IMPROVING ACCURACY, LEAD TIME AND CONTINGENCY IN FLUVIAL FLOOD FORECASTS TO ENHANCE EMERGENCY MANAGEMENT

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Abstract

Flood forecasting techniques have become more advanced over recent years in response to increased demands for more accurate, timely and reliable flood warnings. The National Flood Forecasting System (NFFS) is the UK Environment Agency's flood forecasting platform and hosts the flood forecasting models and techniques for all seven regions of the Environment Agency. The NFFS has a high level of resilience, but the risk of partial or total failure cannot be completely removed. Thus, contingency forecasting techniques that are completely independent of the NFFS are required to provide flood forecasting duty officers with alternative forecasting methods.

This paper first describes and evaluates the improvements in flood forecasting that have been achieved through development of real-time hydrological and hydrodynamic models for the Meon, Beaulieu and Lymington catchments in southern England. Performance of the models has been assessed at a range of lead-times to determine the typical accuracy of the forecasts. Importantly, this provides flood forecasting duty officers with an indication of the level of confidence that can be placed in the forecasts.

The paper's focus then shifts to the contingency forecasting techniques that have been developed for these and other catchments in southern England. The contingency forecasting techniques include rate-of-rise extrapolation, peak-to-peak correlations and rainfall correlations, as well as more innovative techniques such as multivariate analyses. Each of the contingency techniques is described, followed by an assessment of their strengths and weaknesses.

The paper finally describes how the improved forecasts are currently used within the flood warning decision making process.

Introduction

Flood warning systems provide a well-established way to help to reduce risk to life, and to allow communities and the emergency services time to prepare for flooding and to protect possessions and property (Sene, 2008). Flood warning systems comprise numerous components that must be coordinated in a clear and efficient way in order to make the system effective. The Australian Government's Flood Warning manual (2009) provides a thorough analysis of the different elements required to develop an effective flood warning system.

Fluvial flood forecasts are a key element in a flood warning system. Abundant literature is available on the topic, however the experience gained during the development and operation of the forecasting systems, and detailed catchment knowledge are always fundamental to understand the full potential of the forecasting tools available.

This paper reviews a range of fluvial flood forecasting tools that were implemented in southern England in the past five years, emphasising the different elements that were considered at each stage and the lessons learnt during development of the tools.

Flood forecasting models

Rainfall runoff models are a form of hydrological model and predict river flow based on observed and/or forecast rainfall. If observed rainfall is used, the maximum lead time achievable is generally similar to the typical response time of the catchment to rainfall. However, factors such as the antecedent catchment conditions, influence of snowmelt, direction and speed of the rainfall event and available storage capacity of reservoirs within the catchment will all affect the response time. In many cases, the lead time provided by the use of observed rainfall (from raingauges or weather radar) can be sufficient, but may be extended by the use of rainfall forecasts (Sene, 2008).

Three flood forecasting models were developed in catchments located in southern England, as shown in Figure 1. The forecasting models developed have two components: a hydrological component that uses PDM (Probability Distributed Model) and a hydraulic component built using an ISIS 1D hydraulic model (www.halcrow.com/isis). Two-dimensional models are rarely used in real-time flood forecasting in the UK, due to their complexity and time taken to run.

Flood forecasting models must be sufficiently robust to ensure they are capable of simulating a wide range of scenarios whilst providing the required level of accuracy and meeting maximum run time requirements. The latter is essential for real time flood forecasting, since it helps maximise the available lead-time and allows mitigation plans to be put into action as early as possible.

