05 - THE LESSONS LEARNED FROM THE FEH IMPROVEMENTS

Dr Thomas Rodding Kjeldsen

Department of Architecture and Civil Engineering, University of Bath, BA2 7AY, Bath, UK

Abstract

Following a brief description of how the UK's national flood estimation procedures have developed from the early 1970s to the present, the paper discusses criticisms and limitation of the current procedures, before, finally, suggesting areas where further research is needed to improve accuracy.

1. INTRODUCTION

In the United Kingdom the national procedures for flood frequency estimation have been evolving since the late 1960 in response to user requirements, methodological developments and the emergence of new data sources. Two different techniques are routinely used in the UK for flood frequency analysis and estimation of design flood event: a statistical method based on extreme value statistics, and a design flood method based on routing a design rainfall event through a simple event-based rainfall-runoff model. While both methods have been extensively used and both methods have been the subject of research and subsequent updates, this papers is primarily concerned with developments of the statistical methods. Other techniques such as continuous simulation modelling and joint probability analysis have also been researched, but apart from isolated applications, have not yet migrated from academic studies into mainstream practice, and are therefore not discussed further here.

This paper will outline the main methodological developments resulting from the latest developments published by the Environment Agency (2008) as the Improved FEH statistical method, discuss how they have been received by the user-community, and suggest future research topics with potential implications for applied hydrology.

2. BACKGROUND

2.1 The Flood Studies Report

The first national set of guidelines was presented in the Flood Studies Report (FSR) published in 1975 by the Natural Environment Research Council (NERC), documenting the outcome of a five year research project. The FSR methodologies were used extensively by the water industry and regulators, and also had significant impact on overseas engineering hydrology. The statistical method for establishing flood frequency curves at gauged and ungauged UK catchments was based on the index flood method developed in the USA by Dalrymple (1960). The FSR methodology divided the UK into ten geographically coherent regions and one region for Ireland. In each of the regions the statistical properties of the AMAX series were considered identical except for the location parameter, the mean annual maximum flood or QBAR, which is closely connected to the catchment characteristics of the considered catchment such as area, soil type and slope.

2.2 Post FSR development

Following the publication of the FSR, research into new methods for flood frequency estimation continued; in particular research into statistical methods for estimation of flood frequency curves at ungauged sites. New developments included the introduction of probability weighted moments (PWM) to replace product moments, and the use of these PWMs in the index flood method (Hosking et al, 1985). Later the PWMs were superseded by L-moment ratios (Hosking, 1990) which were developed into a comprehensive framework for regional frequency estimation by Hosking and Wallis (1997). Another important development was the attempt to define homogeneous regions based on hydrological similarity rather than geographical coherence (Acreman and Wiltshire, 1989) which resulted in the region of influence (ROI) approach proposed by Burn (1990) where homogeneous groups of catchments are formed based on similarity in catchment descriptor space. Finally, progress in computing power and digital mapping technology enabled the development of an integrated hydrological digital elevation model (IHDTM) from which new digital catchment descriptors could be derived, effectively replacing the catchment characteristics used in the FSR and derived manually from 1:50,000 paper maps.

2.3 The Flood Estimation Handbook

A Defra funded project was initiated in 1995 under the leadership of Duncan Reed at the Institute of Hydrology with the aim of bringing together these new developments into a new generation of flood estimation tools. The results were published by the Institute of Hydrology in 1999 in the Flood Estimation Handbook (FEH) and the associated software; primarily the FEH CD-ROM which enabled user friendly facilities for identifying catchments and extracting the relevant catchment descriptors such as catchment area, standard annual average rainfall (SAAR) etc, and the WINFAP-FEH software which enabled pooled frequency analysis for gauged and ungauged catchments. The FEH was adopted by most of the UK water industry and regulators, and just like the FSR also had significant impact on academic and practical flood estimation beyond the UK.

2.4 Post FEH developments

Following the publication of the FEH, the UK gauging authorities launched the HiFlows-UK website, which enables online access to a comprehensive database of quality controlled AMAX and POT series of instantaneous flow from gauged UK catchments. The HiFlows-UK database is regularly updated, giving hydrologist access to the most recent flood data. Also, aspects of risk and uncertainty were becoming more important in discussions of flood management (e.g. Reed, 2002), requiring new research avenues to open up. The launch of HiFlows-UK combined with methodological developments at the Centre for Ecology & Hydrology (now ex Institute of Hydrology) resulted in the Environment Agency funding a R&D project in 2005 aiming to use these methods to improve the FEH statistical method.

