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**VALIDATION OF FSR AND FEH
DEPTH/DURATION/FREQUENCY USING RECENT MET
OFFICE RAINFALL DATA**

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Abstract

Quality controlled, 5-minute resolution, "Deluge" rainfall data was analysed. The data covers 73 gauges with record lengths up to 15 years. A peak-over-threshold analysis (POT) was carried out on selected gauges to yield depth/duration relationships for one-year return periods. These results were then compared with the Flood Studies Report and the Flood Estimation Handbook design depths. FEH overestimated sub-hourly rainfall in the South East. FEH and FSR were found to closely match the Deluge results in the South West and North West. FSR was found to over-predict rainfall depths in the North East for durations up to 3 hours. To assess higher return periods the Salisbury method of pooling data was employed. Pooling within a region was found to produce one-year return period results consistent with those from individual gauges but pooling data nationally was not satisfactory. This allowed rainfall depths to be produced for return periods up to 20 years.

Key Words

Deluge, FEH, FSR, Rainfall, Return Period, Pooling Rainfall Data, Urban Drainage.

Introduction

The work contained in this paper forms part of a wider project being conducted by the Met Office and Micro Drainage. Its objective is to make the very important Deluge rainfall data available to the urban drainage industry in an accessible and useful form. A range of analytical tools will be included with the data.

We have compared Deluge data with the Flood Estimation Handbook's and Flood Studies Report's Depth Duration Frequency predictions. Single sourced and analysed short duration data of the quality and quantity of Deluge was not available to either the FEH or FSR researchers. It presents the opportunity to validate the use of these methods for urban drainage where storm durations from 5 minutes to 6 hours are usually the most critical. The Deluge records are not long enough to validate extreme events. However Deluge contains

sufficient high return period data to identify some of the important characteristics of these events.

The Deluge Data

The study of rainfall in the UK has suffered from the scarcity of sub-daily rainfall and in particular sub-hourly rainfall records. These represent the most important durations for pluvial flooding in urban areas.

The Deluge database contains over 700 years of rainfall data recorded at 5 minute intervals at 73 sites across the UK (Table 1). The measurements were taken between 1987 and 2001. Apart from the importance of the short interval used to store the data, Deluge had several other important advantages. The data came from a single source, the Met Office, and used tilting bucket rain gauges. The data was also quality controlled by the Met Office against nearby daily check gauges.

Urban drainage design requires results in the form of peak-over-threshold (POT). It is not usual to extract these results directly from the data. Annual maximum (AM) analysis is normally done and then converted by means of a standard formula to POT. In this study software was developed to extract POT and AM from first principles for all durations from 5 minutes to 24 hours.

POT analysis also provides more information than AM and is preferable when exploiting short records.

Also design rainfall should ideally be sliding data which measures the maximum rainfall regardless of the starting time of the storm. Fixed data measured on the clock hour, or on a daily basis, must be converted to sliding data to account for what is called the descretisation effect⁽¹⁾ – fixed data underestimates peaks. As the original data was logged at a fixed 5 minute interval it can be demonstrated that no significant descretisation error is present above 1 hour.

Again the analysis of the Deluge data used a sliding duration at intervals from 2, 4, 6 minutes etc. to 1440 minutes, sliding by 1 minute at a time, through 700 years of data. The very detailed study took weeks of computer time and would not have been possible several years ago.

FEH and FSR

FEH and FSR are formidable works but as this paper demonstrates there is a need to continually improve our understanding of short duration rainfall and extreme events.

The FEH authors⁽¹⁾ identified that short duration data was not plentiful and that further research using tilting bucket recorders would provide a useful source of information. This weakness is merely of interest to hydrologists but it is very important to urban drainage engineers who are not well served simply by the use of hourly data.

It should be noted that FEH used over 7000 years of hourly data across the UK which was 3 times the amount available to FSR⁽⁴⁾ (Figure 4). The North and West of the country had the lowest number of gauges and the additional information available to FEH in these areas is therefore of particular importance.

The FEH work concentrated on rainfall event durations between 1 hour and 8 days. The FSR report did attempt to analyse sub-hourly data and was intended to be used for the prediction of rainfall depths down to 5 minutes duration. The Deluge tilting bucket gauges confirmed the strength of FSR in its prediction of short duration rainfall.

FEH does vary the growth curve with storm durations and the Deluge short duration data provided further confirmation for its approach. FSR also takes some of these effects into account.

The complex relationships between rainfall and topography makes it difficult to interpolate between stations in mountainous areas. The methods used by FEH to map the index storm RMED took several topographical effects into account. There was very good agreement between the Deluge results and FEH in the North and West of Britain and this may have been due to both the greater quantity of rain gauge information available to FEH as well as its ability to take topographical effects into account.

Pooling Station Records

Very few sub-daily records used by FEH to produce hourly annual maximum extended longer than 20 years. The longest record in the Deluge data is 15 years. The minimum record length needed to obtain RMED (2 year RP) is 9 years and most of the Deluge gauges were sufficient for this purpose. FSR, FEH and this study had to pool records to obtain longer return periods.

Care needs to be exercised when pooling data for sub-daily rainfall. The nature of extreme short duration events differs across the British Isles. This can be demonstrated in a number of ways. The ratio r map produced by FSR (Figure 3) showed that East Anglia suffered from short duration heavy rainfall while the North West has more prolonged and less intense rainfall – what the Irish would call a “soft day”. The west and north of Britain (referred to in FEH as the “Celtic” rain gauges) is affected by frontal rainfall from the Atlantic while the South East Zone, east of the Cambrian Mountains, is under the influence of thunderstorms (convective rainfall) tracking from the continent. This is not to suggest that thunderstorm cells and super cells never affect the Celtic region, as Boscastle is a recent example!

There is also a seasonal variation between these zones where the extreme storms typically hit the Celtic Zone in late October and the South East Zone in August⁽¹⁾.

It may therefore be unwise to combine rainfall data from stations across these zones. FEH used the FORGEX method for deriving growth curves. It gives

priority to local data for short return periods and data from farther afield is only used to extend the record for long return periods.

This study adopted the Salisbury Method⁽⁸⁾ for combining data first developed by Henderson⁽¹⁰⁾ and Garside⁽⁹⁾ and revised by Blanksby. The method was enhanced by also adopting the approach of using local data where possible. In addition Britain was divided into 4 climatic regions based on the AECI programme⁽¹²⁾ (Figure 1) to avoid the possibility of combining data from the frontal and convective rainfall zones of the country.

The Salisbury Method was successful in combining gauges within the regions but, as expected, the method did not produce satisfactory results when gauges were combined nationally across the Celtic (NE, NW, SW Regions) and South East Zones (SE Region).

The Salisbury Method makes no allowance for spatial interdependence in rainfall extremes which was also a criticism made of the FSR methodology. When combining data from different gauges it is assumed that each event is independent and this cannot be guaranteed. Two nearby gauges may record the same event particularly if it is a long event. However the effect was not significant for events from 5 minutes to 6 hours on the distribution of Deluge rain gauges. We did observe that the single and regional combined gauge data diverged for durations above 12 hours and this may have been due to spatial interdependence.

Analysis

Low Return Periods on Individual Gauges

The 1 year POT return period was obtained at gauges with more than 8 years of data and the 2 year return period for gauges with records longer than 9 years. A comparison of Deluge/FEH/FSR at individual gauges for a one year return period is given in Figures 5 to 17.

The analysis of each individual rain gauge is important for two reasons. Any possible error associated with pooling gauges is absent and the 2 year AM return period (RMED) is used by FEH as its index storm. If the Deluge data and FEH prediction differ at low return periods then they are likely to differ for all return periods. Also FEH states that local data may be important in validating RMED.

Regions

The Deluge/FSR match was marginally better than the Deluge/FEH agreement in the **SE Region** (Figure 8). For the 2 year return period above 6 hours FEH, FSR and Deluge are almost identical. However both FEH and FSR were generally 5% to 15% higher than Deluge for the 1 year return period. The study did not provide any general justification for the increase in rainfall prediction by FEH for low return periods in this region.

In the **South West & North West Regions** FEH and FSR compared equally well with Deluge for durations from 10 minutes to 16 hours. FEH was a little more consistent which was confirmed by the lower standard deviation (Figures 11 & 17).

In the **North East Region** FSR over predicted for short durations up to 3 hours and FEH was the better match. Both FEH and FSR produced an almost perfect match with Deluge above 3 hours (Figure 14).

FEH produced good results for durations as low as 10 minutes in the West and North of Britain but it should not be used for 5 minute prediction anywhere in the UK.

Pooling Gauges for High Return Periods

The need to pool gauges and the possible pitfalls have been discussed earlier. We confirmed the performance of the Salisbury Method by comparing it with the results of the single gauge at the subject site, for 1 and 2 year return periods. We also compared the results with FEH and FSR prediction.

Pooling gauges within regions proved to be successful but combining them nationally was not. We were therefore limited to records of approximately 200 years within each region. There did not appear to be any advantage in pooling gauges in smaller local areas. The SE Regional pooling performed as well as the Thames Valley local combination.

The pooling yielded a combined regional record length of approximately 200 years in each of the 4 regions. We were able to determine return periods up to 20 years for durations between 5 minutes and 6 hours with reasonable confidence.

Comparisons of the pooled 20 year return period results, at 8 locations across the country, are shown in Figures 8 to 25.

The Variation of Growth Curves with Storm Duration

The ratio r (ratio of the 1 hour storm to 2 days) was used in the FSR formula (Figure 3). The proportion of rain that falls in a short period however increases with return period. This may be due to the nature of extreme rainfall which is often convective and occurs usually around summer to early autumn. Thunderstorms do not rain evenly for long periods but deposit the precipitation in bursts. Therefore if the ratio r is 0.4 for a 5 year RP storm it may be much greater for a 100 year RP which would require a different growth curve to be applied to different storm durations.

FEH addressed this issue. However it is not true to suggest that it had been ignored by FSR. The ratio r does vary with return period but this variation is more pronounced in FEH.

An analysis of the Lesnewth TBR gauge near Boscastle on 16th August 2004 had a very high return period over a 4 hour duration (Figures 26 & 28) and this return period reduced over 24 hours. In other words the majority of the rainfall

occurred in just 4 hours and a daily gauge would have greatly underestimated the storm's impact. This confirms the importance of collecting and analysing short duration data for urban and rural studies.

An analysis of all events between 1988 and 2001 at the nearest Deluge gauge (St Mawgan, Figure 27) revealed that the highest return period is also generated for a four hour duration. It could be a coincidence or perhaps the proportion of rainfall that falls in short duration extreme events has been underestimated on this coastline.

We examined the ratio of the 30 minute rainfall depth to the 6 hour depth as it is important in urban drainage and also because the Deluge data is informative in this range.

Results for Heathrow, St Mawgan and Loch Levan are shown in Figures 29 to 31.

The Applications of Deluge Data.

- Calibrate FEH
- Modified Rational Method
- Continuous Analysis

Calibrate FEH

FEH is being widely adopted but it is not a full solution for urban drainage engineers. Sub-hourly rainfall is not reliably predicted by the method. Deluge may be used to construct the sub-hourly totals at any location using the Salisbury Method. It may also be used to construct a more general local relationship with the FEH 1 hour data to extend FEH prediction down to a 5 minute interval.

FEH (FEH 2.12) does not recommend altering the growth curves using local data as it would ideally require 1000 years of data at a site and Deluge cannot provide this at the moment.

However FEH does state that local data is valuable in the prediction of RMED and it may be used to adjust the index storm. Any adjustment would have a pro-rata effect on the predicted rainfall for all return periods.

Modified Rational Method

Intensity duration frequency curves for use with the Modified Rational Method may also be reliably estimated using the Deluge data, as FEH is not applicable to the Rational approach which needs reliable sub-hourly rainfall totals.

Continuous Analysis

Long records are required for continuous analysis. There is only a 65% probability that a 10 year record will contain a 10 year RP storm. However the Bracknell rainfall record is only 8 years long yet it contains several storms with return periods greater than 200 years. Due to the random nature of extreme

events it is necessary to have a long enough record so that the extremes may be discarded and conversely long records are required to ensure that the required return period event is present in the record.