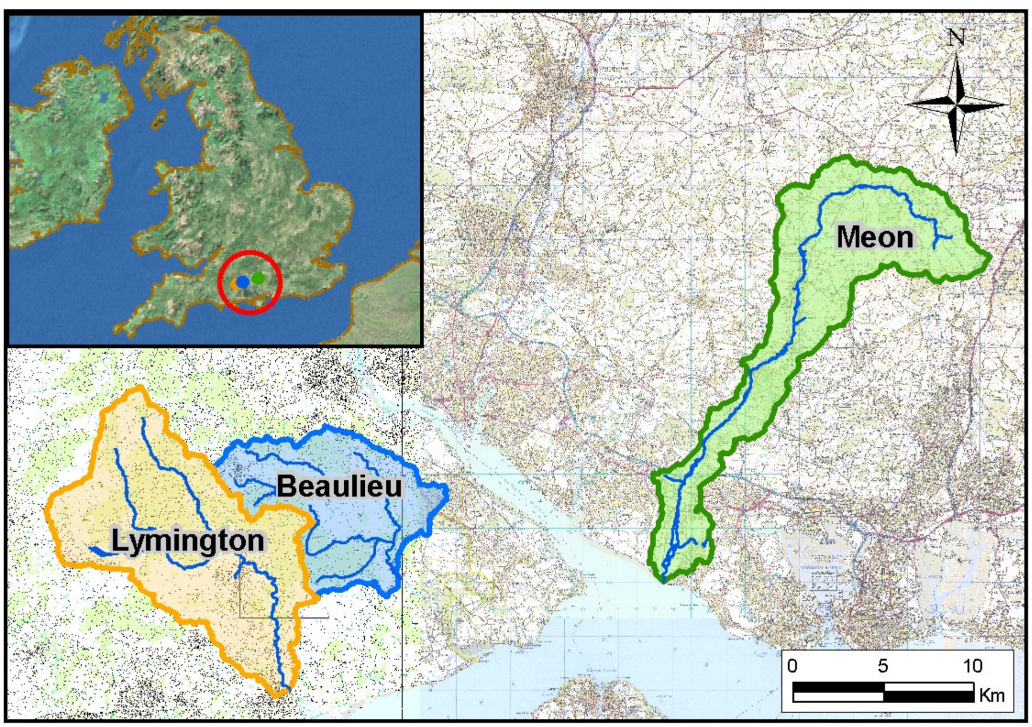

Figure 1 – Location of the catchments where flood forecasting models were developed

Model updating

One distinguishing feature of forecasting models compared to off-line simulation models is the ability to use observed data from telemetered river monitoring stations to modify forecasts as they are generated. This real time updating of forecasts can significantly improve the accuracy of model outputs. Several techniques have been developed for updating forecasts, including error prediction methods and techniques which adjust the internal state of the model components and model parameters respectively. The PDM model has the option to use state correction and error prediction modes, the latter of which also allows the estimation of future errors by means of an auto-regressive moving average (ARMA) model.

Analysis of practical cases

Some physical characteristics of the three catchments studied are given in Table 1, while Figure 1 shows their location in southern England. Figure 2 shows a picture of Beaulieu river (near Beaulieu gauging station), taken during the March 2008 flood event. The typical time-to-peak of these three catchments is less than 8 hours. In all cases Tipping Bucket Raingauge (TBR) data series were available for at least three raingauges within or near (less than 10km) the catchment boundaries, as well as catchment average radar rainfall data series for the catchments. In all cases 15-min datasets were used.

The geology of the Lymington and Beaulieu catchments is broadly uniform, with baseflow representing a very small proportion of the total flow during high-flow events. In contrast, the Meon catchment has a highly permeable stratum mid-catchment that notably modifies the flow regime and characteristics of high-flow events. In this catchment flooding events typically occur during winter when the catchment is partially or totally saturated. Additionally, hydrogeological studies in the Meon catchment have demonstrated that the gauging stations located in the middle reach consistently measure significantly lower flows than those detected upstream, as a result of natural by-passing of the river channel. The forecasting model for the Meon river was modified in order to consider this by-pass effect (and calibrated using observed borehole data), which significantly improved the results. Nevertheless, it should be highlighted that the quality of results for the Meon river was generally lower than that of results obtained for the Beaulieu and Lymington rivers.

Catchment	Area [km^2]	Mean longitudinal slope (terrain) [%]	Urban area [%]	Number of gauging stations	Mean flow near the catchment outlet [m^3/s]	Max. obs. flow [m^3/s]	Data series length [years]
Beaulieu	64.7	2.5	0.7	2	0.86	20.4	7.5
Meon	107.6	7	1.5	5	1.11	8.61	9
Lymington	120.9	3.8	0.6	3	1.37	68.8	10

Table 1 - Physical characteristics of the catchments studied

Figure 2 – Flooding in Beaulieu river, March 2008

Main results for the study cases

Table 2 shows the performance statistics for the events analysed. The results shown in Table 2 and Figures 5, 6 and 7 reflect model performance without the use of state updating.

	River Lymington at		**River Beaulieu at**	**River Meon at**			
	Meerut Road	Brockenhurst	Hartford Bridge	East Meon	West Meon	Mislingford	Wickham
Peak error [m]	0.080	-0.010	0.020	0.155	0.072	-0.068	0.005
Standard deviation (peak) [m]	0.110	0.310	0.144	0.096	0.190	0.110	0.146
Average R^2 (event) (Nash-Sutcliffe)	0.70	0.58	0.69	0.38	0.28	0.23	0.33
Mean square error (event) [m]	0.067	0.228	0.170	0.043	0.075	0.080	0.060

Table 2 - **Performance statistics for the three models**

Table 2 shows that, even when the peak water level mean error is in line with expectations (i.e. within ±0.20m) in all the cases, there is some important variation in the results. This can be particularly seen for the low R^2 values obtained for the river Meon models. Various causes were suggested to explain these low R^2 values, in particular the low quality of the flow data series and ungauged net water transfers with neighbouring catchments (there is hydrogeological evidence in the Meon catchment confirming this occurs).

Figure 3 and 6 show examples of the results obtained for the calibration events, while Figure 5 shows a verification event. These figures show the ability of the flood forecasting models to replicate the different hydrograph characteristics. They also show how the observed rainfall based on TBR and radar (Hyrad) vary quite significantly.