3. THE IMPROVED FEH STATISTICAL METHOD (SC050050)

The Environment Agency commissioned the R&D project SC050050 'Improving the FEH statistical procedures for flood frequency estimation' in 2005 and the final report was published in 2008 (Environment Agency, 2008). The methods developed as part of the project have largely been adopted by the Environment Agency as best practise for flood frequency estimation, and the have also been implemented in the latest version of the WINFAP-FEH v.3 software package (WHS, 2010). A number of new developments were introduced in SC050050, with the most important of these discussed below.

3.1 New catchment descriptors

One of the key FEH catchment descriptors is the flood attenuation from lakes and reservoirs (FARL). The importance of attenuation from floodplains was also recognised in the FEH, but no accompanying descriptor was developed. The SC050050 project developed a new catchment descriptor of flood plain extend (FPEXT) for all UK catchments, defined as the fraction of the total catchment area covered by the 100 year flood extend as defined by the first generation flood risk maps of England and Wales developed by Morris and Flavin (1996) in the IH130 report, and subsequently extended to Scotland and Northern Ireland. Accompanying descriptors of floodplain location (FPLOC) and mean flood depth (FPBAR) were also developed, but only FPEXT found its way into the final operational procedures.

3.2 Estimation of the index flood

Through a series of methodological developments and an extensive exploratory analysis a new model was developed enabling the prediction of the index flood (QMED) in ungauged catchments using catchment descriptors only. The new QMED model is of the form

$$\text{QMED}=8.3062\ \text{AREA}^{0.8510}\ 0.1536^{(1000/\text{SAAR})}\ \text{FARL}^{-3.4451}\ 0.0460^{\text{BFIHOST}^{\wedge}2} \tag{1}$$

This model has a factorial standard error (*fse*) of 1.431 which is an improvement over the *fse* value of 1.549 reported for the equivalent QMED model from the original FEH publication. What is less obvious from the model in Eq. (1) is the close link between the structure of the underlying statistical model and the benefit of data transfer from nearby gauged donor catchments. The FEH strongly encouraged the use of data transfer from nearby and hydrologically similar gauged catchments when estimating flood frequency in an ungauged catchment. The use of donor transfer technique is valid and can be viewed as compensating for the inability of the catchment-scale lumped catchment descriptors used in Eq. (1) to capture more local factors controlling flood response. But research by Kjeldsen and Jones (2007; 2010) showed that the donor transfer scheme suggested by the FEH could potentially result in estimates of the index flood with inflated levels of uncertainty when compared to estimates obtained using the FEH regression model only. They went on to propose a revised transfer scheme where the influence of a donor site is weighted according to the geographical distance between the centroids of the catchments draining to the subject site and the donor site, respectively. The revised donor transfer method has become an integral part of the improved FEH methodology.

3.3 Pooled analysis

For estimating the growth curve at ungauged catchments and for sites where only a short record is available, the FEH developed a procedure combining the index flood method with the Region-of Influence (ROI) method for creation of site specific homogeneous regions; a pooling group. In practice a pooling group was created for the target site by selecting gauged catchments from the database of 1000 gauged UK catchments considered to be hydrologically similar to the target site. Hydrological similarity was defined by a similarity distance measure based on a comparison of catchment area, standard annual average rainfall and soil type as determined by the BFIHOST dataset (Boorman *et al.*, 1995). Catchment were added to the pooling group until the sum of AMAX events from all pooling group members exceeded five times the target return period (the 5T rule), i.e. a minimum of 500 AMAX events for a 100 year design flood. The pooling procedure was retained in SC050050, but the measure of hydrological similarity was updated; the sol factor was replaced by measures of attenuation from lakes and reservoirs (FARL) and flood plain extend (FPEXT).

Another important development introduced in SC050050 was a new method for assigning weights to the L-CV and L-SKEW estimates from the each of the pooling group members. Where the original weights introduced in the FEH accounted for record length and rank of catchment within the pooling group, the new weights more explicitly relate to the record length and the actual value of the distance similarity measure used for judging hydrological similarity. Consequently a user is no longer required to consider and revise the ranking of pooling group members. The new pooling group method was found to perform better than the original FEH method when considering ungauged sites. However, the biggest innovation was the introduction of a separate set of weights when considering a gauged catchment, where the at-site estimate of L-CV was given more weight than in the previous FEH weighting scheme. This results in enhanced single site growth curves that are more akin to the single site growth curves, but derived using all the pooled data and thus associated with lower level of uncertainty.