If the sub-yearly performance of a network is to be examined (for example the performance of CSOs) it is possible to obtain a “typical year” from 10 to 20 years of data. If a new design needs to be checked for exceedance for return periods above 30 years then ideally 300 years of data are required. A design based on a 30 year RP would be expected to fail less than 10 times in 300 years. It is possible to get reasonable results from 200 years of data for a 30 year RP.

The quantity of deluge data across the country makes it possible to apply continuous analysis for flooding service levels of 30 year return periods (annual probability 0.33%) on new designs. The flood flow paths of the many extreme events contained in the record may also be tracked.

Availability

Rainfall data is currently expensive. It is also difficult to abstract meaningful information from raw data. Micro Drainage with the Met Office are developing a suite of software which will relocate the Deluge Data to any site in the UK using the most appropriately sited gauges. It will output a range of continuous data including

- Typical year all events
- Typical year main events
- Bathing season all events
- Bathing season main events
- Long series all events
- Long series main events

24 hour design storms for the above will be produced to speed productivity.

Design information for use with the rational method will also be output for any location. The software, with the Deluge data embedded, will be available by the end of the year.

Further Research

It is fair to point out before making further comment on the FEH approach that it had river catchment hydrology in mind and not urban drainage analysis. If it delivered all that urban drainage engineers required it would have been a bonus but it was not the objective (unfortunately).

One consistent feature of these results is that there is scope for improving the FEH model for durations below 1 hour. In some cases in Scotland it performed better than expected but the current advice on the FEH CD not to use it below 30 minutes is sensible. The FSR model performed very well and demonstrates that extending the FEH model to include durations as short as 5 minutes is possible and would be a very worthwhile project. The FEH model

is being reviewed but unfortunately at the time of writing there is no proposal to extend its use to sub-hourly rainfall.

FSR was a state of the art demonstration that accurate design storms could be produced for use with urban drainage analysis and FEH, as yet, is not a full substitute for it.

There are other pooling methods which may be considered to extend the record. The FEH approach to pooling catchments uses hydrological similarity. One of the most important variables to determine hydrological similarity is SAAR. Deluge⁽⁷⁾ also recommends the use of SAAR to pool gauges. This variable can change significantly in the Celtic Zone over short distances where the influence of topography is important. Jenkinson⁽⁴⁾ combined gauges that had similar M5 – 2 day rainfall. These approaches are currently being examined.

Finally, more data, and access to more data would help everyone. The Deluge data would provide a basis for an FEH study of sub-hourly rainfall. There is also more data already recorded and awaiting quality control. The author hopes this project, with the support of the Met Office, will make a contribution in this regard.

Acknowledgements

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References

1. Flood Estimation Handbook, Volume 2. Rainfall Frequency Estimation. Institute of Hydrology. 1999.
2. Flood Estimation Handbook, Volume 3. Statistical procedures for flood frequency estimation. 1999.
3. Flood Estimation Handbook CD-ROM, Version 1.0. Institute of Hydrology. 1999.
4. Flood Studies Report, Volume 2. Meteorological Studies. Institute of Hydrology. 1993.
5. The Wallingford Procedure, Volume 1. Design and Analysis of Urban Storm Drainage. HR Wallingford. 1981.
6. The Wallingford Procedure, Volume 3. Design and Analysis of Urban Storm Drainage, Maps. HR Wallingford, 1981
7. Deluge, Rainfall data for a cleaner environment. Met Office. 2002.
8. Blanksby, J. Garner, L. The Salisbury Method. WAPUG Meeting. 2001.
9. Garside, I. Using Annual Rainfall Time Series. WaPUG User Note No 23. 1990.
10. Henderson, R.J. Rainfall Time Series For Sewer System Modelling. WRc External Report ER195E. 1986
11. Dale, M. Gill, E. Getting the Right Rainfall? – Gauged versus Stochastic Rainfall Data for Urban Drainage Modelling. Met Office, WaPUG. 2002
12. British Climate. Atmosphere, Climate & Environment Information Programme, Manchester Metropolitan University, DEFRA & ARIC. 2005.

Appendix Gauge Locations and Regions

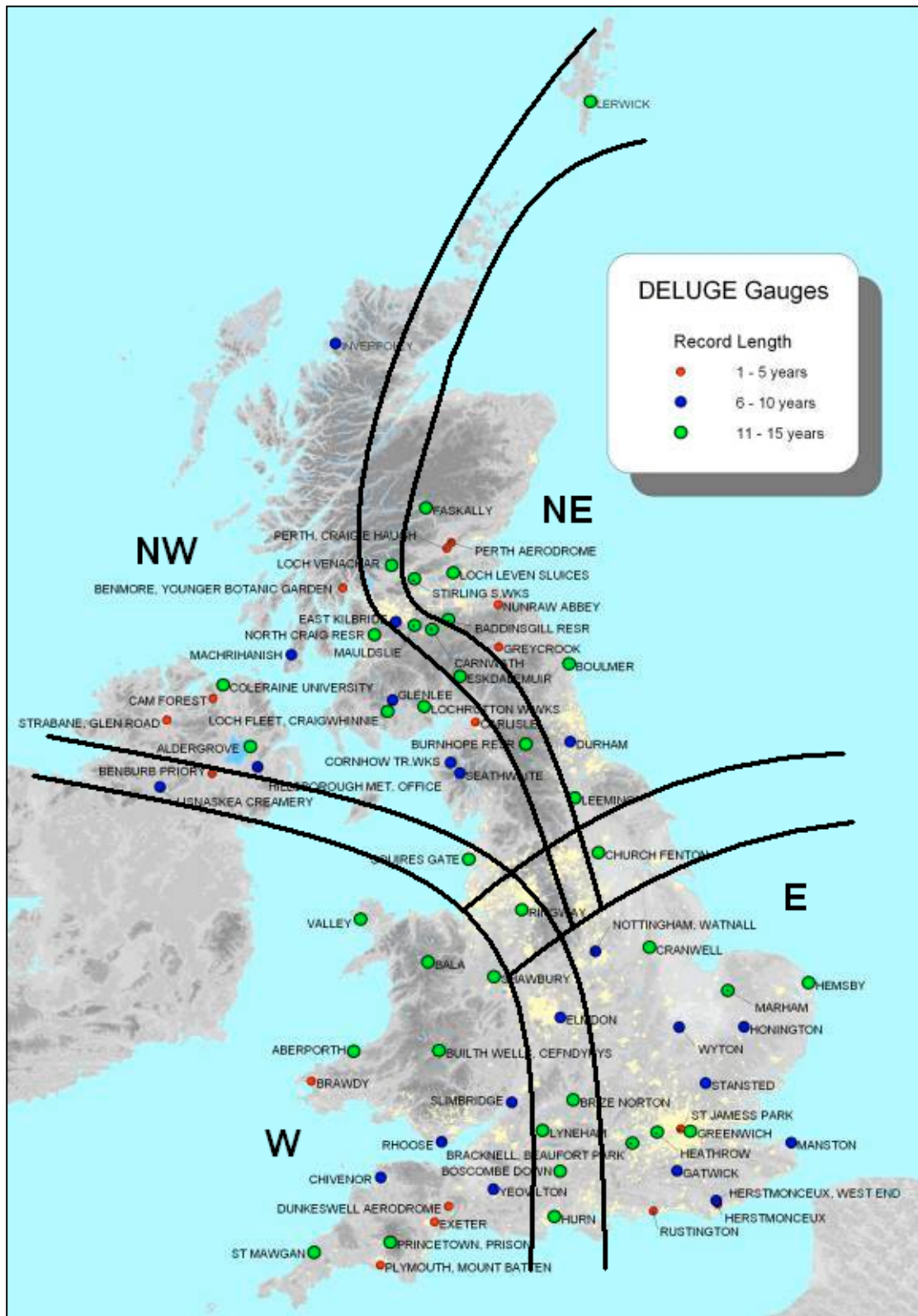


Figure 1 - The climate in the British Isles divided into 4 Regions after the Atmosphere Climate and Environment Information Programme.

Gauges

Climate Region	Gauge ID	Easting	Northing	Start Date	Record Length (Years)	AAR (mm) 1941-1970	FEH SAAR (mm)	M5-60 (mm)	Ratio-r	M5-2day (mm)
W	Aberporth	224100	252100	02/01/1988	14	995	948	18	0.3	60
NE	Baddingsgill	312600	655400	01/01/1987	15	1117	1092	15	0.25	60
W	Bala	293500	335600	01/01/1990	12	1847	1846	20.5	0.25	82
NW	Benmore	214100	685700	01/01/1998	4	2573	2449	18	0.175	103
E/W	Boscombe Down	417200	140300	01/01/1988	14	732	721	18	0.35	51
NE	Boulmer	425300	614200	01/01/1988	13	696	688	16	0.3	53
E	Bracknell	484600	166400	01/01/1993	8	683	666	19	0.4	48
W	Brawdy	185100	224800	01/01/1988	4	1156	1106	18	0.275	65
E/W	Brize Norton	429200	206700	01/01/1988	14	737	663	20	0.4	50
W	BuilthWells	303800	253000	01/01/1987	14	1001	1002	16	0.25	64
NE/NW	Burnhope	385000	539100	01/01/1987	11	1594	1593	18	0.218	83
NW	Carlisle	338300	560300	01/01/1989	5	805	827	17	0.35	49
NE/NW	Carnwath	297400	646400	01/01/1988	14	823	859	13	0.28	46
W	Chivenor	249600	134400	01/01/1988	6	913	910	17	0.3	57
E/NE	ChurchFenton	452800	438000	01/01/1988	13	623	607	19	0.392	48
NW	Cornhow	315000	522200	01/01/1987	8	2384	2233	18.7	0.281	67
E	Cranwell	500400	349300	01/01/1988	12	599	594	19.3	0.4	48
W	Dunkeswell	312800	107600	01/01/1992	4	1056	1029	20	0.35	57
NE	Durham	426700	541500	01/01/1988	10	897	866	17	0.35	49
NE/NW	EastKilbride	263800	653500	01/01/1987	9	1197	1247	17	0.28	61
E/W	Elmdon	417600	283900	01/01/1987	10	701	695	19	0.402	47
NE/NW	Eskdalemuir	323500	602600	01/01/1987	13	1691	1666	22	0.25	88
W	Exeter	300100	93300	01/01/1988	3	782	796	21	0.4	53
NE	Faskally	291800	759900	01/01/1988	14	896	867	16	0.25	64
E	Galwick	526500	140700	01/01/1988	10	824	810	20	0.35	57
NW	Glenlee	260600	580500	01/01/1987	13	1531	1638	18	0.225	80
E	Greenwich	538700	177600	01/01/1988	14	599	586	20	0.45	44
NE	Greycrook	359900	630500	01/01/1998	4	759	706	15.5	0.3	52
E	Heathrow	507700	176700	01/01/1989	13	626	614	20	0.4	50
E	Hemsby	649300	316200	01/01/1988	13	611	595	18	0.4	45
E	Herstmonceux	563000	112700	01/01/1987	14	765	773	20.5	0.35	59
E	Honington	588800	275000	01/01/1988	6	597	595	20.5	0.45	46
E/W	Hurn	411700	97800	01/01/1987	14	804	800	19	0.35	54
NW	Inverpolly	207400	913400	01/02/1988	9	1722	1690	14	0.2	70
NE	Leeming	430600	489000	01/01/1988	14	634	624	18.3	0.392	47
NW	LochFleet	255700	569800	01/01/1987	8	2201	2246	21	0.2	105
NE	LochLeven	317100	699400	01/01/1987	15	941	923	15.5	0.2	78
NW	Lochrutton	290100	574300	01/01/1987	14	1292	1263	17	0.25	68
NW/NE	LochVenachar	259800	706300	01/01/1987	15	1573	1594	15	0.17	88
E/W	Lyneham	400600	178200	01/01/1988	14	741	718	20.3	0.4	51
NW	Machrihanish	166300	622600	01/01/1988	8	1193	1121	15	0.2	75
E	Manston	633200	166900	04/01/1989	10	607	594	20.5	0.4	51
E	Marham	573700	309100	01/01/1988	14	628	625	20	0.45	44
NW	Maudslie	280800	650200	01/01/1987	15	836	816	14	0.3	47
NW	NorthCraig	243800	641200	01/01/1987	15	1370	1398	14	0.25	56
E	Nottingham	450300	345600	01/01/1988	7	687	698	18.5	0.375	49
NE	NunrawAbbey	359400	670000	01/01/1998	4	771	788	15.5	0.25	62
NE	Perth	311300	722600	01/01/1988	9	753	791	14	0.3	47
W	Plymouth	249200	52700	01/01/1988	3	1017	1019	18	0.3	60
W	Princetown	258300	74000	01/01/1987	14	1916	1949	21	0.2	105
W	Rhooose	306600	167700	01/01/1987	7	968	940	19	0.35	54
E/W/NW	Ringway	381400	384400	06/01/1988	14	801	827	18	0.4	45
E	Rustington	504500	103400	01/01/1990	4	730	730	19	0.35	54
NW	Seathwaite	323500	512100	01/01/1987	8	3992	3653	23	0.15	153
W	Shawbury	355300	322100	01/01/1988	14	699	669	18.5	0.4	46
W	Slimbridge	372200	204700	01/01/1990	8	776	696	19	0.35	54
W/NW	SquiresGate	331600	431600	01/01/1988	14	883	868	18	0.35	51
E	Stansted	553100	222600	04/01/1989	8	624	611	20	0.4	50
NE	Stirling	280800	693500	01/01/1988	6	1011	997	15	0.25	60
E	StJamesPark	529800	180000	01/01/1996	2	616	620	20	0.45	44
W	StMawgan	187200	64100	01/01/1988	14	1020	1031	17	0.3	57
W	Valley	230800	375800	01/01/1988	14	877	867	15.5	0.3	52
E	Wyton	528400	274500	01/01/1988	7	551	546	20	0.45	44
W	Yeovilton	355100	123200	01/01/1988	6	750	699	18	0.37	49

Table 1 – Details of the Deluge Gauges.

