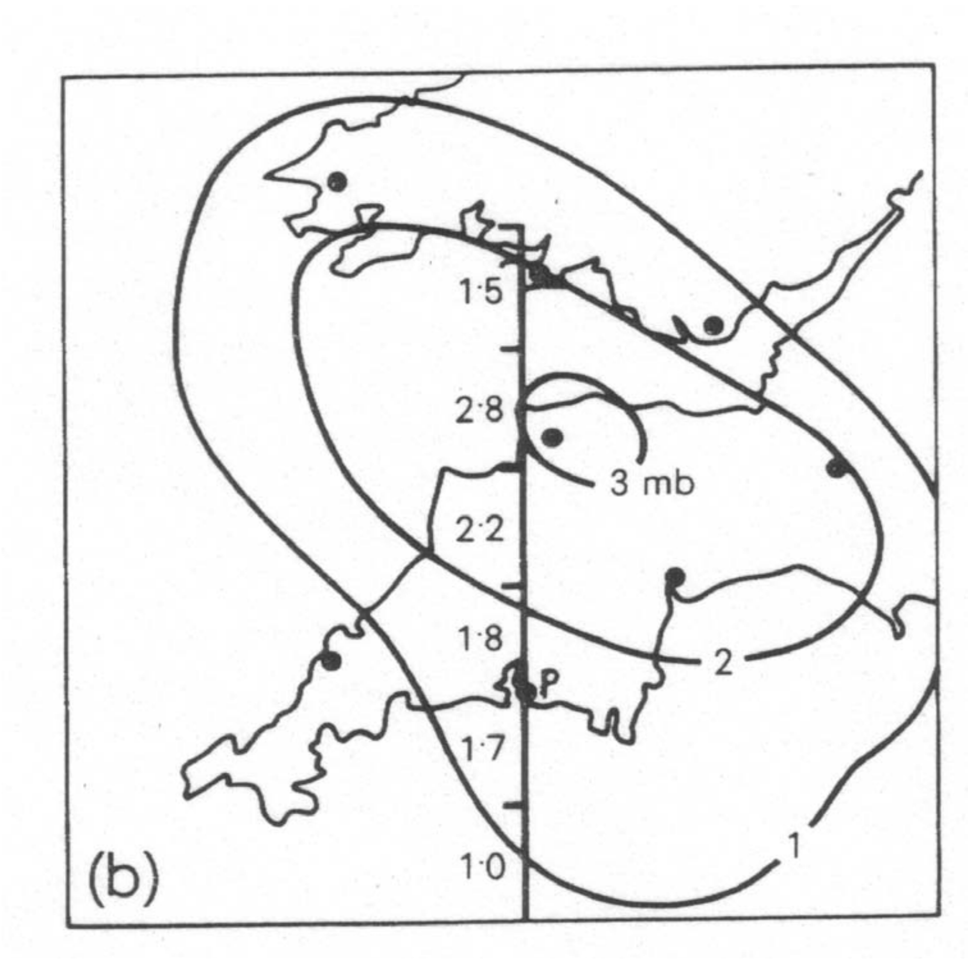

Figure M.4 Spatial distribution of an MCS pressure anomaly at 24 GMT, obtained by plotting the hourly anomalies along south-north lines at locations displaced according to the mean velocity of the rain area i.e. 40 km h^{-1}. Contours show smoothed anomalies at 1 mb intervals. Actual values are plotted only for the Plymouth (P) barograph trace, however, the contours are based on barograph traces from all the stations indicated by dots. (From Browning and Hill, 1984)

imagery for the event. Note that the cloud shield extends over a circle of approximately 100 km diameter (area 8,000 km^2), and a compact area of intense radar echoes (locally exceeding 32 mm/h) developed and extended westwards in association with the expanding convective cluster (Figure M.2). Browning and Hill (1984) analysed the spatial distribution of the pressure anomaly for an MCS, and found that the core of this anomaly, within which the most intense rain fell, was not much larger than 200 km^2 (equivalent to a circle of 16 km diameter) (Figure M.4).

Gray and Marshall (1998) identified thirty MCSs between 1981 and 1997, which might indicate a rate of about two per year. Hand *et al.* (2004) analysed all the 20th century rainfall events that were categorised as extreme by Flood Studies Report (NERC, 1975) criteria. Of these 50 events, there were five of duration 10-24 hours that could have been MCSs; these events were categorised as 'frontal with a significant convective component', a description which is consistent with the structure of MCSs, and comprised Boston (1931), Boston & East Leicestershire (1937), Lynmouth (1952), Martinstown (1955) and Whitstable (1968). In addition, a storm at Chew Stoke (Bristol) in 1968 having a duration of 9 hours is also included in this category. Other storms also have durations which might suggest that they could be MCSs. For example, Bruton (1917) has a duration of 8 hours according to Hand *et al.* (2004), although this depends upon where one defines one storm ending and another starting. Clarke and Pike (2007) suggest that the duration of this storm is about 13 hours. Therefore we will assume here that the recurrence interval for a very severe MCS, acting over 1000 km^2 and lasting around 15 hours, is once every ten years.

If the same approach as in Section M.4 is used and if the same assumptions are made, for example regarding surface heating, this gives the average number of PMP events per year (of around 15 hours duration) for an individual large catchment in England and Wales = 0.0053 × 0.025 × 0.14 × 0.1 = 0.0000019, i.e. 1 in 5.4 × 10^5 years.

M.6 Conclusion and risk context

The above analysis suggests that the return period of rainfall of around 10 hours duration *approaching* PMP is approximately 1 in 2 × 10^5 years for catchments of around 200 km^2 in England and Wales. For larger catchments, a return period of 1 in 5 × 10^5 years has been estimated, and for point locations the estimate is 1 in 10^4 years.

It is clear that the results are highly sensitive to the various assumptions that it was necessary to make. It should be noted that any attempt to estimate the return period of PMP, rather than rainfall approaching PMP, using this approach would result in a return period of infinity. This should not be viewed as a weakness, since it is not inconsistent with the concept of PMP as an upper bound.

It is interesting to note that such a probability may be compared with the risk of death in the USA from a motor vehicle accident of 1 in 10^2 years (that is a risk of death of 0.001 per year), from a flood of 1 in 3×10^4 years and from a tornado of 1 in 6×10^4 years (Chapman and Morrison, 1994).

Further work to evaluate the PMP and the return period associated with it nationwide could be carried out using the approach articulated in this appendix.