4. USER FEED-BACK AND CRITISISMS

Despite the improved FEH method having been the Environment Agency's recommended procedure for flood frequency estimation since 2008, the amount of direct feedback has been limited. This could suggest that i) it is not obvious how to register a concern, or ii) that in general users are generally satisfied with the performance of the method. Assuming that the lack of feedback is primarily related to the latter option, a few features have been queried at a number of occasions by users.

4.1 BFIHOST is not used for forming pooling groups

The definition of hydrological similarity used in the formation of pooling groups was changed, replacing BFIHOST with FARL and FPEXT. This change has been queried by a number of users, but this modification of the method was based on the outcome of an extensive exploratory data analysis which consistently showed that for the 602 catchment analysed in SC050050, BFIHOST, i.e soil type, did not exert significant control over the shape of the dimensionless growth curve. The analysis in SC050050 did not focus specifically on permeable catchments, and it is possible that growth curves for permeable and chalk dominated catchments should still be treated as special cases (see for example Bradford and Faulkner, 1997). It should be noted that the particular form of the BFIHOST term in the QMED equation (Eq. 1) was chosen specifically as it provided a better description of QMED estimates in highly permeable catchments. However, it is clear that flood estimation in permeable catchment remains a challenge.

4.2 Hydrological similarity is less important for donor selection

The new procedure for choosing suitable donor sites gives the analysis less freedom, as the impact of the sites is weighted according to the geographical distance only. For example, if the most nearby site is considered not useful, the second closest site will have less impact as it will be located further away from the target site, and thus be assigned a smaller weight, and thus reduce the impact of the data transfer. Also, there is no mechanism in the donor transfer scheme to ensure that QMED should always increase when moving downstream on the river network and therefore the procedure can in some cases lead to counter intuitive results.

4.3 Comparing SC050050 to other methods

For some specific applications, methods other than those presented in SC050050 are sometimes used for design flood estimation. This is particularly the case for flood estimation in small catchments such as required for housing developments and SuDS design. In a recent study by the Environment Agency (2011), the SC050050 methodology was found to outperform other older methods for flood estimation on small catchment such as the IH124 method (Marshall and Bayliss, 1994) and the ADAS 341 (ADAS, 1982). It is questionable if advising the use regional growth curve developed as part of the FSR in the early 1970 can still be considered good practise. For example, the FSR regional growth curve for region 5 was constructed using 47 stations with a mean record length of about 11 years, far short of the average record length of almost 40 years available in the HiFlows-UK database. Another serious limitation of the FSR growth curves is that they do not include the effect of catchment area on steepness of the growth curves. To illustrate this point Figure 1 shows the second order L-moment ration (L-CV) plotted against catchment area for two subsets of good quality data from rural catchments in the HiFlows-UK dataset in FSR Region 8 (South West England). The first subset is derived using all AMAX events up-to and including water year 2007, while the second dataset represent the same catchments but with L-CV estimated using a censored version of the dataset containing only AMAX events up to and including water year 1969, thus representing the data that would have been available to the FSR team. The second subset contains fewer catchments as some AMAX records only begin after 1969.

