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1. INTRODUCTION

The Flood Estimation Handbook[1] (FEH) published in 2000 together with the new software released with the FEH have provided invaluable tools for the Drainage Engineer. Whilst the main research was aimed at estimation of flood flows and flood return periods in rivers it is every bit as applicable to urban sewerage systems.

The FEH software provides a more advanced means of producing design storms for any given return period and duration and is more sophisticated than the Flood Studies Report[2] (FSR) approach used in the Wallingford Procedure. The FEH software utilises digital terrain modelling and has data for over 4 million catchments in the UK from 0.5km^2 upwards (ie almost everywhere). The FEH software uses a far larger data set than was used for the FSR approach and also much of the rainfall data is more recent.

The results of assessments using the FEH software and comparing this with the design storms from FSR shows that in some parts of the country the FEH storms are more severe whilst in other areas they are less severe.

2. Flood Studies Report (FSR)

The Flood Studies Report was published in 1975 and was initially, primarily intended for use with major river catchments rather than small urban catchments. Between 1977 and 1988 a total of 18 Supplementary Reports[3] (FSSR's) were produced. The methods included in the Flood Studies Report were adapted for other purposes, in 1978 for Reservoir safety, in 1979 for urbanised catchments and it was not until 1981 when it was adapted for use in storm sewer design.

The FSR methods for determining design storms was incorporated into the Wallingford Procedure[4] and was then built into the simulation programs WASSP, WALLRUS and HydroWorks. The design rainfall produced within these programs is widely known and readily used by Modellers.

There has always been some criticism of the Flood Studies Report that it was too over-generalised, that it did not take sufficient account of local features and that important local or regional variations were masked. For example, it has long been held to underestimate rainfall frequency depths in the Bridgewater district of south west England (Bootman and Willis[5], 1977). It has been suggested (Dales and Reed[6], 1989 and others) that the FSR method is excessively generalised, in the sense that local and regional differences in rainfall frequency are not fully represented. In an elongated study region from East Sussex to the Peak District (May and Hitch[7], 1989) found pronounced fluctuations in the 5-year 1-hour rainfall between 13mm and 22mm whilst the Wallingford Procedure maps indicated a design value of 18-22mm throughout most of England.

In spite of these problems the methods used and embodied within the mainstream simulation programs were (and still are) widely used for storms with return periods of less than 1 year to over 100 years. The main data used in the development of the FSR methods comprised 96,000 station years of daily data and 2,300 station years of hourly data. From this the annual, monthly and summer maximum rainfall was established. The 1 in 5 year (M5) rainfall was used as the index.

Synthetic design storms are generated using the FSR methods with just 3 variables:- the M5-60 rainfall, the ratio of the M5-60 rainfall to the M5-2day rainfall (r), and the catchment area (the latter applies the Areal Reduction Factor). The only other variable being the location which is accounted for by the use of plans with the above data for the whole of the UK plotted on individual maps. At best the above factors can be interpolated on these plans to one significant place.

3. Flood Estimation Handbook (FEH)

The Flood Estimation Handbook was published in January 2000. The 5 volume document is complimented by a suite of software programs. The most important software is contained on the FEH CD-ROM with which the catchment descriptors can be identified and in turn the rainfall depth-duration-frequency (DDF) graphs can be generated. The basis of the FEH CD-ROM is a digital terrain model in which the drainage routes within each 50m by 50m grid square are determined irrespective of whether there is actually a watercourse along that route (ie 'dry' valleys are also considered as drainage routes). All catchments in England, Wales and Scotland which are greater than 0.5km^2 are included within the digital terrain model. The number of catchments included is in excess of 4 million.

The preparation of the Flood Estimation Handbook was undertaken between 1992 and 1999 by the Centre for Ecology and Hydrology (formerly the Institute of Hydrology). The work was based on a far greater amount of rainfall data from 6,106 daily raingauges and 375 hourly raingauges. The amount of hourly data available at 7,389 station years was over 3 times that available for the FSR.

The FSR used the 1 in 5 year rainfall (M5) as the index and it is this which is the cause of some criticism that the FSR over-generalised rainfall in several areas of the UK. The FEH approach is different as the index used is the Annual Maximum Rainfall interpreted as the median annual maximum rainfall (RMED). The growth curves are generated using the FORGEX method. These are combined in a 6-parameter depth-duration-frequency (DDF) model.

The RMED values are provided on a 1-km grid with values interpolated between raingauges with at least nine years of recorded rainfall. The interpolation takes account of topographic information from a digital terrain model (DTM). The FORGEX method of calculating the growth curves was developed by Reed *et al*[8] (1999) and comprises an empirical, graphical method to plot points on a rainfall-return period scale and to then fit a line through the points. The DDF model is applied to the required site and comprises a 6-parameter model fitted to exhaustive evaluations of the index rainfall (RMED) and the rainfall growth factors (by FORGEX). The 6 parameters are d_1, d_2, d_3, c, e and f which control the slope and position of the lines of the graphs and their variation with return period.