FEH/FSR Variation

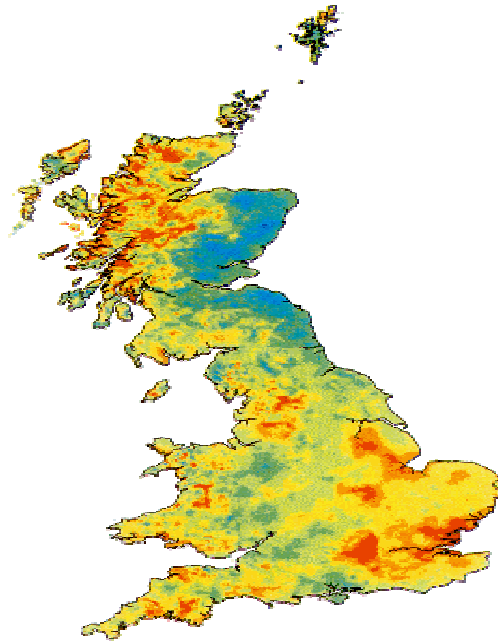
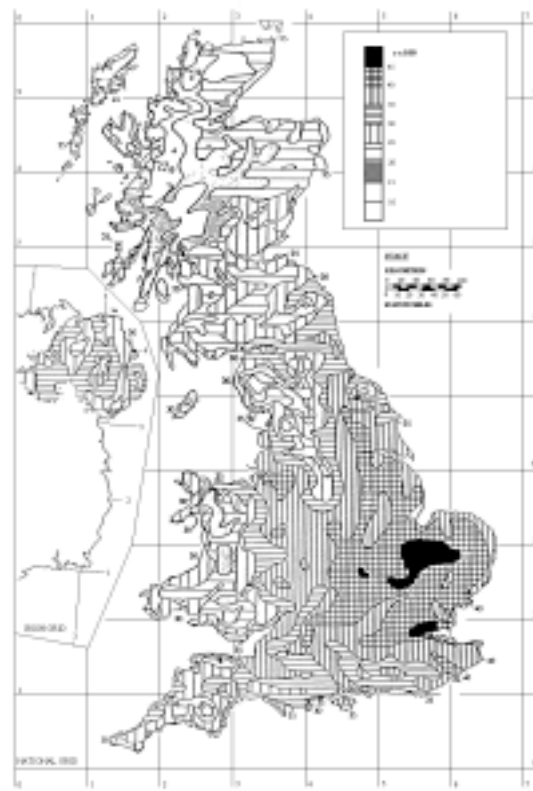


Figure 2 - Red areas show where the 100 year 1 hour FEH storm contains 1.4 times the depth of the equivalent FSR event. (FEH Figure 2.11.8)



Ratio of sixty minute to two day rainfalls of five year return period (r)

Fig 8.2

Figure 3 - Jenkins' ratio r. The higher the ratio (dark areas) the more intense short duration extreme events. (Wallingford Procedure Figure 1.6.2)

FEH Gauge Locations

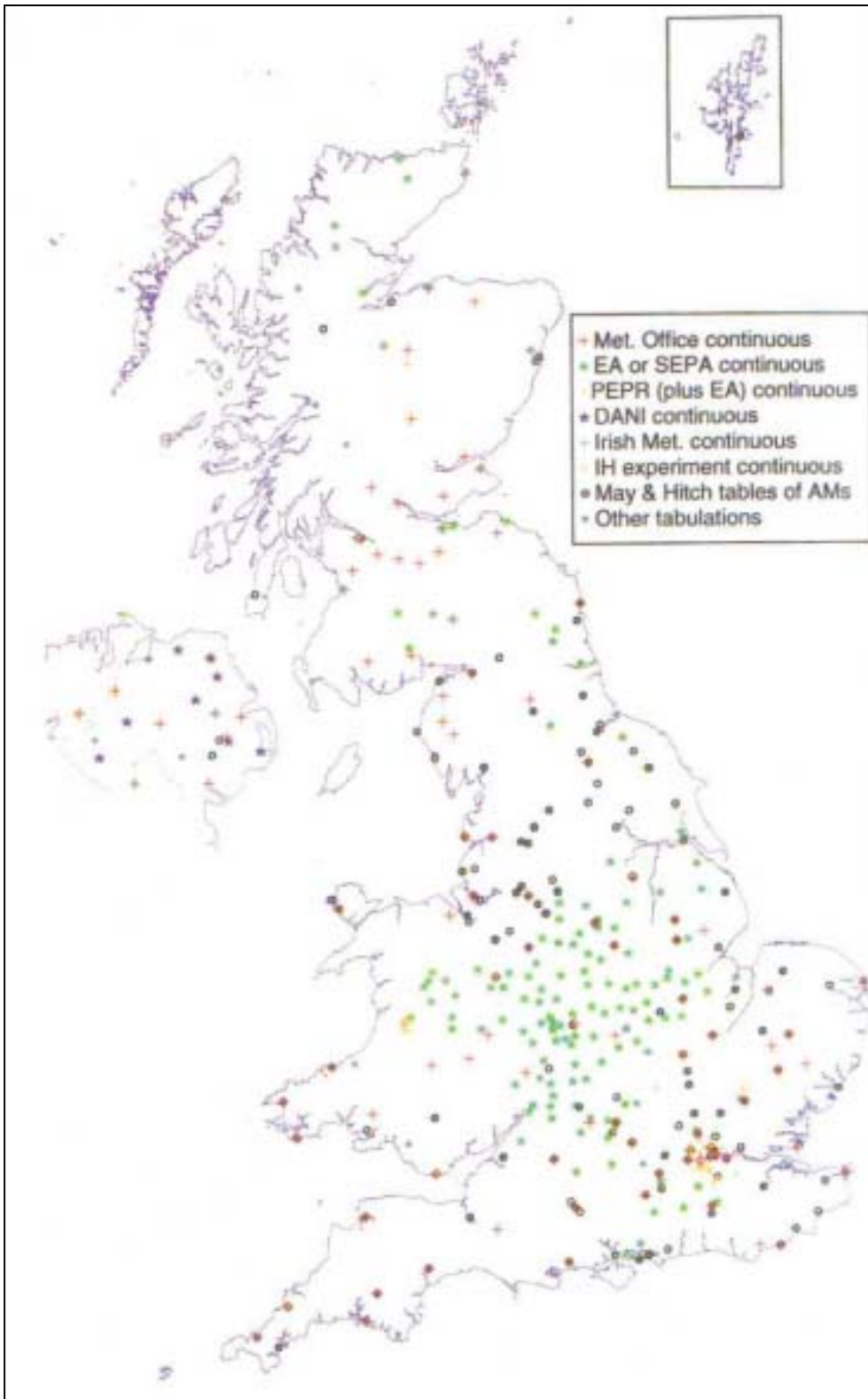


Figure 4 – Location of the rain gauges used in generating Annual Maxima data for the FEH. (FEH Figure 2.13.3)

South East Region Low Return Periods

Single Gauges

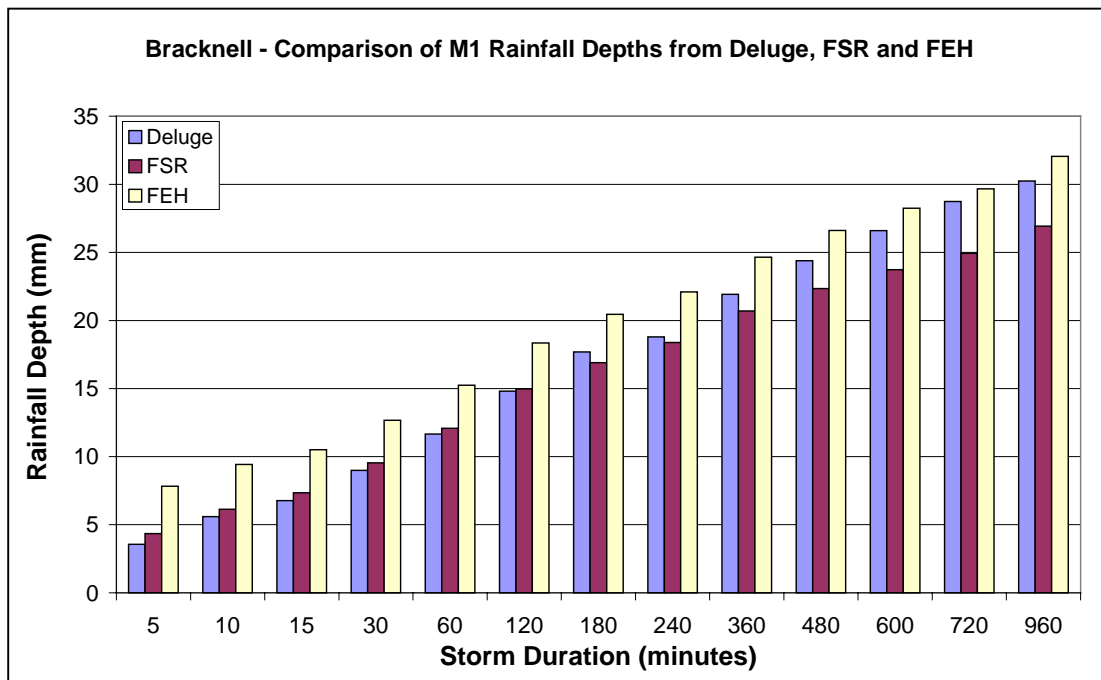


Figure 5 – Comparison of rainfall depths for a one year return period event at the Bracknell gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