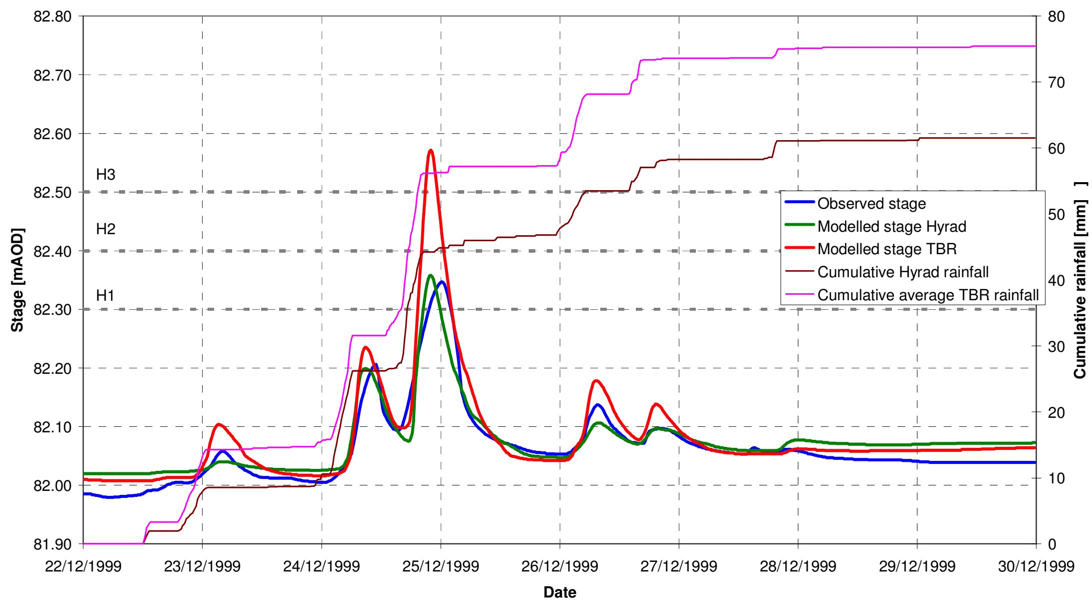

Figure 3 - Calibration event: Meon river at West Meon

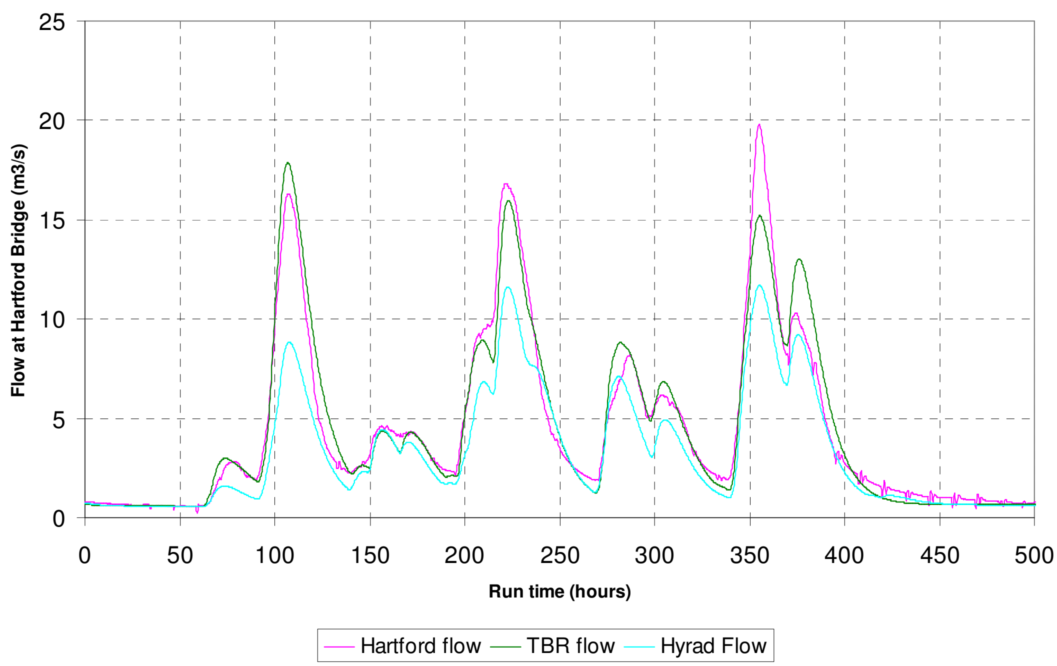

Figure 4 - Calibration event: Beaulieu river at Hartford Bridge

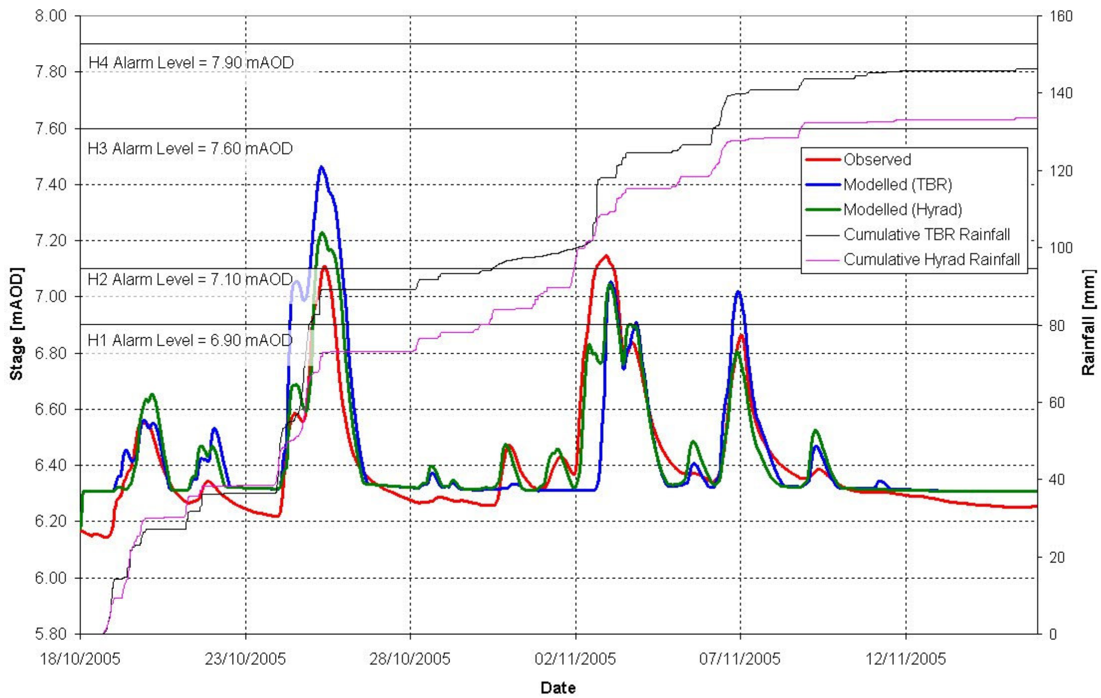

Figure 5 - Verification event: Lymington river at Brockenhurst

Results evaluation process and forecasting accuracy assessment

The performance of the models was initially evaluated without the use of state updating. In each catchment between three and five events were used for calibration, plus two or three for verification.

Once the models were calibrated and verified, the accuracy of the forecasts using state updating was assessed, assuming that the models are updated every six hours. The models were run with state updating and the observed data series compared with the forecasts for a range of lead times. Finally, the errors were analysed and confidence intervals were calculated for each lead time tested and combinations of different data sources and state updating methods used. Figure 6 shows an example for the river Lymington at Brockenhurst gauging station, for a time window between 6 hours before the