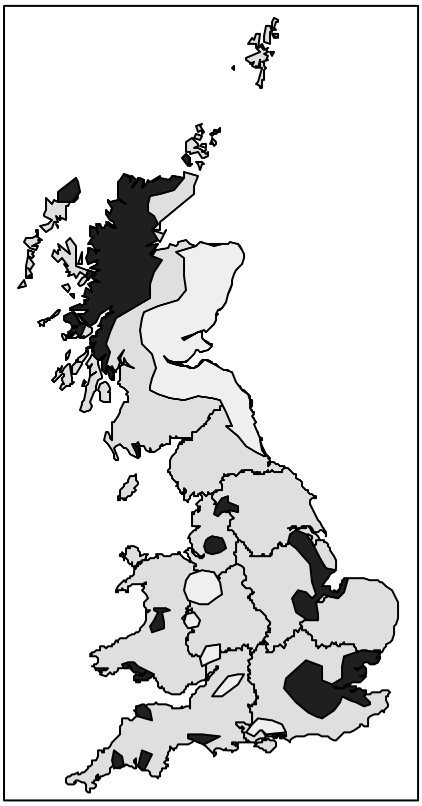
The FEH CD-ROM enables a digital approach to be taken which is far quicker and avoids the need for any manual calculations. With the greater number of variables achievable it has been possible to take far greater account of local conditions, local topography, prevailing winds, distance from coast, land cover, soil types, urban and suburban areas. However, it is recommended that some manual checks are undertaken, for example, catchment area against paper mapping and as with all modelling studies, site visits are required to confirm the locations of outlets etc.

The FEH explains in great detail the approaches taken in the different aspects of flood estimation. These are beyond the scope of this paper but interested readers are advised to consult the FEH for more detail.

In a more simplified manner it can simply be concluded that the FEH approach uses far more data than the FSR approach and uses a far more sophisticated analytical procedure which takes better account of local conditions.

One aspect worth noting however is in relation to return periods of less than 1 year. The Depth-Duration-Frequency (DDF) Model is designed to provide rainfall estimates for return periods longer than 1 year. For shorter return periods, frequently required in analysing urban pollution events, the annual maximum scale is inappropriate, as it only allows for one extreme rainfall event per year, and the peak-over-threshold (POT) scale must be used instead.

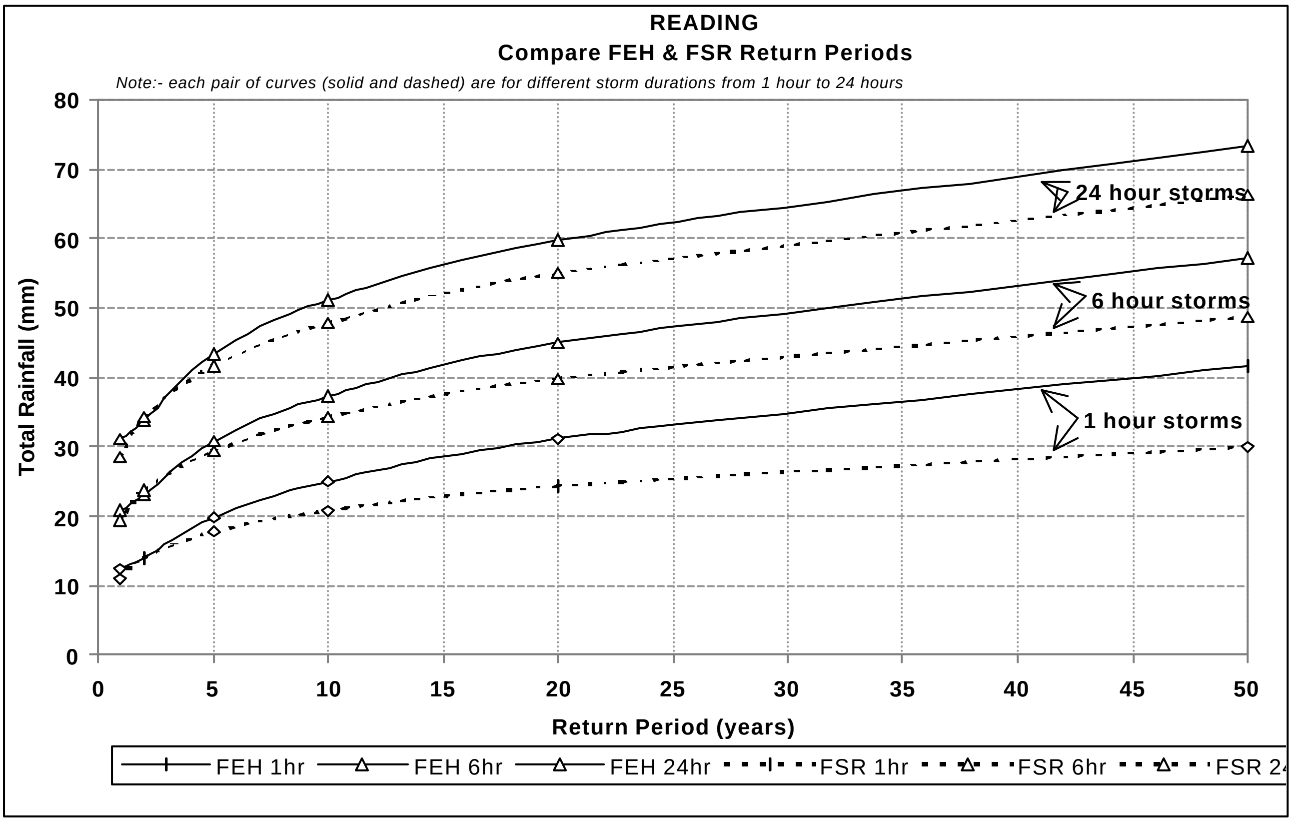
4. Differences between FSR and FEH Storms



Volume 2 of the FEH handbook includes some useful maps of the UK which illustrate some of the differences between FSR and FEH Storms in terms of depth of rainfall. The plan to the left is reproduced to illustrate the differences in total rainfall for storms with return periods of 100 years and 1 hour duration. The dark areas which are principally on the western side of Scotland, in the Thames valley and between the Wash and the Humber have greater rainfall in FEH storms than in FSR storms. The differences can be up to 40% difference.