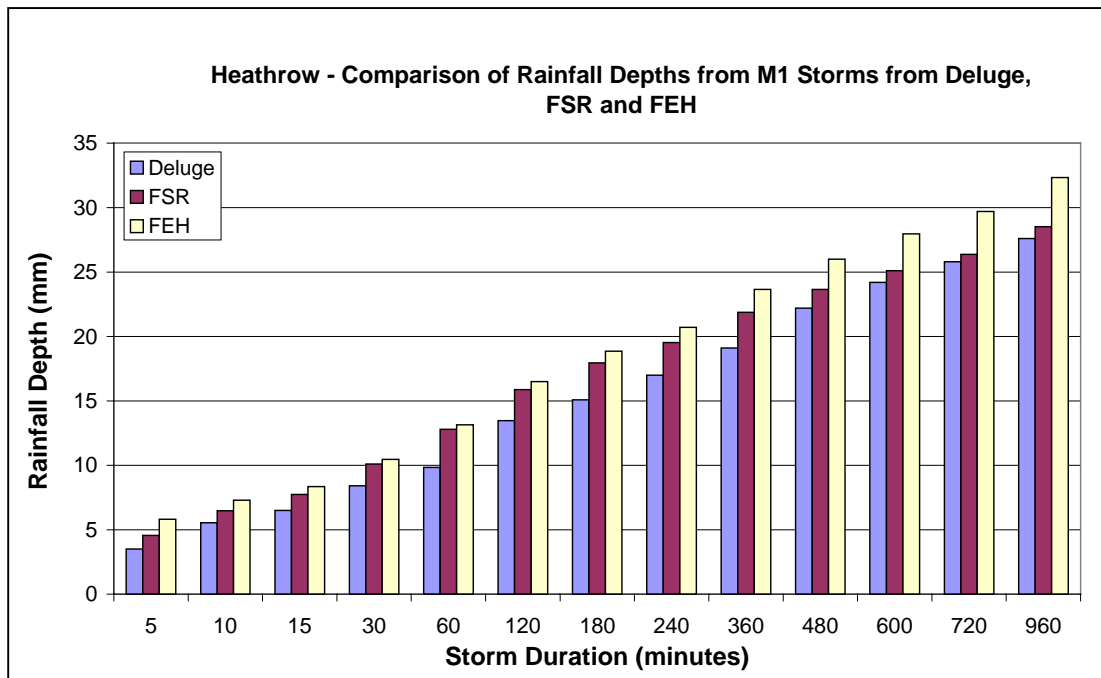


Figure 6 – Comparison of rainfall depths for a one year return period event at the Heathrow gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

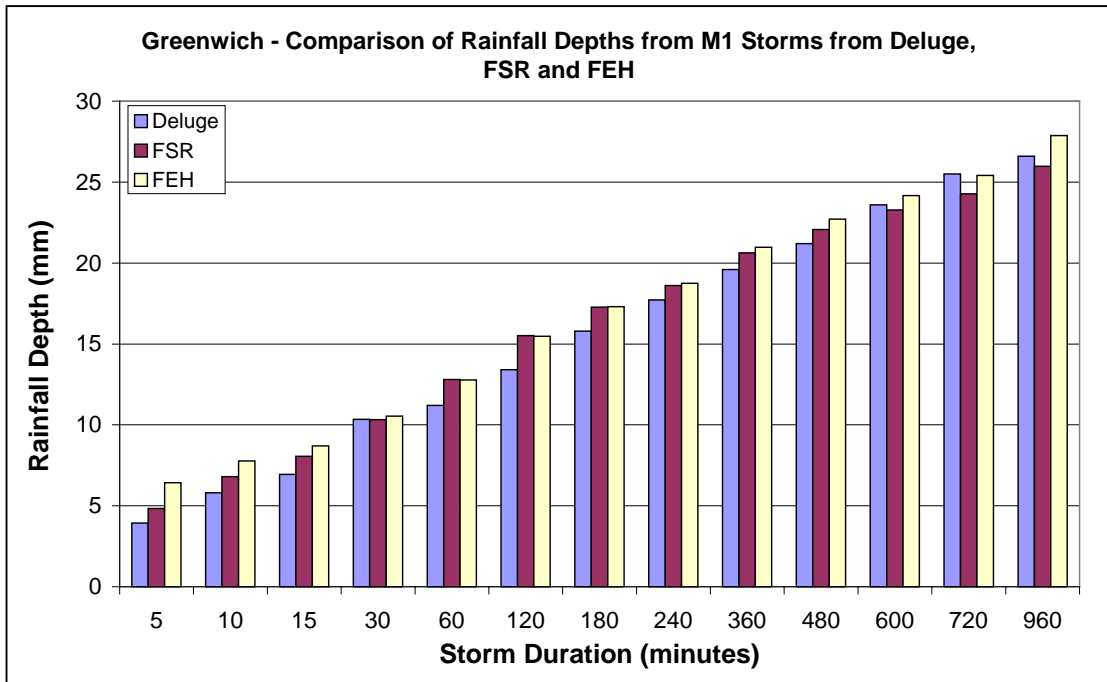


Figure 7 – Comparison of rainfall depths for a one year return period event at the Heathrow gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

Evaluation of Gauges in the South East Region

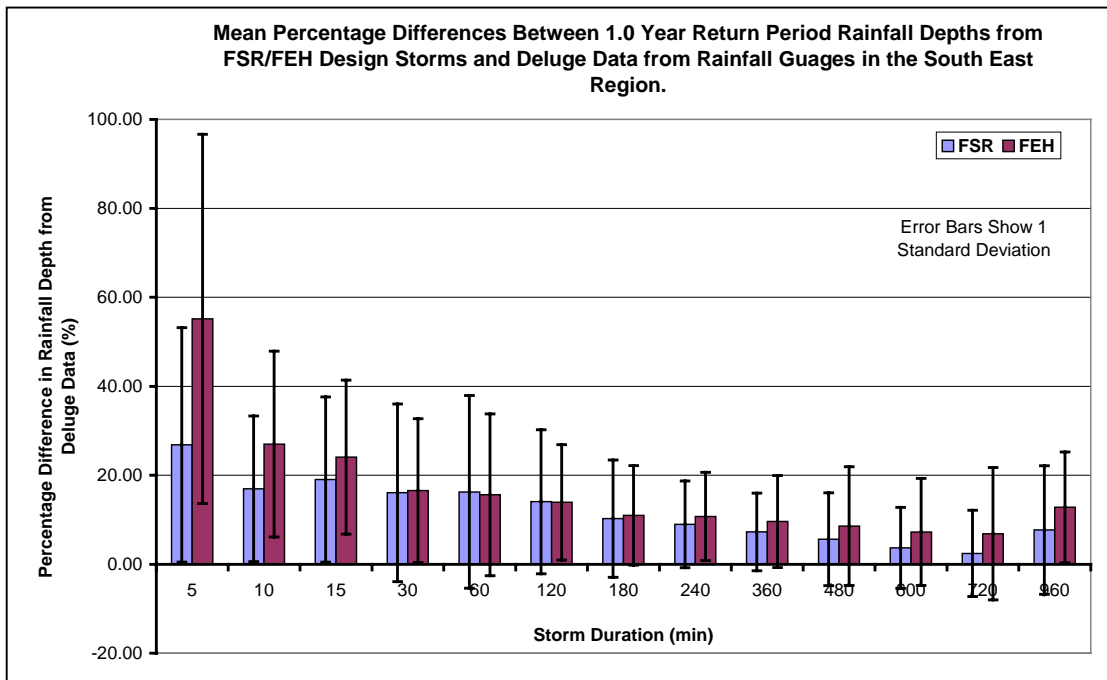


Figure 8 – Analysis of differences in the one year return period rainfall depths found from “Deluge”, FSR and FEH in the South East Region.

South West Region Low Return Periods

Single Gauges

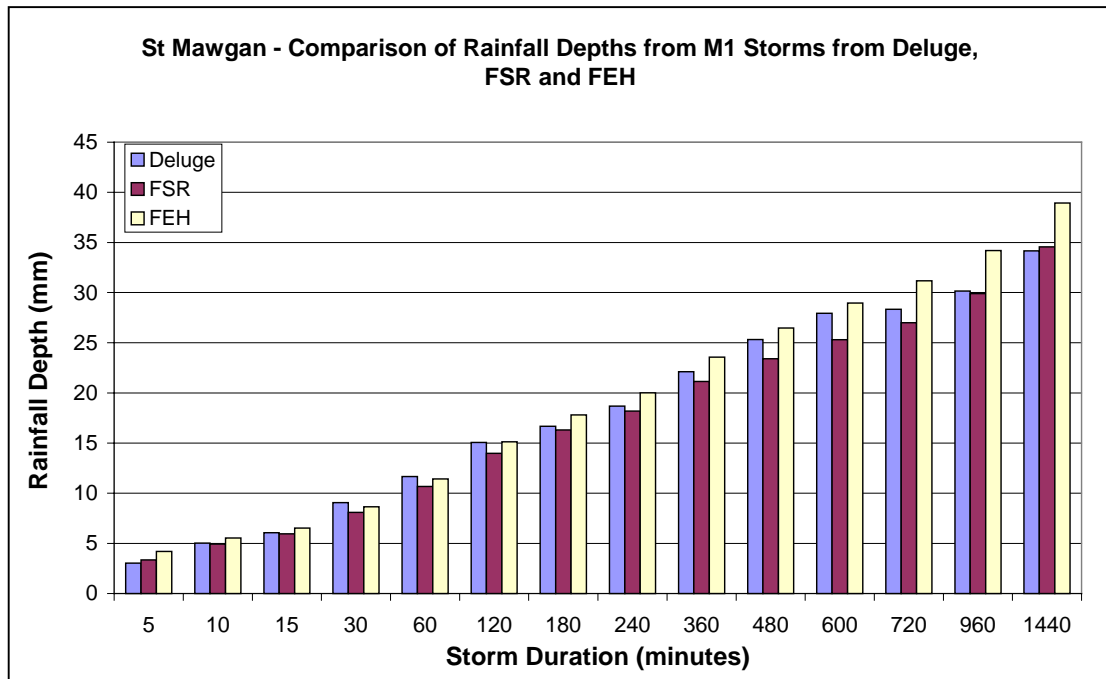


Figure 9 – Comparison of rainfall depths for a one year return period event at the St Mawgan gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

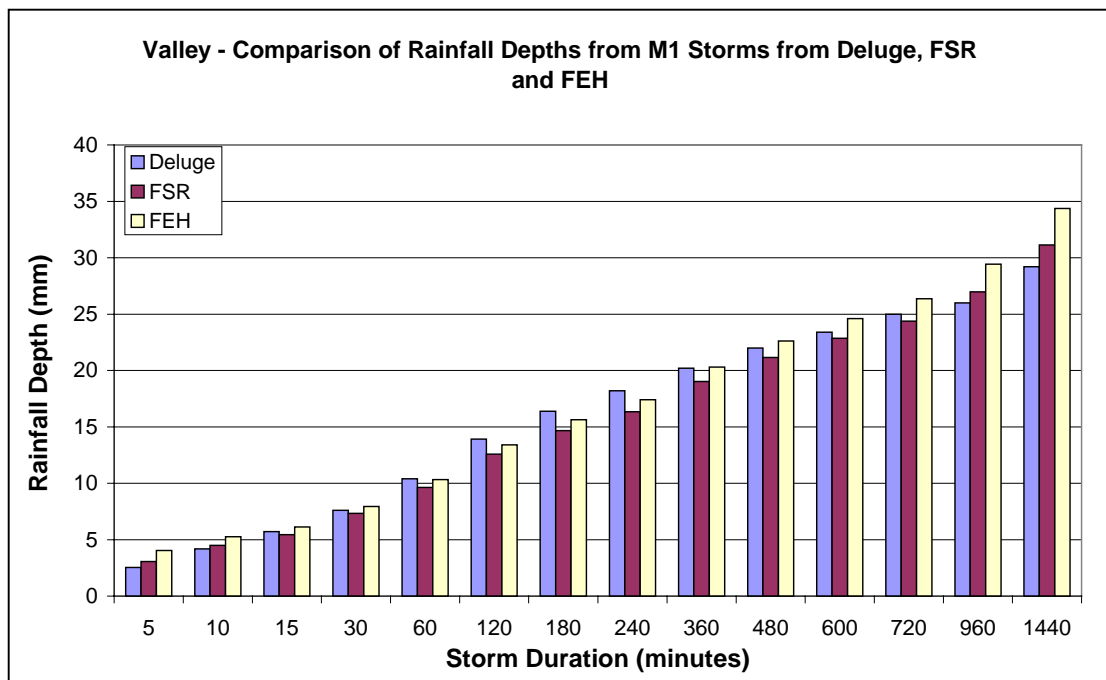


Figure 10 – Comparison of rainfall depths for a one year return period event at the Valley gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