start of rainfall and the moment after the peak when predicted flow is 20% lower than the observed peak. It can be seen that in this case, for a lead time of 3 hours the errors are within ±0.20m in 95% of the cases.

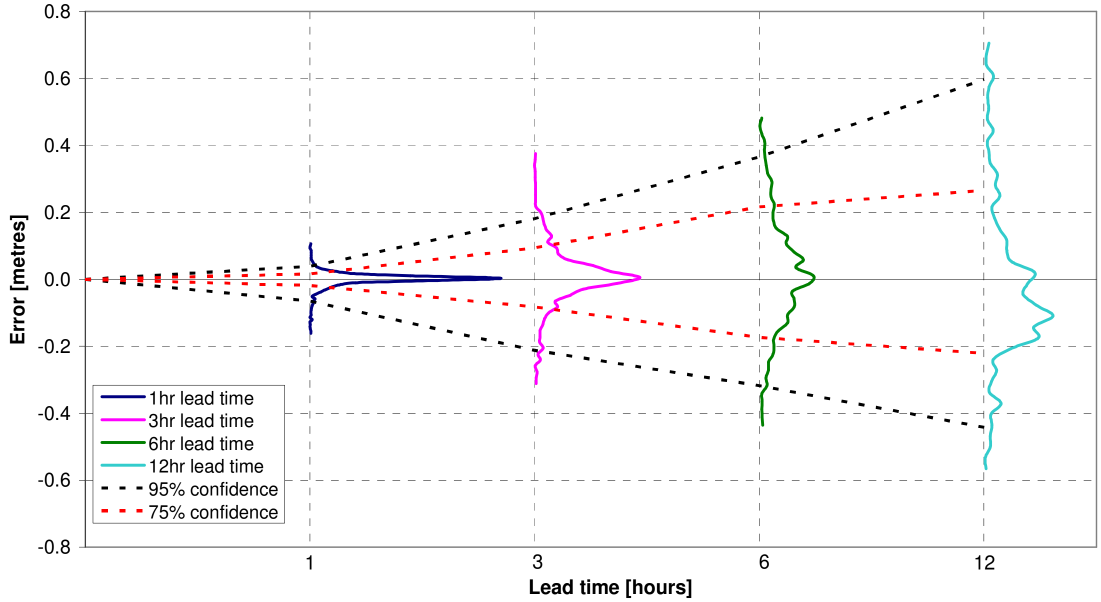

Figure 6 - Example of analysis of forecasting errors

This type of analysis provides valuable information to the forecasters since it gives a statistical estimation of the likely accuracy of the forecasts, measured in an easy-to-read parameter such as peak water elevation. At each forecasting point there is an inverse relationship between accuracy and lead times (as shown in Figure 6), and hence the operators need to trade-off between accuracy and uncertainty.

Contingency flood forecasting: Overview

Contingency flood forecasting tools (CFFTs) provide duty officers with a back-up method of forecasting in case of failure of the primary methods. The Environment Agency's Flood Warning Level of Service states that serviced flood risk areas must have a contingency method of forecasting. Reasons for failure of the primary methods include data problems, model failure, unreliable performance or poor results.