The light areas, principally on the eastern side of Scotland and northern England but also in other pockets have less rainfall with FEH storms than FSR storms. These differences can be as much as 30% but are generally less than 20%.

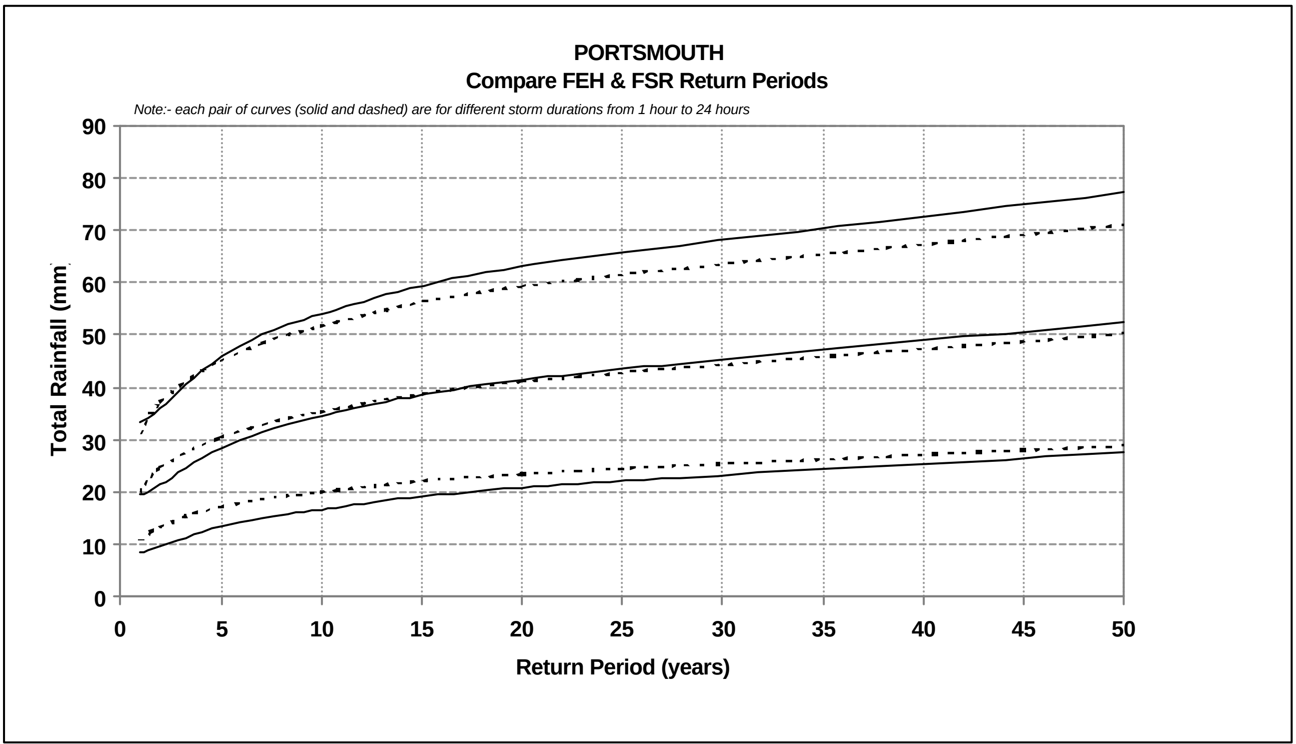
For this paper a number of catchments were studied in more detail looking at a wider range of durations and return periods for comparison purposes. The graph overleaf shows an example of the analysis undertaken (in this graph for Reading).



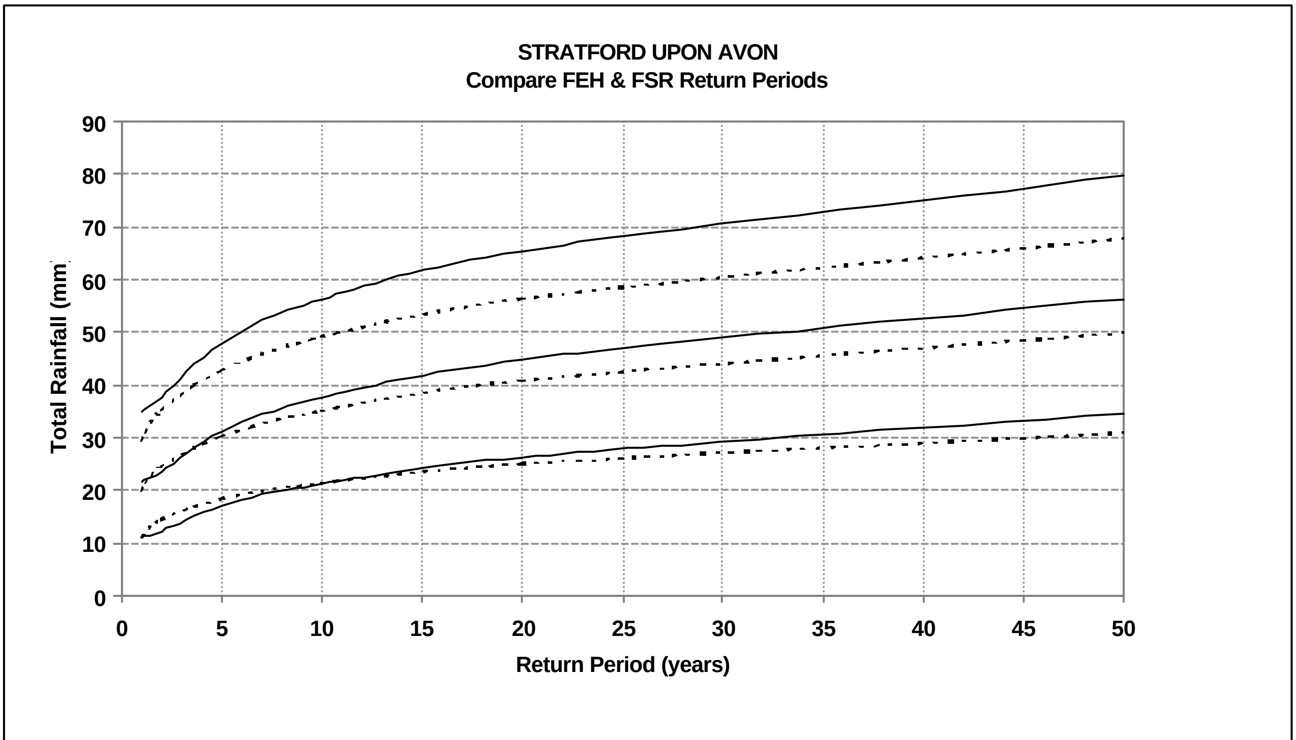
The graph shows storm return period along the X-axis, total rainfall along the Y-axis and has a number of curves for different duration storms and also for FSR and FEH storms. The dashed lines are FSR storms and the solid lines are FEH storms. The lines are not actual storms but join together points at which the total rainfall was calculated for specific return periods. The FSR data was calculated using the Rainfall Generator in Hydroworks in the normal manner. The FEH data was determined for the same catchment using the FEH CD-ROM software.