Evaluation of Gauges in the South West Region

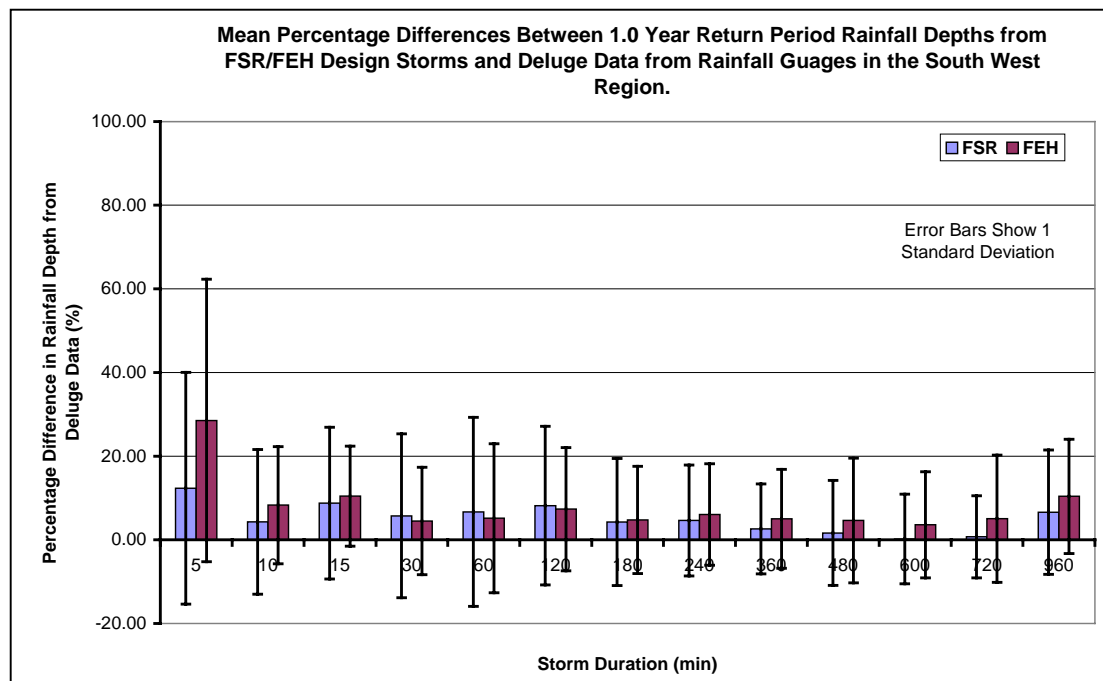


Figure 11 – Analysis of differences in the one year return period rainfall depths found from “Deluge”, FSR and FEH in the South West Region.

North East Region Low Return Periods Single Gauges

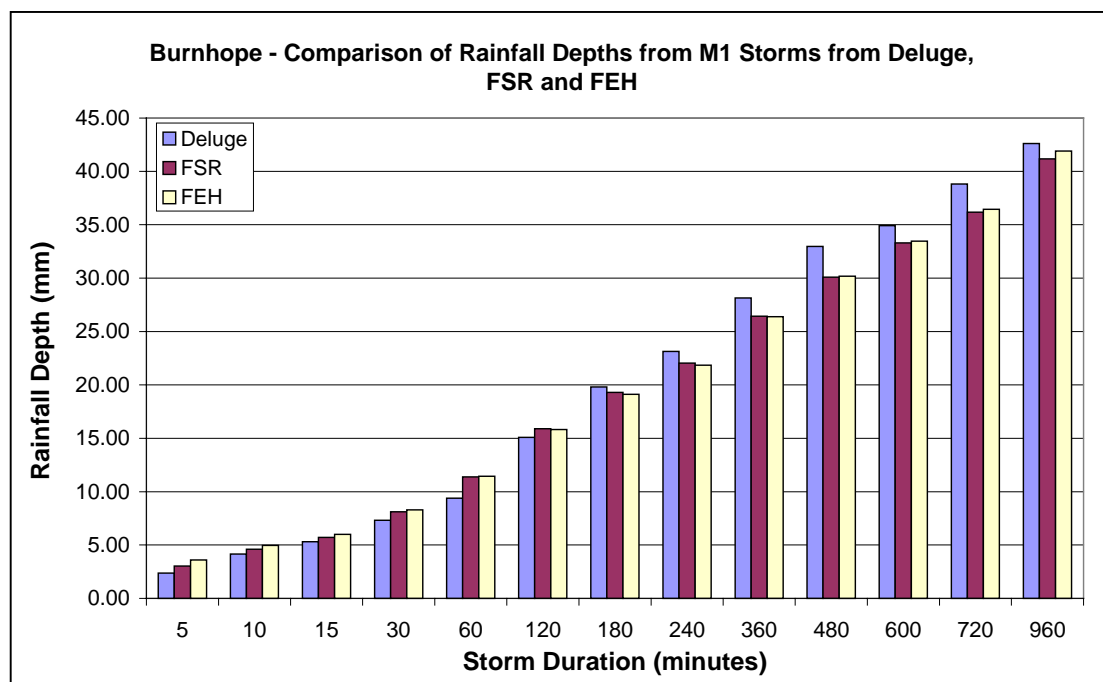


Figure 12 – Comparison of rainfall depths for a one year return period event at the Burnhope gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

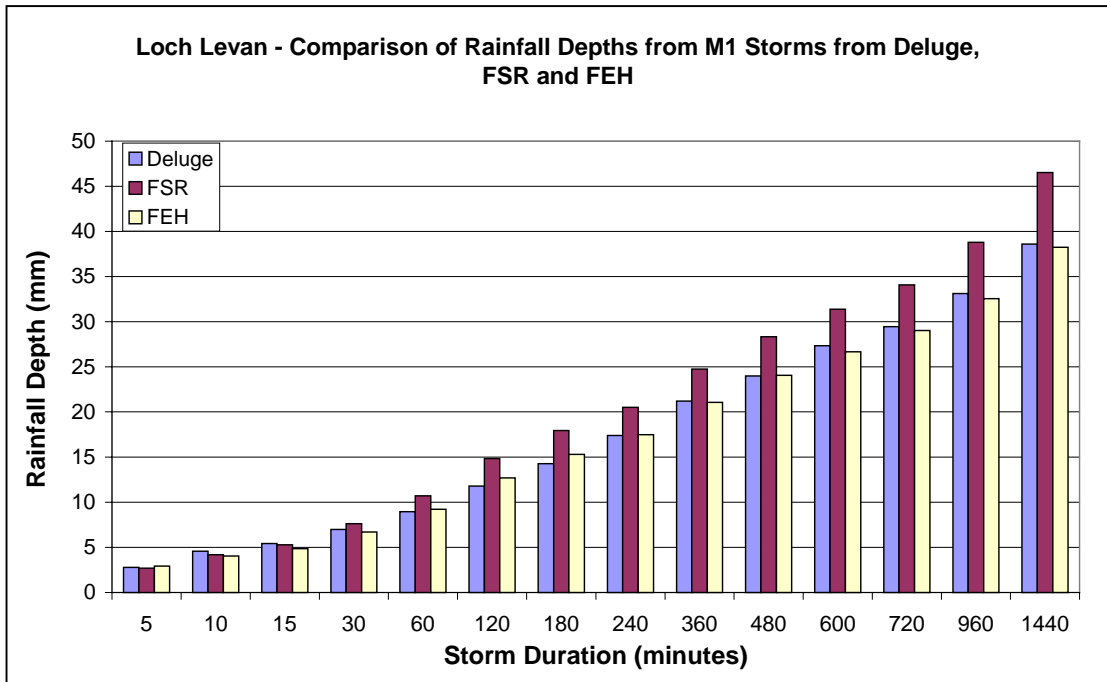


Figure 13 – Comparison of rainfall depths for a one year return period event at the Loch Levan gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

Evaluation of Gauges in the North East Region

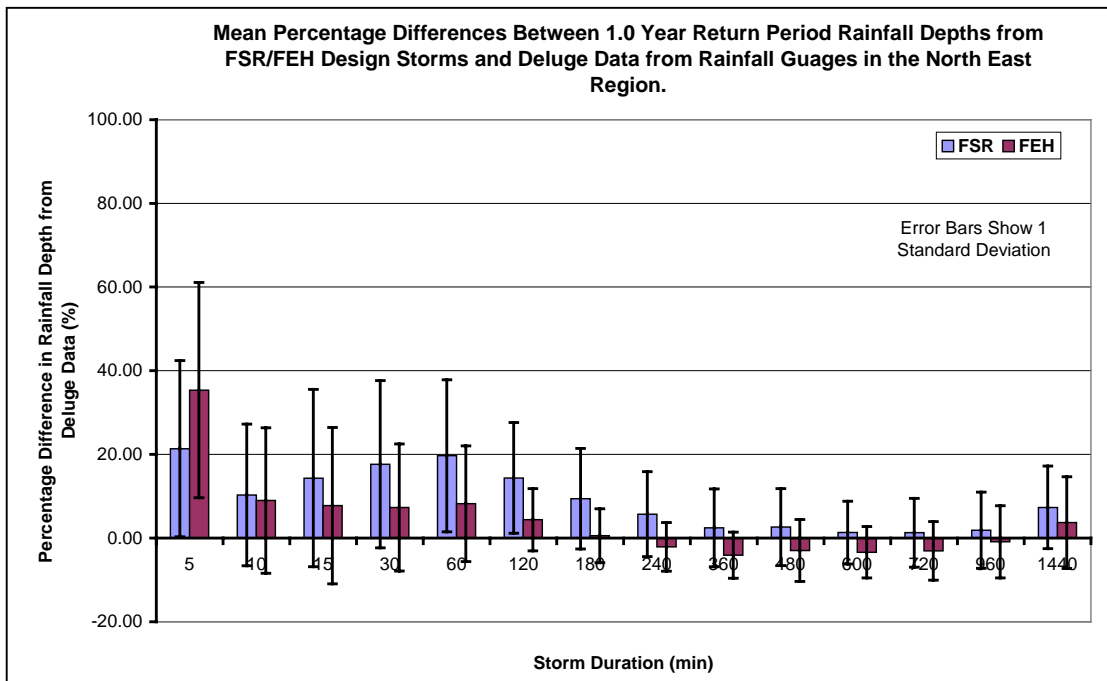


Figure 14 – Analysis of differences in the one year return period rainfall depths found from “Deluge”, FSR and FEH in the North East Region.

North West Region Low Return Periods Single Gauges

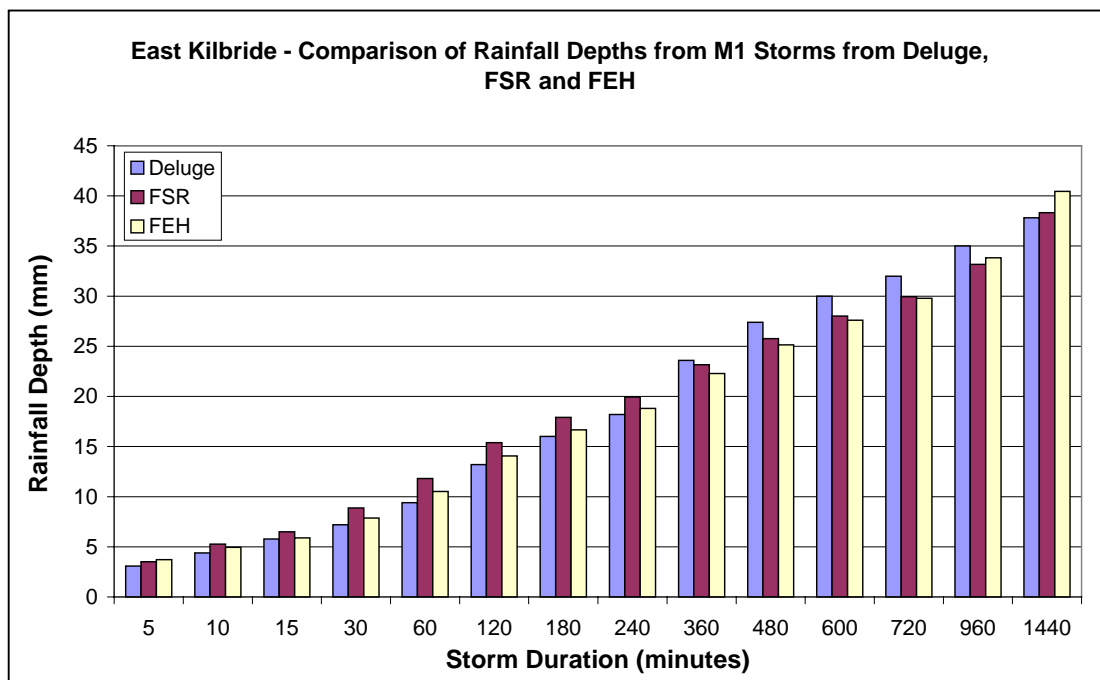


Figure 15 – Comparison of rainfall depths for a one year return period event at the East Kilbride gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