CFFT's have been developed at 126 forecast sites in the Environment Agency's Southern Region, though at some forecast sites these will actually be the primary method of forecasting in the current absence of other forecast methods.

The CFFTs comprise a set of simple forecast tools that can be used operationally to predict the magnitude and timing of the peak. Additional analysis has also been undertaken to provide further useful information for flood forecasting duty officers. This includes an estimation of the rarity of historic events and a summary of relevant event information such as the contributing rainfall. The simplistic nature of the CFFT's means that they do not provide a full hydrograph prediction. Additionally, some of the CFFT's provide a statistical estimation of the accuracy of the forecasts, which gives duty officers a quantitative measure of the likely accuracy of the real-time forecasts.

Data used and catchments analysed

The CFFTs were applied to 29 catchments in southern England, as shown in Figure 7

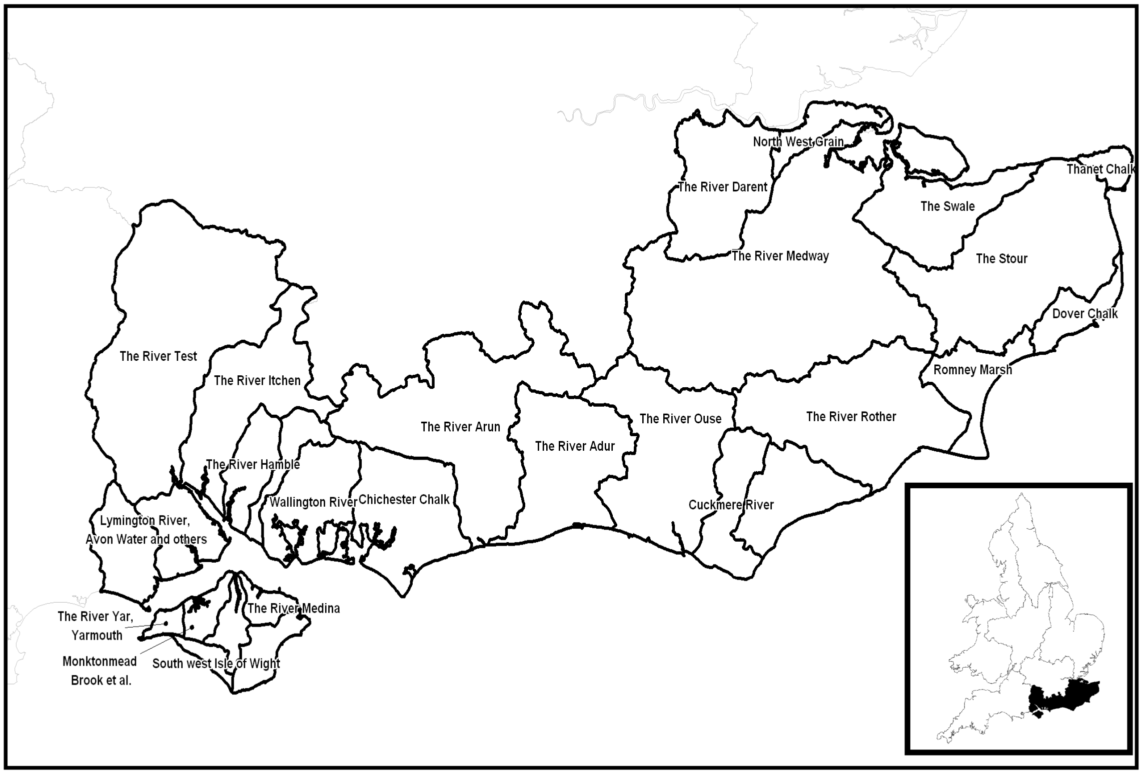

Figure 7 - Catchments where contingency flood forecasting techniques were developed

Fifteen-minute data for the period January 1999 to August 2008 for a total of 126 river monitoring stations (forecasting points) were analysed. The data quality was variable and at a small proportion of stations data problems prevented development of CFFT's. Fifteen-minute catchment average rainfall data were provided for the same time period, derived from existing TBR data in the region. Other data were also provided, including Soil Moisture Deficit values (SMD) and historical flood information, which are important for some of the forecasting techniques.

Contingency flood forecasting techniques – Details and examples

The CFFTs can be separated into three main groups, according to the hydrograph element they estimate:

- Peak value: Rate of rise, rainfall correlations and peak to peak correlations
- Peak timing: Catchment lag and travel time techniques
- Relative peak magnitude: Event rarity analysis and historical event data

The different techniques are described in the following sections.

Rate-of-rise extrapolation

Rate-of-rise extrapolation is a forecasting technique that uses the rate-of-rise of the rising limb of the hydrograph (defined by the gradient) to estimate the peak level likely to be reached. For practical reasons, extrapolation is usually linear, though this does reduce the accuracy since in reality the gradient of the hydrograph rising limbs will vary. A key challenge of this method is deciding when to stop the extrapolation, i.e.

estimating the time at which the level will peak and start to recede, however this can be estimated using other CFFTs. For these reasons, the error (presented in plots as the 'residual') of the forecast level is examined against historic observed hydrographs. This technique was undertaken using level hydrographs with a good clean rising limb that was free from 'noise'.