In this case it can be seen that for all durations plotted (1 hour, 6 hour and 24 hour) the rainfall from FEH storms is significantly greater than for the FSR storms. By plotting the graphs in this manner it is possible to compare return periods for storms generated using FSR to those which would be generated nowadays with FEH. As an example for the FSR storm with return period of 30 years there is 27mm of rain but for a 1 hour storm generated by FEH the same rainfall occurs with a storm with a return period of only 12 years. With greater return periods the differences get bigger. With 6 hour storms the picture is similar but this time the equivalent return period is 17 years and with 24 hour storms is 19 years.

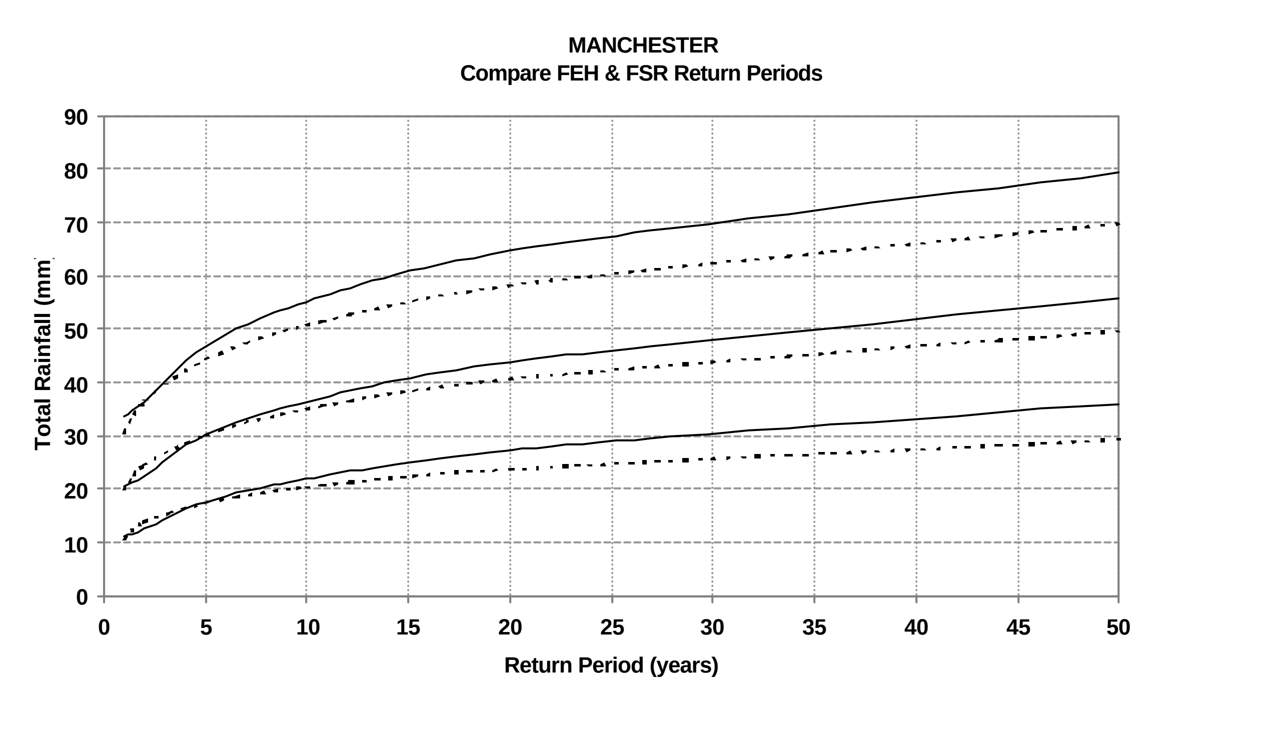
Not all parts of the country show a similar pattern and indeed many areas are completely different.