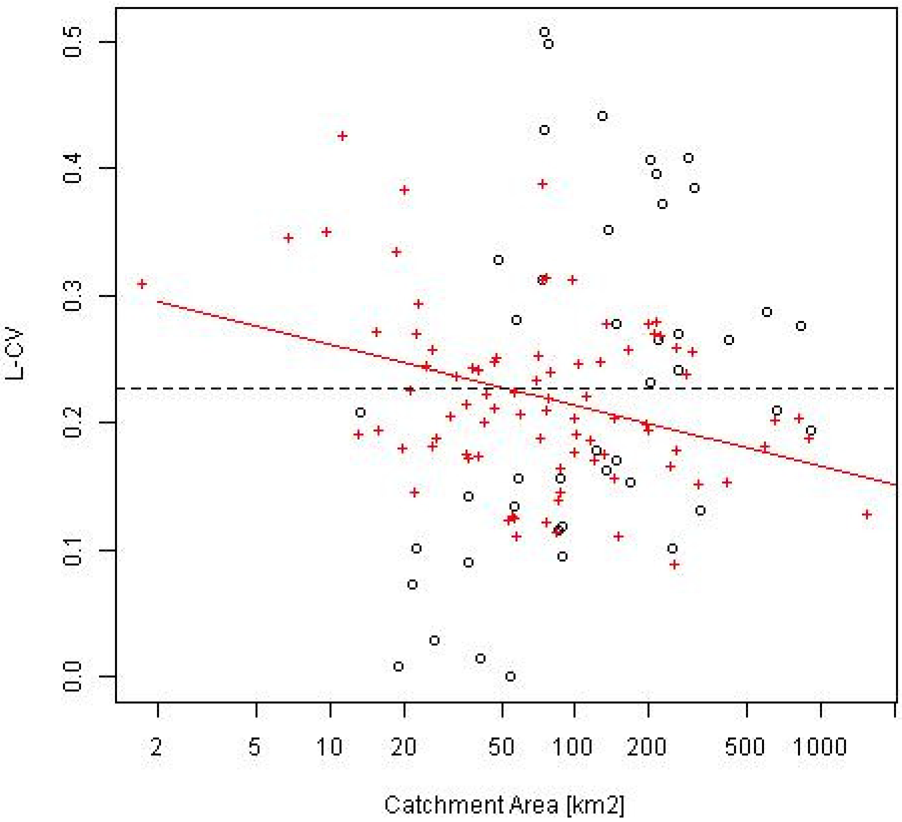

Figure 1: *Black circles represent L-CV values estimated using AMAX data up-to 1969, and red crosses represent L-CV values for the same catchments estimated using all AMAX data in the HiFlows-UK catchments. The red line is the best linear relationship between L-CV and log(AREA) based on L-CV values estimated using the complete dataset. The black hatch line is the mean of the black circles.*

Using the latter (censored) dataset, no significant relationship can be detected between L-CV and catchment area, thus a constant value would be chosen. However, using the full dataset it is clear that there is indeed a very significant relationship between L-CV and catchment area for this dataset. This would suggest that that design floods estimated using the FSR growth curves are at risk of underestimating the actual flood risk on small catchments. Notably, the FSR team (FSR, Vol. 1, Section 2.6.7) speculated that catchment area could indeed influence the growth curve as shown in Figure 1, but could not detect such effects in the data they had available at the time; again this is consistent with Figure 1, and a testament to the insight of these early pioneers.

5. FUTURE DEVELOPMENTS OF APPLIED FLOOD HYDROLOGY

Applied research into flood estimation continues to be an important topic. There are several aspects of the current methods that are in need of critical evaluation and innovative new approaches. The list below reflects the opinion, experience and limited imagination of the author, and other topics could be equally valuable

5.1 Better use of local data

"*You say keep saying the FEH methods work reasonably well across the UK, but how come they never work for my catchment?*" (annon. EA hydrologist, 2011). This comment was directed at the author during a discussion of FEH methods, and highlights the need for better tools to inform users about the utility of the estimates and the true level of uncertainty associated with estimates obtained using these methods. In the past, the main aim of flood estimation research was to develop new datasets and methods to enable the most accurate prediction of the flood frequency relationship in cases where little or no hydrometric data were available. Less attention was paid to the quantification and reporting of the levels of uncertainty associated with these estimates; even though the levels of uncertainty can be very high. Notably neither the FSR, the FEH, nor the SC050050 report provide an assessment of the uncertainty of a T-year event when derived from a regional flood estimation procedure such as required for flood estimation in ungauged catchments.

For example, using the improved FEH statistical method in combination with 48 years AMAX data at the site of interest, Miller *et al.* (2013) showed that the return period of the record breaking 700m3/s recorded on the River Derwent at Camerton in the Lake District in November 2009 had a return period somewhere between 500 and 17500 years, with 2100 years being the best estimate. Similarly, Kjeldsen (2014) showed that the uncertainty associated with a 100 year event when estimated at an ungauged catchment represent a ratio of 5.5 between the upper and lower 95% confidence limits. There is clearly a need to develop better tools for estimating and communicating the level of uncertainty. But more broadly the real need is for a more joint-up framework that will provide analysis with methods for making better use of local data in whatever form they might be available while at the same time provide an assessment of the additional benefit derived from including these data into the analysis. Such local data could, for example, be: short records of AMAX or POT data available from data loggers temporarily installed at strategic locations, level only data from flood warning stations, or historical data pre-dating the installation of flow gauging structures (e.g. Bayliss and Reed, 2001; Macdonald, 2013). In a recent study, Kjeldsen (2014) developed uncertainty measures for design flood estimated for a range of different scenarios with regards to data availability. The study illustrated the benefit of using even short records if the procedures for including the data have been designed to accommodate such data.