Up to 10 historic events were analysed per forecast point, incorporating the highest peak events and a range of mid to low events. The assumption is that these historic events will be a good indicator of future events: the spread of the hydrograph rising limb slopes and event magnitude provide an indicator of likely future event behaviour characteristic of each forecast point.

Developing the rate-of-rise technique

The accuracy of the technique was assessed using a combination of different start points (termed 'extrapolation origins') on the rising limb and different time periods over which the rate-of-rise was calculated (rate periods). The following guidance was used to define the number of extrapolation origins and rate periods used:

- For forecast points where the median duration of the rising limb is ≤ 8 hours then a minimum of 3 extrapolation origins and rate periods of 1 and 2 hours were used

- For forecast points where the median duration of the rising limb is > 8 hours then a minimum of 5, and up to 8, extrapolation origins and rate periods of 1 and 3 hours were used

The extrapolation origins (which were unique to each event hydrograph) were not necessarily evenly spaced on the rising limb but were spread appropriately after a steady rate-of-rise had been observed on the event hydrograph. Figure 8 shows a theoretical hydrograph with typical extrapolation origins shown, while Figure 9 shows just one extrapolation origin and how the rate-of-rise and forecast is produced from this.

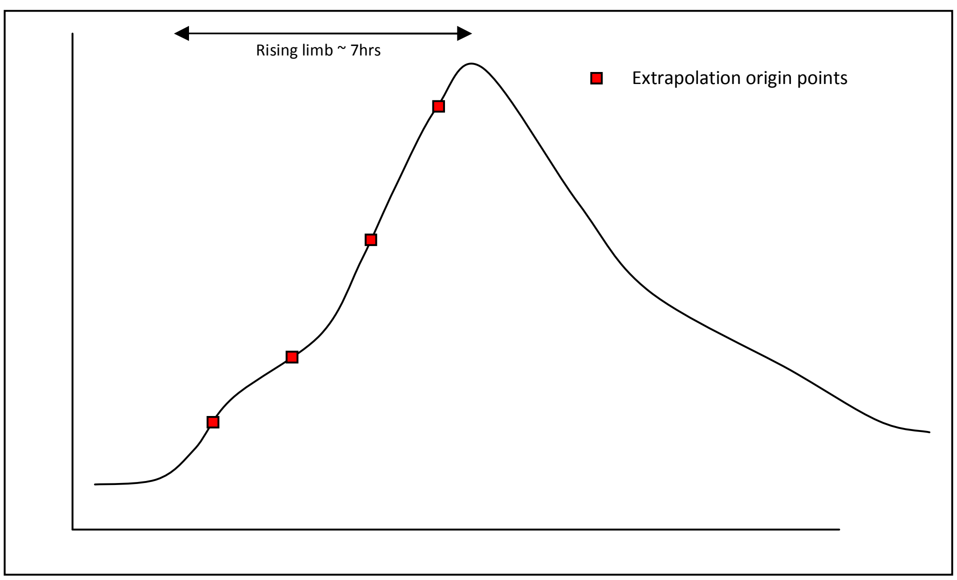

Figure 8 - Example showing extrapolation origins on theoretical hydrograph

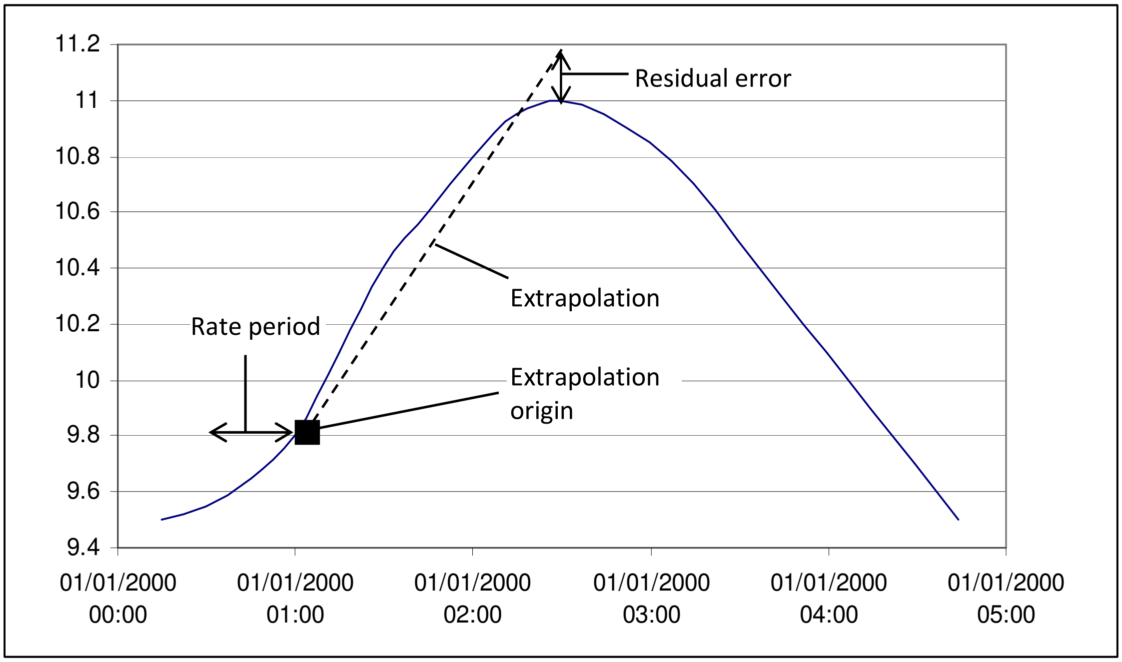

Figure 9 - Example of rate of rise forecasting

Presentation of results

Residuals were calculated at 15-min intervals from the extrapolation origin to the time at which the observed peak occurs. Using this information, charts were produced showing how the residual varies with lead time for all the events at each forecast point; an example is shown in Figure 10. Each data series represents a single event.

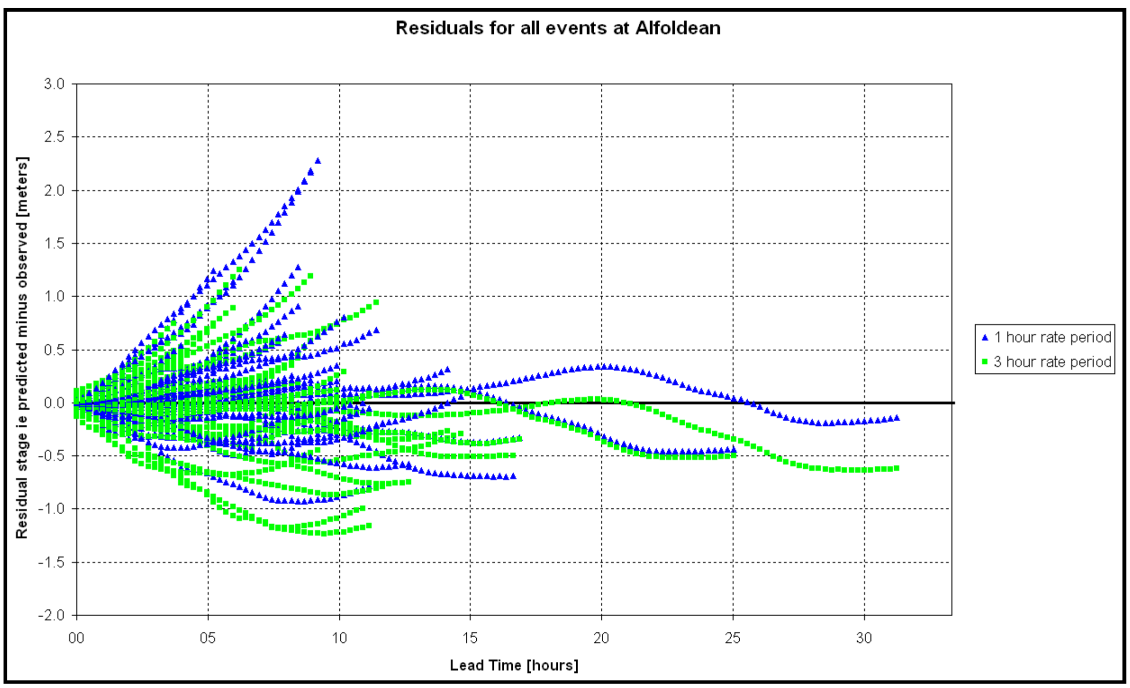