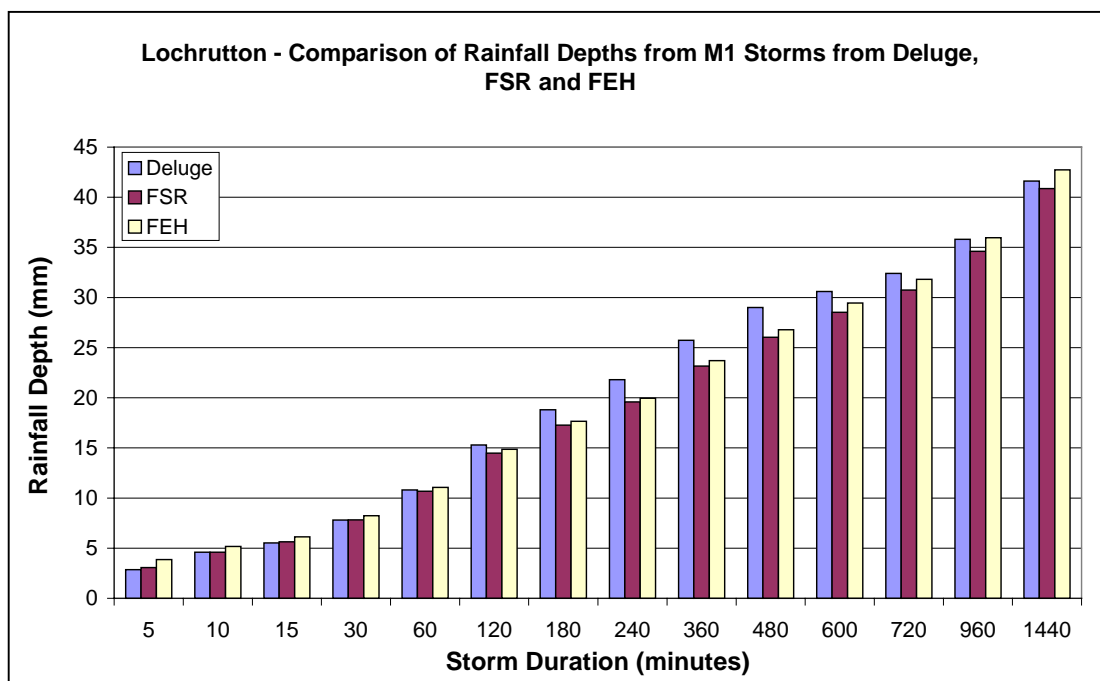


Figure 16 – Comparison of rainfall depths for a one year return period event at the Lochrutton gauge location. Comparison is between values obtained from Met Office “Deluge” data, FSR design storms and FEH design storms.

Evaluation of Gauges in the North West Region

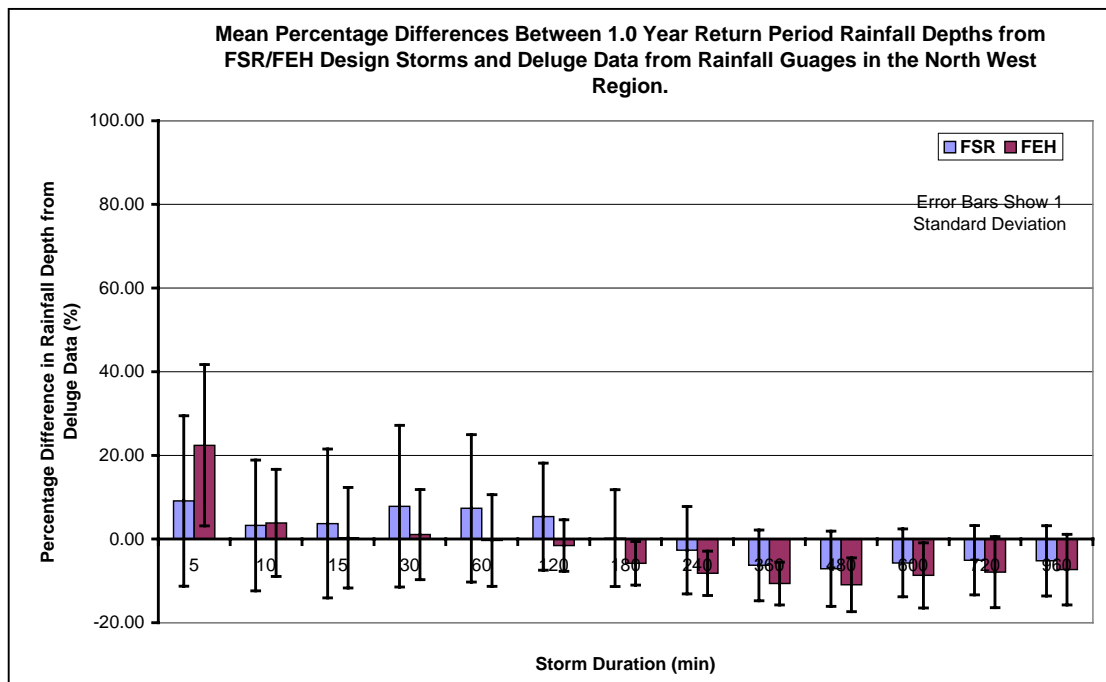


Figure 17 – Analysis of differences in the one year return period rainfall depths found from “Deluge”, FSR and FEH in the North West Region.

Results of Relocating Data within the South East Region Greenwich

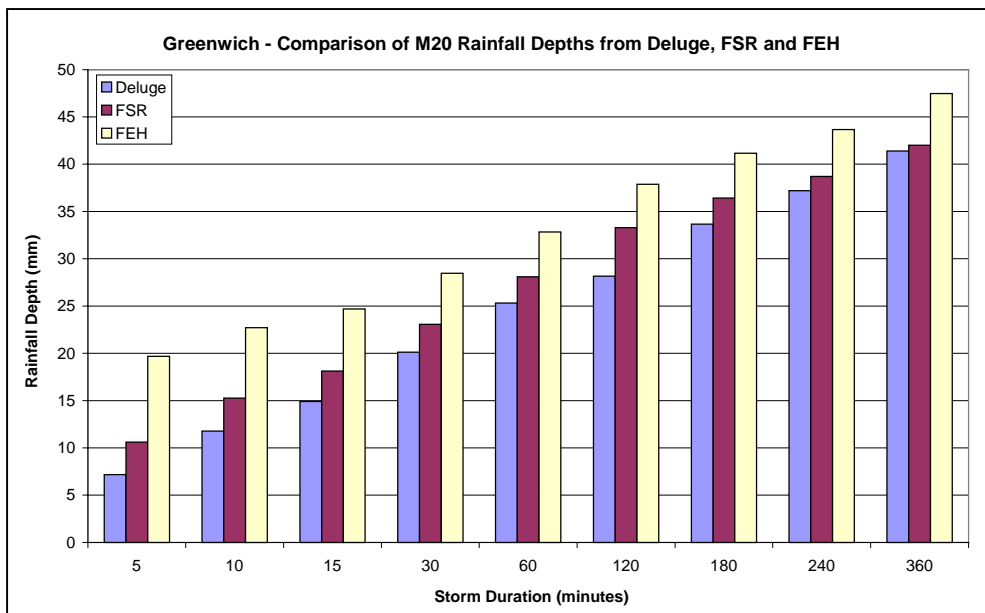


Figure 18 – Comparison of rainfall depths for twenty year return period events at the Greenwich gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **15 – 48%**. 30-360min: **1-18%**.
FEH difference to Deluge: 5-30min: **42-175%**. 30-360min: **15-42%**.

Heathrow

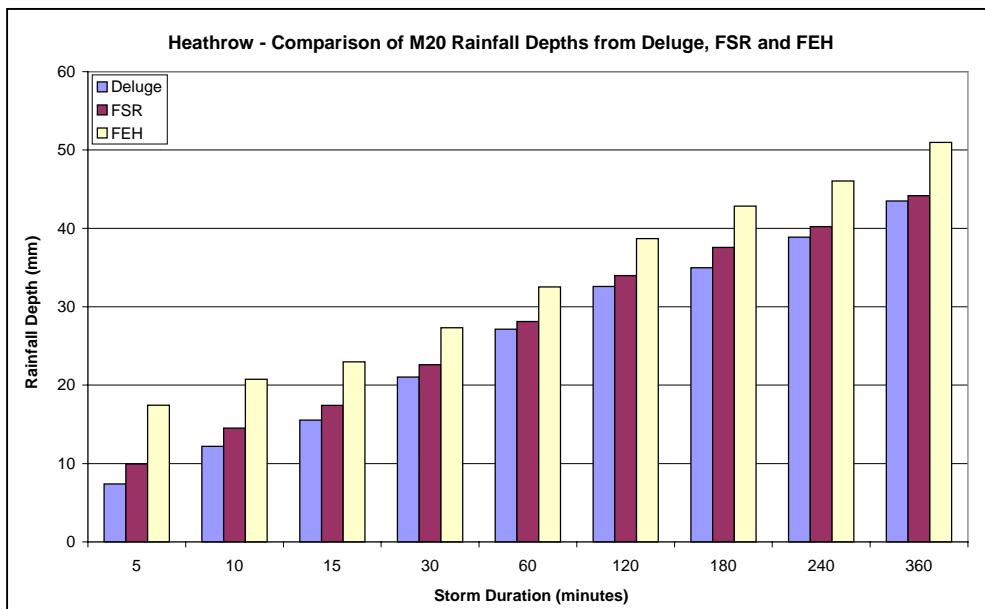


Figure 19 – Comparison of rainfall depths for twenty year return period events at the Heathrow gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **7-35%**. 30-360min: **2-7%**.
FEH difference to Deluge: 5-30min: **30-136%**. 30-360min: **17-30%**.

Results of Relocating Data within the South West Region St Mawgan

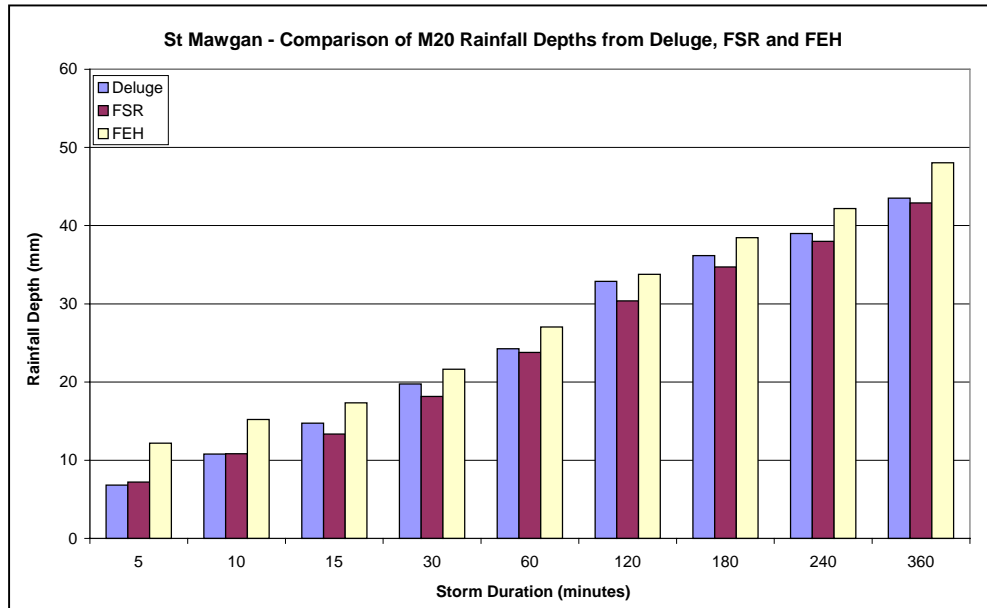


Figure 20 – Comparison of rainfall depths for twenty year return period events at the St Mawgan gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-10-5%**. 30-360min: **-8 - -1%**.
FEH difference to Deluge: 5-30min: **10-78%**. 30-360min: **3-12%**.