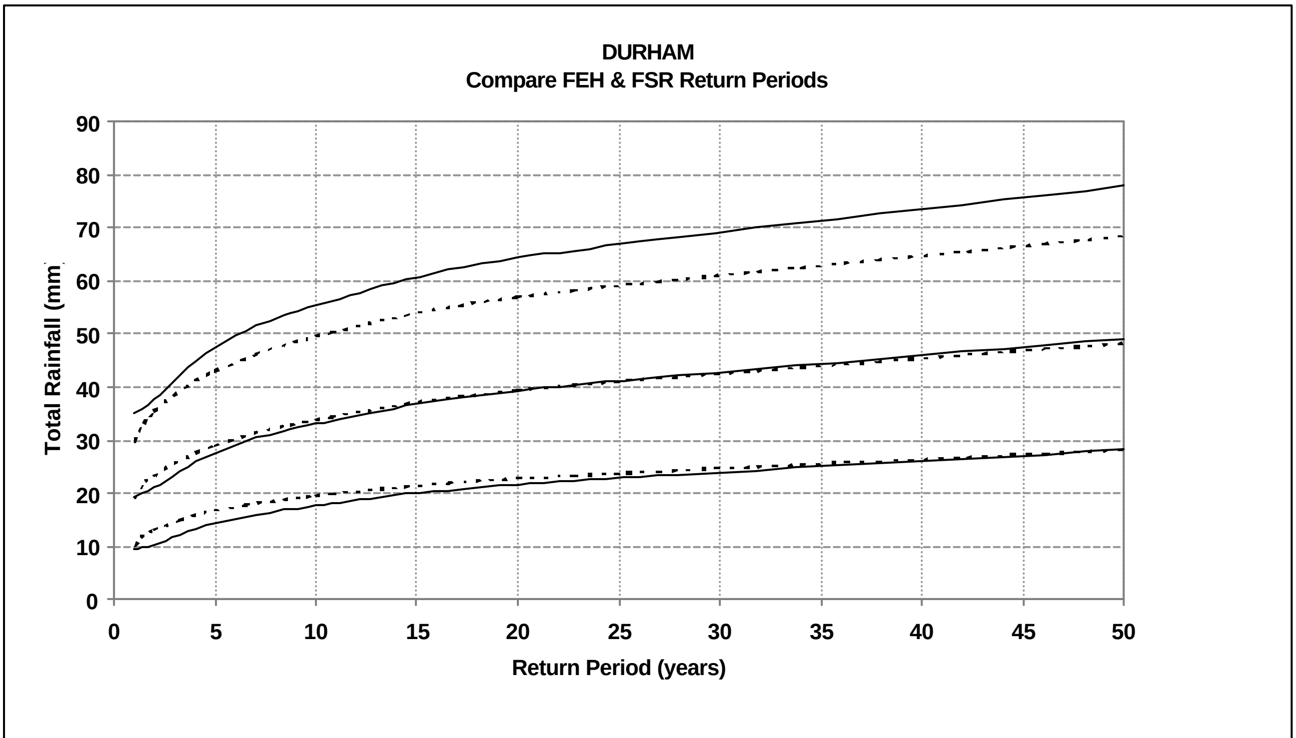
For Portsmouth it can be seen that for the 1 hour and 6 hour storms there is not a large difference and on the shorter storms it is generally the case that the FEH storms have less rainfall. This changes with the longer duration storms and it is clear that for the 24 hour storms there becomes a noticeable difference with the FEH storms having more rainfall.



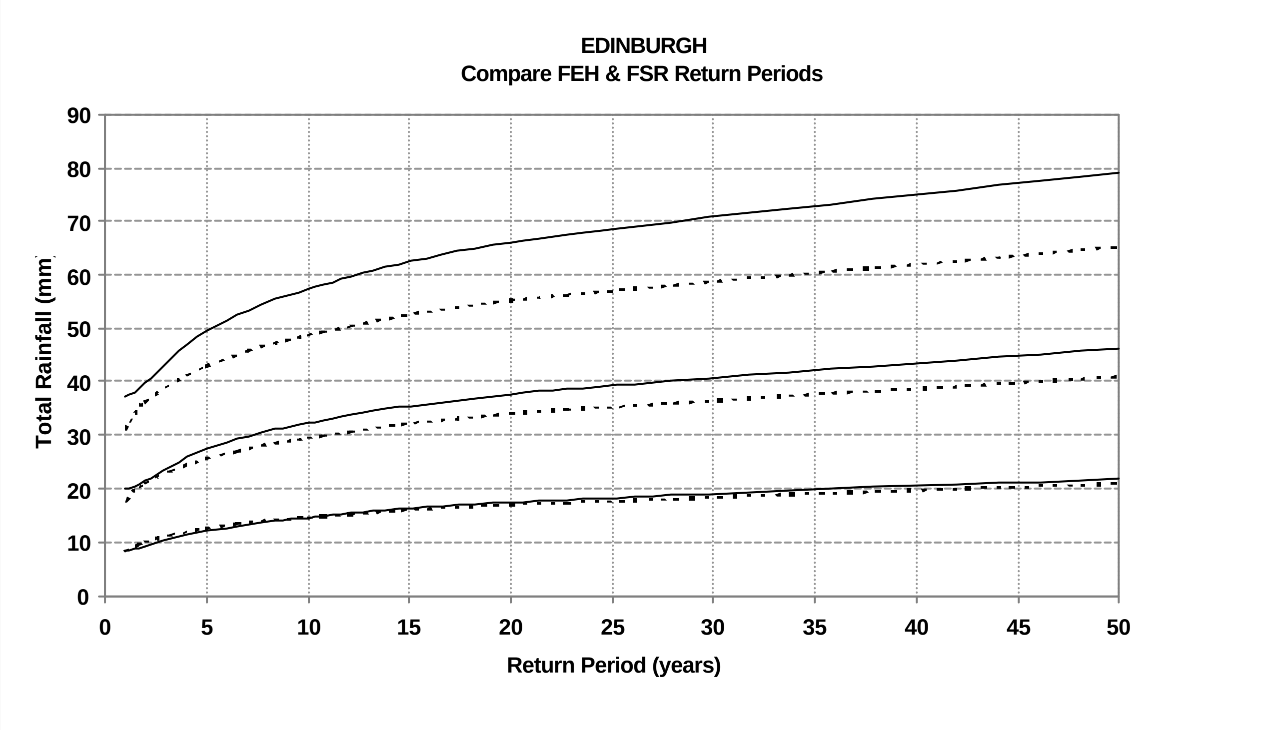
For Stratford upon Avon it can be seen that there is a progressive divergence as the storm duration increases so that by the 24 hour storms there is a significant difference.