5.2 Non-stationarity

Quantifying the effects of both land-use and climate change on the flood frequency relationship is an important but also very difficult task. The effects of land-use change on flooding characteristics in UK catchments have been studied both from the perspective of rural land-management and increasing urbanisation. In a comprehensive review of the link between rural land-management and flooding McIntyre *et al.* (2013) concluded that the current ability to quantify the impact of rural land use change on the water cycle is limited and not able to provide consistently reliable evidence to support planning and policy decisions. In contrast it has long been recognised that the expansion of urban areas will result in a reduction of catchment lag-times and increased flood volumes, both acting to increase the downstream flood risk (Hollis, 1975). Urban effects are most pronounced for smaller events, and less important during large events (Robson and Reed, 1999). The result is flood frequency curves that are shifted upwards more for lower return periods than for higher return periods, i.e. less steep flood frequency curves, which again is synonymous with a reduction in the variability of the flood records. In a comparison of flood frequency in 200 urban UK catchments with expected flood behaviour in similar rural catchments, Kjeldsen (2010) found that while a general tendency for increased flood magnitude and reduced variability, contrasting behaviour could be detected, i.e. decreased flood magnitude and increased variability. These results indicate that more research is needed to provide better tools for enabling hydrologists to predict land-use effects (rural and urban) on flood frequencies.

The potential effect of climate change on flood risk is a topic that has occupied researchers and policy-makers for a considerable time. The problem has been approach from two different directions. A large number of studies have used downscaled predictions of future climate scenarios in combination with rainfall-runoff models (Wilby *et al.*, 2008; Prudhomme *et al.*, 2010). These projections have generally found that future flood risk is likely to increase, and Defra (2006) adviced that a precautionary 20% should be added to estimates of design flood made based on use of historical flood data, such as the FEH methodologies. More recent studies based on UKCP09 scenarios have suggested that the 20% factor might insufficient (Prudhomme *et al.*, 2010). The other approach is based on trend analysis of historical records of flood flow series such as (Robson and Reed, 1999; Hannaford and Marsh, 2008). These studies generally find no or little evidence of trend in the existing flow series. In a recent study, Prosdocimi *et al.* (2013) concluded that for most catchments, the trends observed in available AMAX series from UK catchments were not sufficiently significant to support the 20% addition by 2085. Clearly, there is more work required to bring together the results obtained from the different methods, and to turn the disparate scientific evidence into actual practical guidance for flood estimation.

6. DISCUSSION AND CONCLUSIONS

The traditional role of flood frequency estimation was providing robust and reliable design flood estimates. However, the developments in hydraulic modelling capabilities, especially in urban areas, combined with increased focus on issues related to impacts of and adaptation to climate change and other environmental impacts has in many cases highlighted the limitations of the current methods. The existing methods are built on sound scientific analysis of flood flow data available in the HiFlows-UK database. But the methods are routinely used in small and urbanised catchment, which is exactly the type of catchments where little hydrometric data are being collected, and thus there is only a limited opportunity to ensure that the methods perform adequately across all such catchments. In addition to the increased complexity of the modelling exercises being undertaken, there has been a steady increase in the appreciation that uncertainty is an integral part of flood estimation. However, there is little advice available on how to assess the uncertainty of the design flood estimates, and, importantly, how to use such uncertainty measures in the decision-making processes as discussed by Kjeldsen *et al.* (2013).

There is, of course, no guarantee that the steady stream of new scientific research into flood hydrology continuously being published into scientific journal and research reports finds its way into best practise. It is therefore important to ensure that there is a frequent dialog between researchers and the many end-users, and that a mechanism for collating and disseminating research results into useful guidance documents is established. Good examples include the Flood Studies Supplementary Reports (FSSR) and the Institute of Hydrology Report series published by the Institute of Hydrology between 1977 – 1998 and the more recent design flood estimation guidelines developed by the Environment Agency. Also, several national meetings have been organised by the British Hydrological Society in the past five years on the topic of flood estimation and forecasting.

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