Valley

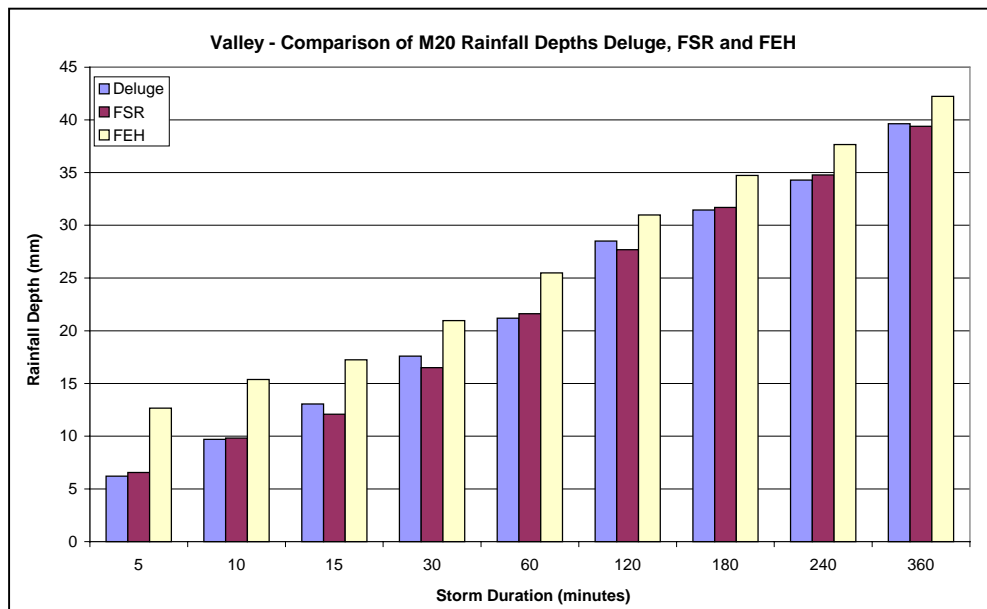


Figure 21 – Comparison of rainfall depths for twenty year return period events at the Valley gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-8 - 5%**. 30-360min: **-6 - 2%**.
FEH difference to Deluge: 5-30min: **19-104%**. 30-360min: **7-20%**.

Results of Relocating Data within the North East Region

Burnhope

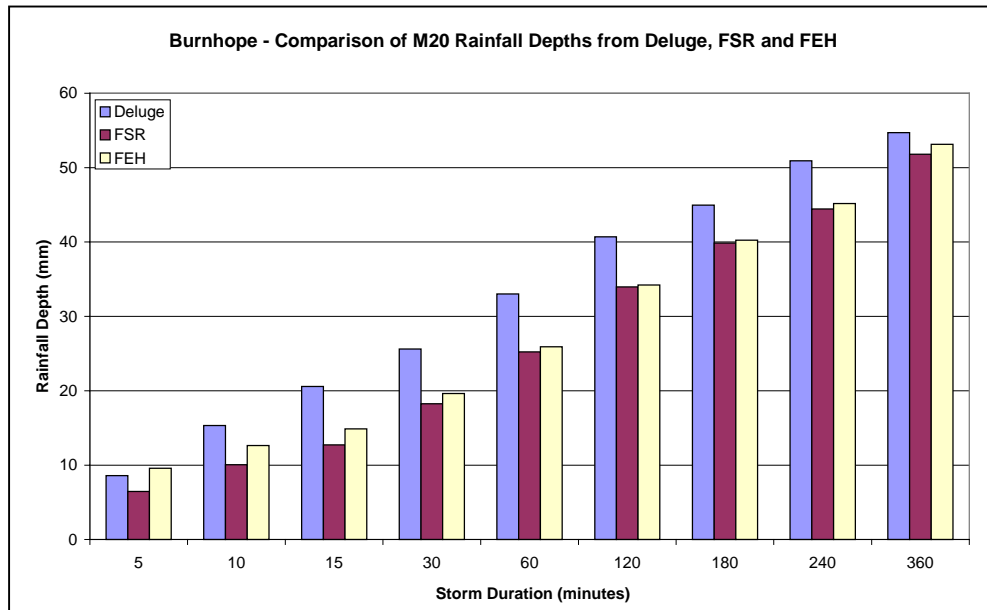


Figure 22 – Comparison of rainfall depths for twenty year return period events at the Burnhope gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-38 - -25%**. 30-360min: **-29 - -5%**.
FEH difference to Deluge: 5-30min: **19-104%**. 30-360min: **7-20%**.

Loch Levan

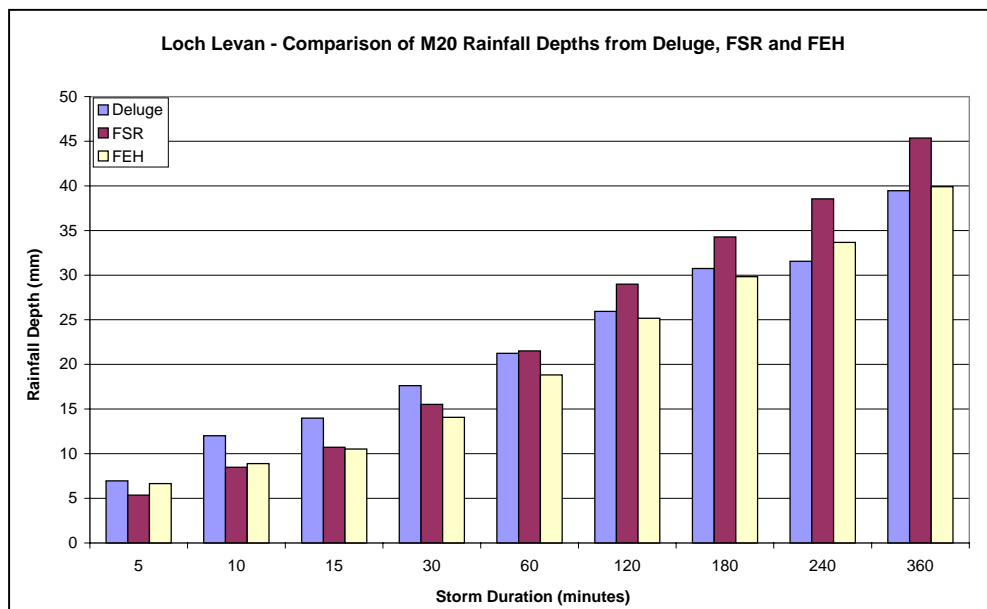


Figure 23 – Comparison of rainfall depths for twenty year return period events at the Loch Levan gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-30 - -12%**. 30-360min: **-12 – 22%**.
FEH difference to Deluge: 5-30min: **-26 - -5%**. 30-360min: **-20 - 7%**.

Results of Relocating Data within the North West Region East Kilbride

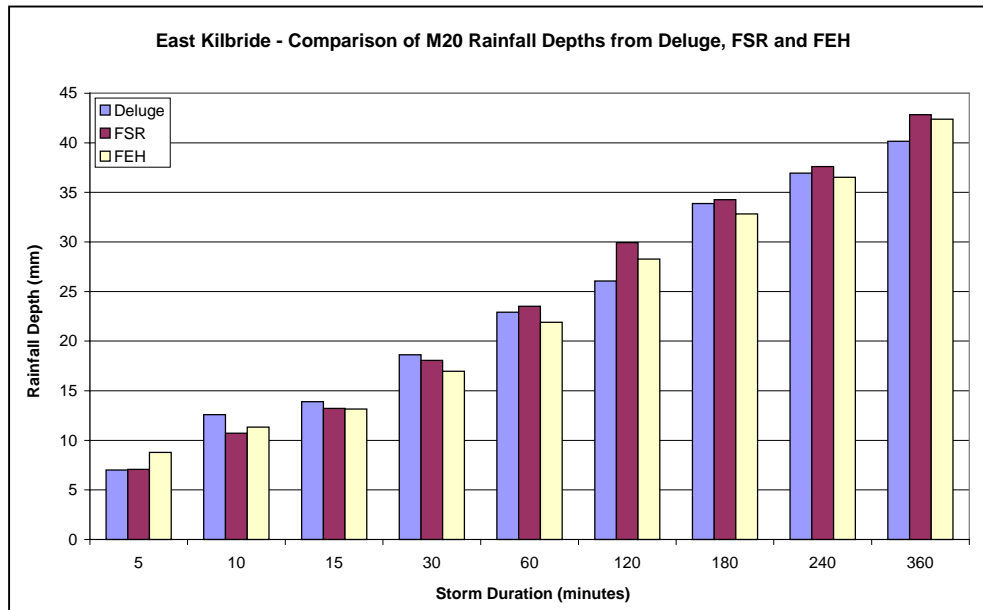


Figure 24 – Comparison of rainfall depths for twenty year return period events at the East Kilbride gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-15 - 1%**. 30-360min: **-3 – 15%**.
FEH difference to Deluge: 5-30min: **-10 - 1%**. 30-360min: **-9 - 9%**.

Lochrutton

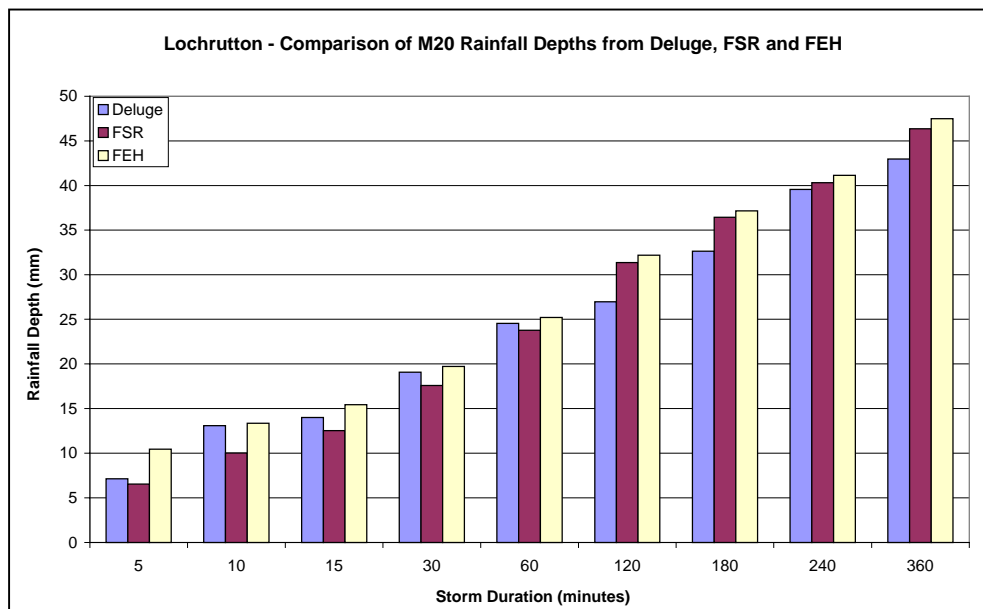


Figure 25 – Comparison of rainfall depths for twenty year return period events at the Lochrutton gauge location. Comparison is between values obtained from regionally relocated Met Office “Deluge” data, FSR design storms and FEH design storms.

FSR difference to Deluge: 5-30min: **-23 - -8%**. 30-360min: **-8 – 16%**.
FEH difference to Deluge: 5-30min: **2 - 47%**. 30-360min: **3 - 19%**.

IDF Analysis of Zero Failure Superstorms St Mawgan & Boscastle



Figure 26 – Map of the Cornwall and Devon area showing the relative locations of Boscastle and the St Mawgan Gauge with a 14 year record.