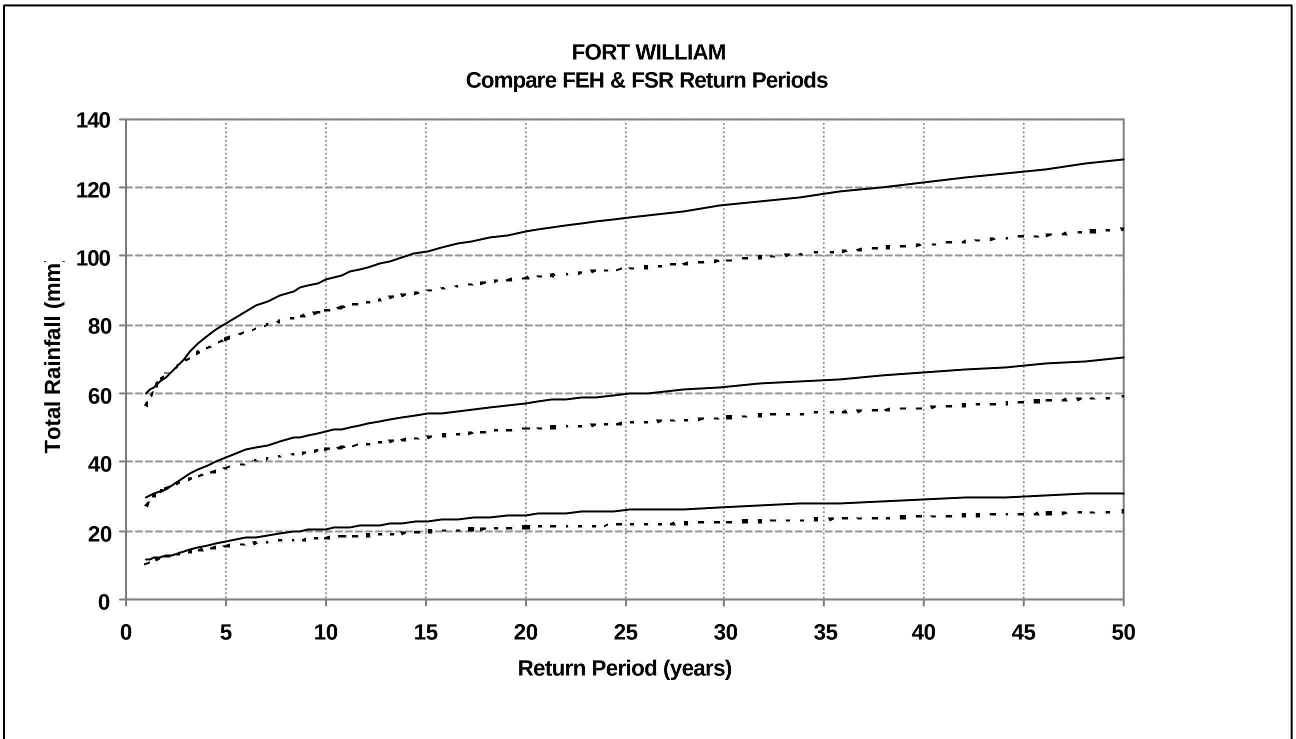
At Manchester it can be seen that there is a progressive divergence both with storm duration and also with storm return period. For storms with a return period of 30 years and above and with durations as short as 1 hour the differences are significant.



At Durham it is clear that there is very little difference with storms with durations of 1 and 6 hours. However, with longer duration storms the differences become significant.



At Edinburgh it can be seen that with the short duration storms of 1 hour there is no significant difference but as the storm duration increases the divergence also increases with the FEH storms having more rainfall.



At Fort William the differences are readily apparent for all storm durations and storm return periods. The FEH storms have significantly more rainfall in all circumstances than the FSR storms.

It can be seen from these graphs that there is a wide variation between catchments but also there is variation within each catchment with different storm durations and with different storm return periods.

5. Floods and Reservoir Safety

In June 2000 at a conference of the British Dam Society some limited studies reported the comparison between the 1 in 10,000 year catchments rainfalls from FEH and from FSR It was found that the FEH methodology produced estimates which were very significantly higher than FSR and in some cases higher than the Probable Maximum Precipitation (PMP). As a result of this the DETR commissioned a study which was undertaken by Babtie Group in association with CEH-Wallingford and Rodney Bridle Ltd. Their report[9] was finalised on 15 September 2000.