Figure 10 - Example rate of rise residual plot

The residual plot provides an indication of the typical error that can be expected from this forecasting technique. In the example in Figure 10, it shows the error is likely to be within the approximate range ±1.0m for a forecast lead time of 5 hours, based on historic event behaviour.

Information from the residual analysis is also tabulated to summarise the accuracy at different forecast lead times. Both maximum and average residuals are given to indicate the variation and uncertainty attached to the estimates.

Rainfall correlation analyses

Rainfall correlation analysis relates rainfall depth and duration to a resultant peak flow or level at the forecast point. This technique provides an indication of the likely peak given observed and/or forecast rainfall amounts. Clearly, the reliability of the technique increases where correlations between rainfall and river level / flow are strong and supported by a large number of historic events; however, a wide spread of results may also indicate that the catchment response to rainfall is likely to be very unpredictable and affected by a range of factors as well as rainfall.

If a good correlation exists, this can be used for forecasting the expected magnitude of the peak and, in particular, provides longer lead times compared to other techniques given that it can be used purely with forecast rainfall.

The main factor affecting the variability of runoff response to rainfall is catchment wetness - the wetter the catchment the higher the runoff for the same rainfall depth. For this reason, historic events have been grouped according to the approximate SMD at the beginning of the rainfall events.

The total rainfall depth was plotted against the rainfall duration and the resultant peak flow (or level) labelled against each data point. From this, contours of approximately equal peak flow or level can be drawn, using the point values as a guide. Where possible, flow data is used for the analysis as level can be influenced by other factors such as channel hydraulics and the operation of control structures.