St Mawgan

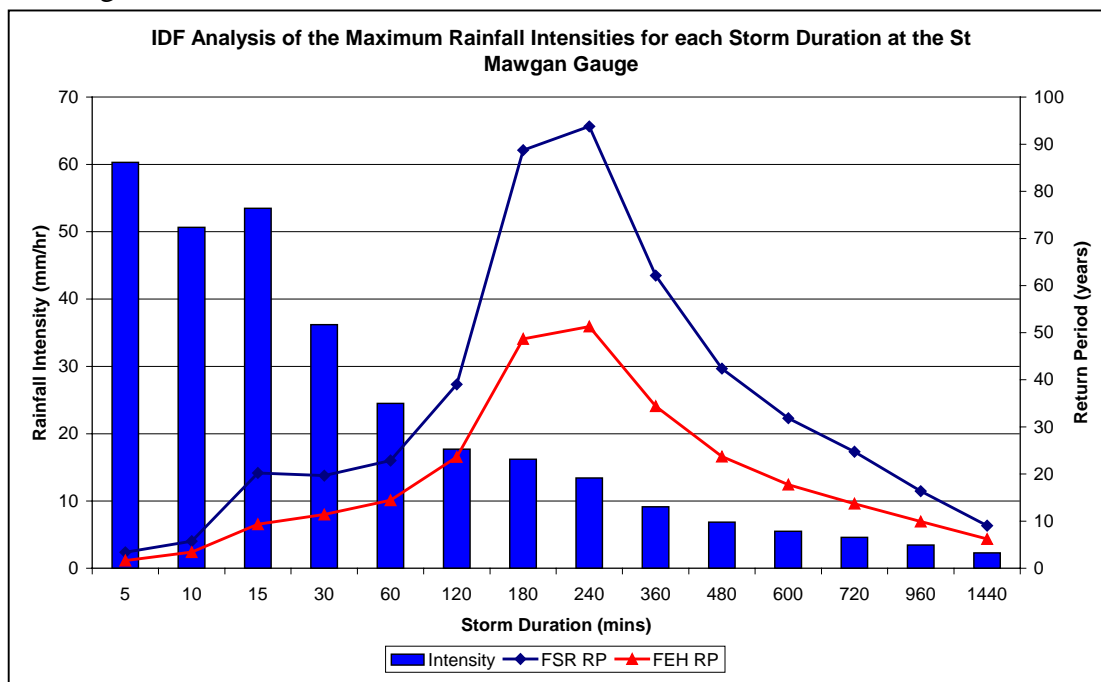


Figure 27 – IDF analysis of the maximum rainfall intensities for each storm duration at the St Mawgan gauge.

Lesnewth TBR Gauge on 16th August 2004 (Boscastle Event)

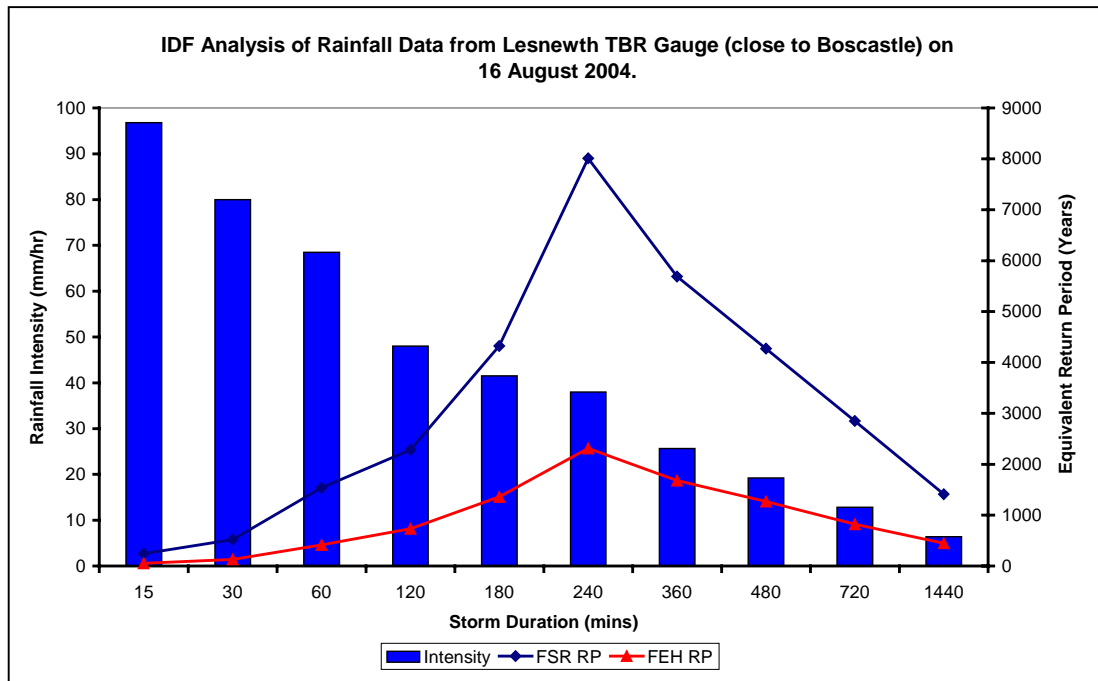


Figure 28 – IDF analysis of the maximum rainfall intensities recorded at the Lesnewth Tilting Bucket Rain Gauge on the 16th of August 2004.

Ratios of 30minute to 360minute Rainfall Depths

Heathrow

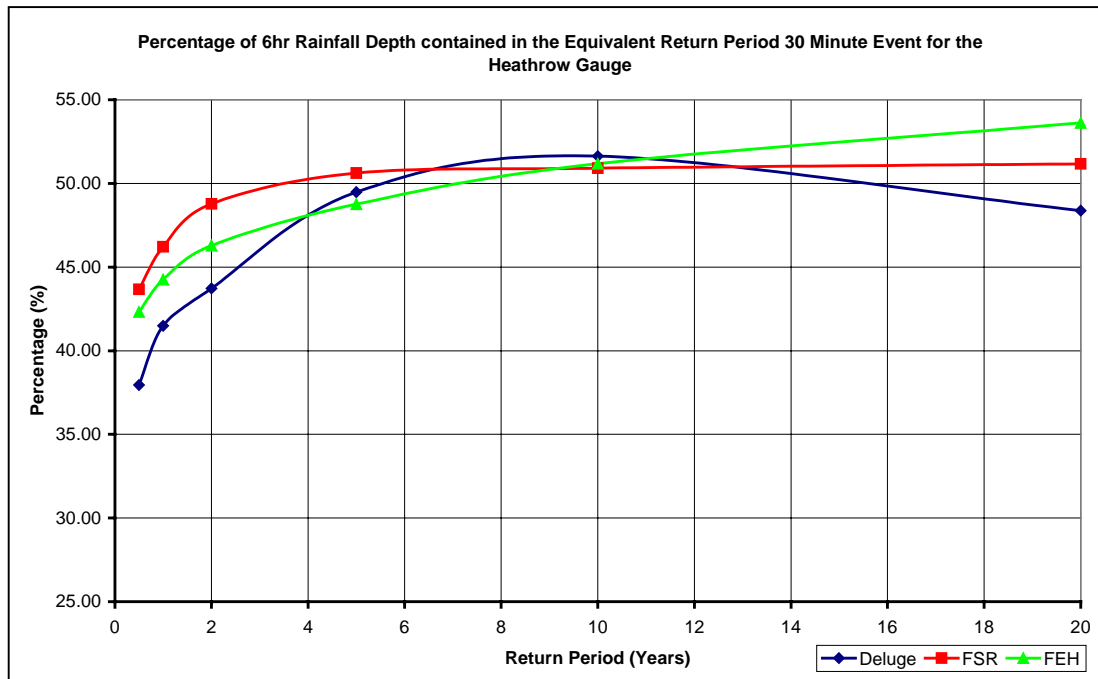


Figure 29 – Percentage of 6 hr rainfall depth that is contained in the 30 minute event for varying return periods at the Heathrow gauge location. Comparison shown is between Deluge data, FSR design storms and FEH design storms.

St Mawgan

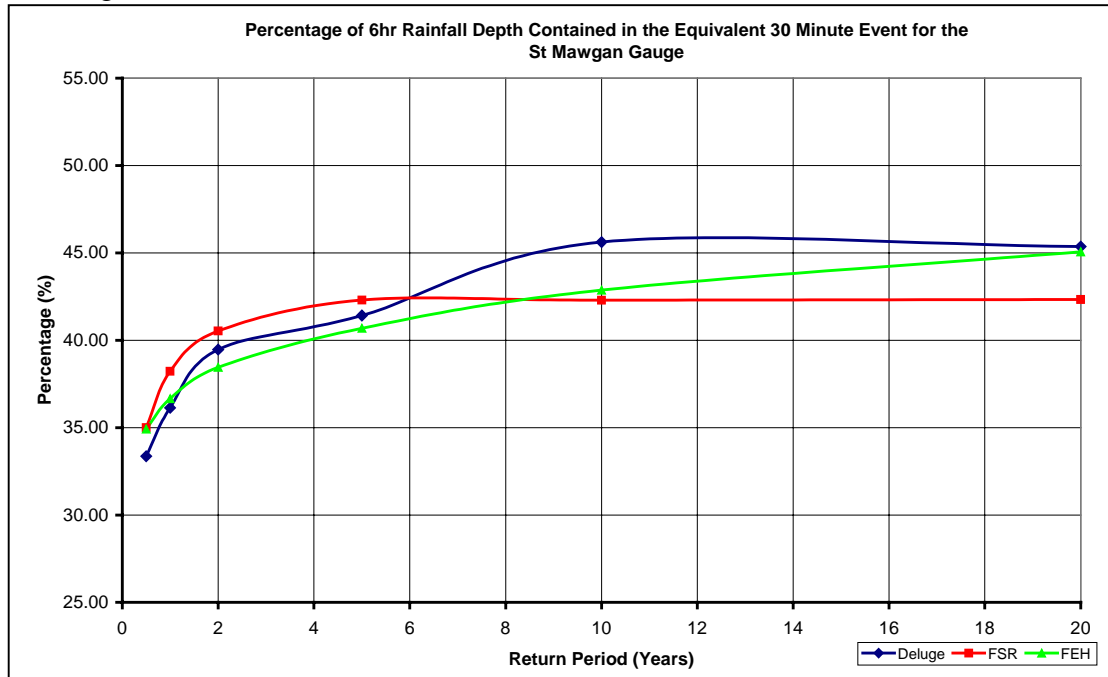


Figure 30 – Percentage of 6 hr rainfall depth that is contained in the 30 minute event for varying return periods at the St Mawgan gauge location. Comparison shown is between Deluge data, FSR design storms and FEH design storms.

Loch Levan

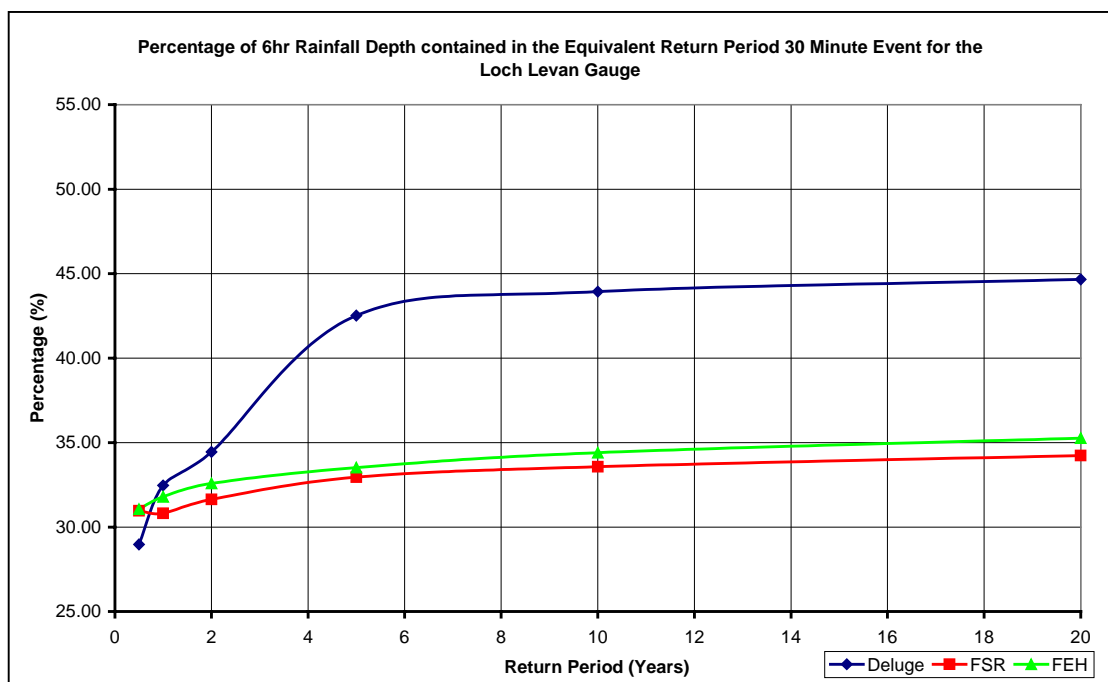


Figure 31 – Percentage of 3 hr rainfall depth that is contained in the 15 minute event for varying return periods at the Loch Levan gauge location. Comparison shown is between Deluge data, FSR design storms and FEH design storms.