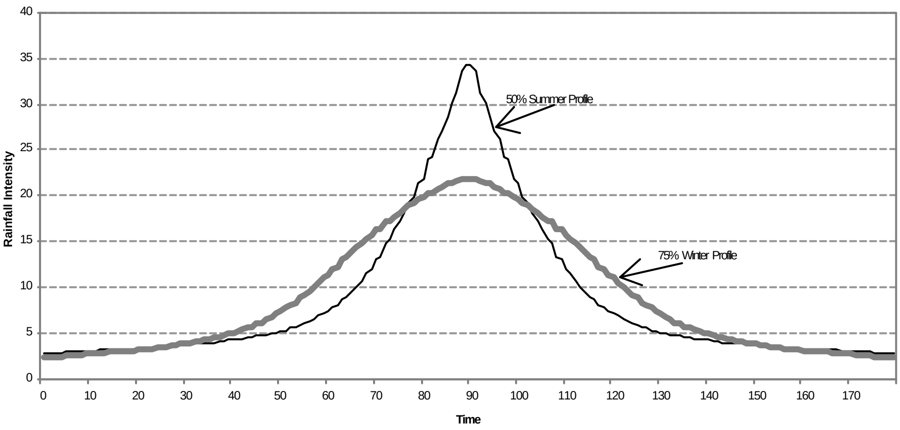
The study investigated various aspects of the FEH methodology and in particular reviewed the depth-duration-frequency (DDF) model. One hypothesis investigated was that whilst the RMED values took account of local topography it was possible that pooled observations from raingauges may not have taken adequate account of elevation differences and that this might in some way influence the growth curves. It was concluded that this factor would have little or no effect on the differences between FEH and FSR found in south-east England. The review of the DDF model included plotting on maps of the UK the values of the six parameters in the DDF model (d_1, d_2, d_3, c, e and f). Attention focused on the parameters 'c' and 'e' which control the growth rates. The maps with these parameters plotted showed a marked interaction between the 'c' and the 'e' parameters and also the unnatural boundary features evident on the maps. These findings suggested that there might be a need for re-calibration of the DDF model to reduce or eliminate the parameter interaction. It was also noted that any recalibration would not necessarily match the FEH and FSR estimates as many of the spatial features evident on the maps are also evident on maps comparing the FORGEX and FSR growth estimates.

A number of recommendations were made in that report. It was recommended that the DDF parameters 'c' and 'e' should be investigated further. It was also recommended that some more validation work should be undertaken including all aspects of the FEH approach rather than validating the individual components. It was also recommended that more of the long term rainfall records are converted to digital format, that work should be undertaken on extrapolation beyond the 2000-year limit set for the original research, that there should be more work to reconcile differences with PMP and that some work should be undertaken to input into risk assessment strategies.

It is not entirely clear whether the interaction of the DDF parameters has any significant effect on the derivation of storms for use in urban storm drainage as the required return periods are well below the upper limit of 1 in 2,000 years within which the FEH was developed and also in most cases the storm durations are also well within the limits of the research. Because there are concerns with use of FEH for reservoir safety when return periods of 10,000 years are important does not necessarily mean that the same concerns exist for urban storm drainage.

6. Rainfall Profile Shapes

The synthetic rainfall profile shapes developed as part of the Flood Studies Report namely the 50percentile storm for summer storms and the 75percentile storm for the winter storms have been retained in the Flood Estimation Handbook. There has been no evidence to suggest that these shapes are inappropriate for synthetic design storms. The FEH CD-ROM provides data on the Depth-Duration-Frequency (DDF) graphs for the chosen catchment (ie it provides the total rainfall) but it does not provide a rainfall profile nor does it state whether the worst case is summer or winter. This could be considered as a missed opportunity.



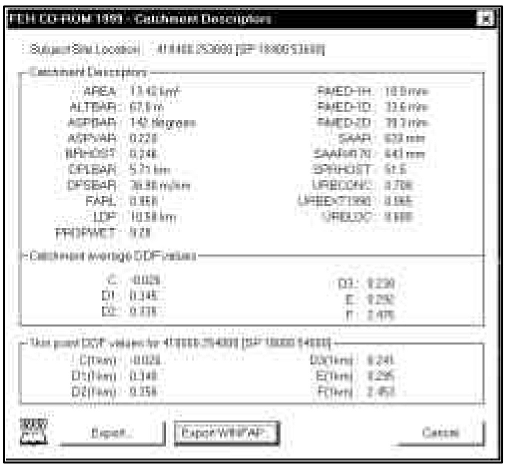
As the rainfall depth is based on the Annual Maximum it is inappropriate to state whether a summer or a winter profile should be applied. It is recommended that the general procedures which have been used by Modellers; namely to use summer storms for flooding and flood alleviation studies and to use winter storms where storage or overall flow volumes are important, is continued.

7. FEH CD-ROM

The FEH CD-ROM can be purchased separately from the FEH handbook though for users who will make extensive use of the CD-ROM it is strongly recommended that the handbook is also purchased so that the user can gain an understanding of the FEH approach.

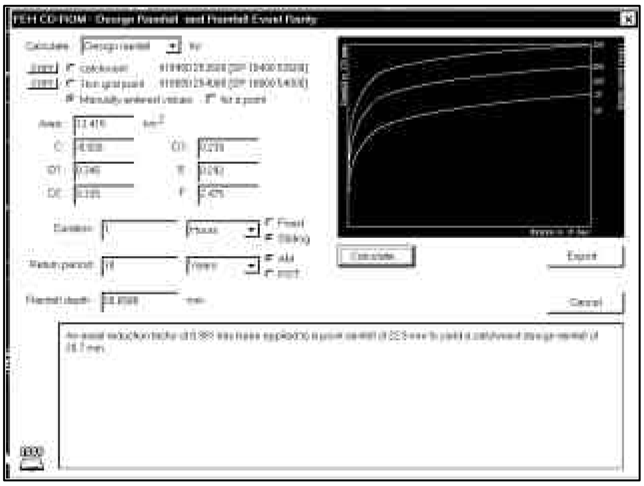
The FEH CD-ROM includes 1 km grids over the UK of the six parameters of the DDF model. Catchment average, 1 km values or point values for the parameters can be determined for every drainage catchment in the UK which has a catchment area greater than 0.5km2 (this is over 4 million catchments).

The FEH CD-ROM is a user friendly means of quickly zooming in on the catchment being considered and then identifying the catchment. Once the catchment has been highlighted by pressing the Query button the characteristics of the catchment are displayed and can be exported as a CSV file which can then be imported into Infoworks or MicroDrainage. The diagram below left is a typical display of the characteristics for a catchment. The upper portion shows all the data for the catchment and provides the catchment average DDF values so that rainfall over the whole catchment can be generated. The lower box provides the DDF values for a 1 km square point at the quoted grid reference (the downstream end of the selected catchment).



It will be seen that the DDF values are subtlety different – this is because of the averaging which has taken place. When importing into Infoworks the catchment average DDF values are used whilst in MicroDrainage the point DDF values are used.

For the selected catchment the DDF values and the rainfall for any given return period and duration can also be displayed. A typical screen is shown to the right. The choices of catchment area, 1km grid, manually entered values or point values are straightforward. When the desired return period and storm duration are entered the rainfall is calculated. When the catchment average values are used the software applies an Areal Reduction Factor to the point rainfall.



7. Creating Rainfall Files

Infoworks and MicroDrainage now have inbuilt facilities to generate FEH storms. In both of these the six DDF parameters can either be manually input or alternatively the CSV file generated with the FEH CD-ROM can be imported.

Infoworks imports the catchment average DDF values and it is therefore important that the correct catchment area is selected. Because the FEH routines are principally aimed at flood estimation from watercourses etc the catchments as defined in FEH CD-ROM always start at the head of the catchment but can be extended as far downstream as required by the user. However for a relatively small urban catchment it maybe inappropriate to also have a large rural upstream catchment which does not contribute to the sewer system. In these cases it maybe better to use the 1-km data or alternatively to average a number of 1-km values to get a more representative average for the catchment.

MicroDrainage (WinDap and WinDes) import the 1-km DDF values either from the CSV file or by manual inputting. The reason why MicroDrainge uses the 1-km values lies in the fact that the programs stem from a design background rather than a simulation background. Generally in sewer design Areal Reduction Factors are not applied and are in reality only applicable to the last pipe in the system. There is a facility within WinDap to change the Areal Reduction Factor which has a default setting of 1.

There are no facilities in Hydroworks for generating any FEH storms. However, suitable RED files can be prepared by creating them in the normal way for the required catchment. The values in the RED file are then factored up (or down) to give the same overall rainfall depth as given by FEH. It is important that all values are factored so that the correct shape of the storm profile is maintained.

8. Areal Reduction Factors

Areal Reduction Factors are the factors which are used to reduce the point rainfall values to catchment wide rainfall values. The Areal Reduction Factors are a function of the size of the catchment and also the storm duration.

Areal Reduction Factors are applied to the rainfall file in Infoworks (and Hydroworks) so that the values included in the rainfall file have already been reduced from the point values. In MicroDrainage the rainfall files have the point rainfall values and any Areal Reduction Factor required (the default being 1.0) is applied at the stage when the rainfall data is read by the program and converted to runoff.

In checking rainfall depths generated in FEH CD-ROM, Infoworks and MicroDrainage it was found that a reasonable agreement was reached with point rainfall. However, for catchment wide rainfall in Infoworks the final values did not agree with FEH – the reasons for this are not fully understood at present and are being investigated by Wallingford Software – it is however thought possible that the differences could be due to the Areal Reduction Factors used.

9. Further Research

The recent DETR funded study on the DDF model has highlighted a number of areas where further research is required. These are principally aimed at use of the FEH for reservoir safety and long return period events but there may also outcomes which are of relevance to urban storm drainage. Most of the research recommended in the report has been put in hand.

The Flood Estimation Handbook has given Engineers and Modellers a far more appropriate tool for estimation of flood flows and for the generation of appropriate rainfall data. However, the FEH approach like all the preceding methods relied upon historical records.

In times of climatic change it may no longer be entirely appropriate to rely solely on historical records but maybe some forward predictions of likely rainfall at scheme design horizons would be more appropriate. A UKWIR research project (*Climate Change and the Design of Sewerage Systems*) is due to commence shortly which will address all these issues and will advise the most appropriate techniques to use for sewerage design.

10. Recommendations

In such a heavily regulated industry as the current UK Water Industry it is difficult to simply recommend that rainfall generated by FEH should be used in hydraulic modelling and in scheme design as none of the Water Companies are currently funded to take that approach. However, it is clear that FEH storms are a considerable technical advance over the previous FSR storms and from a technical perspective the FEH storms should be used in preference to FSR storms. This will however probably only be an interim measure as forthcoming research will hopefully provide better guidance for the future. The DETR funded research into reservoir safety whilst raising some doubts about use of FEH for long return period storms should not be considered as a valid reason for non-implementation of the FEH in urban storm drainage.

In the interim it is strongly recommended that all proposed schemes are checked with FEH storms and if a significant difference in scheme cost is found then it should be carefully assessed by the Water Company (and possibly the Regulator) which approach should be used. For sewers constructed by other parties (eg Developers) it is recommended that the FEH storms be a requirement in the sewer adoption process.

11. References

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