Discussion on expected results

Hydrological theory would suggest that the expected flow response to rainfall would exhibit a relationship like the one shown in Figure 11, where the higher peak flows are expected for higher rainfall depths and for rainfall that is more intense (shorter duration). However, the results of the analysis did not always show this to be the case. The results sometimes show a relationship similar to that depicted in Figure 12 in which peak flow increases with increasing rainfall depth but not always for shorter durations.

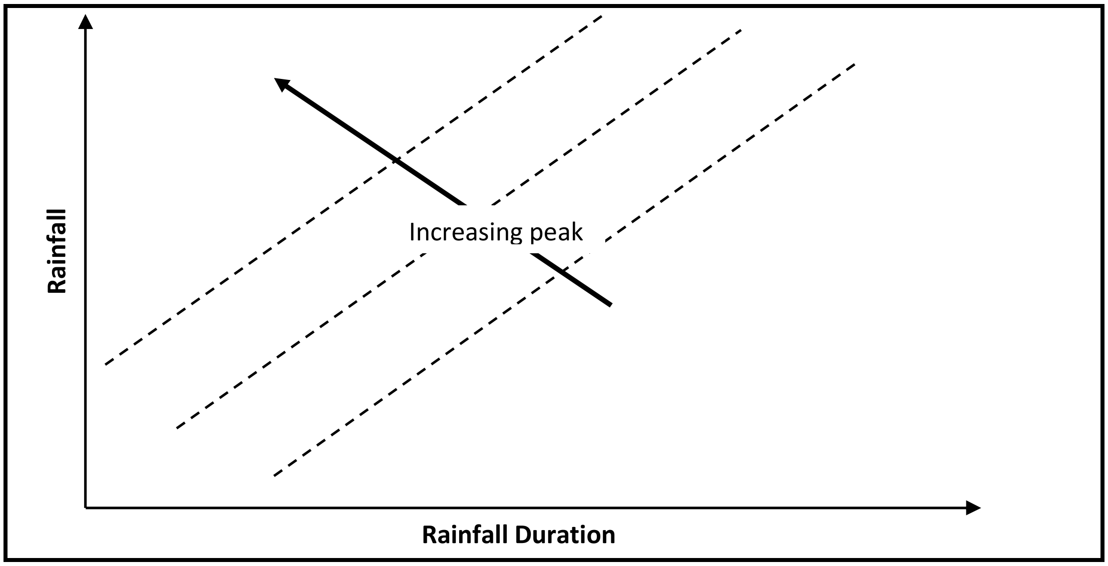

Figure 11 - Theoretical rainfall correlation, particularly for fast responding catchments

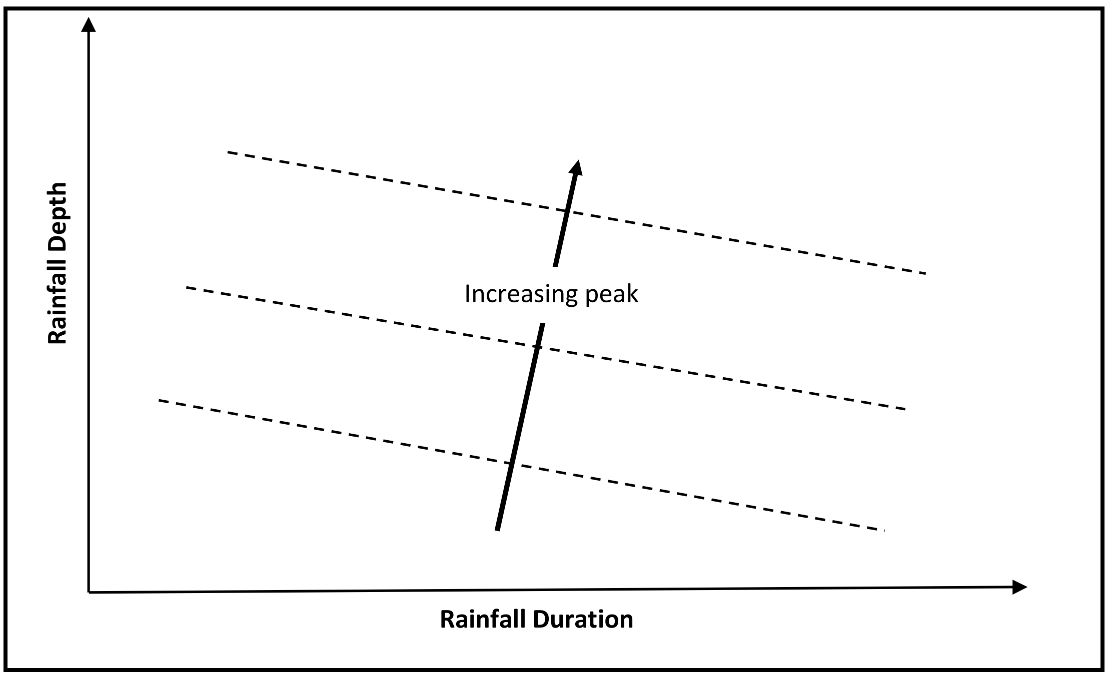

Figure 12 - Observed rainfall correlation (illustrative only) for slower responding catchments

Results Format

The time and magnitude of the peak level or flow, contributing rainfall and the SMD values were then processed; events with similar SMD values were grouped into up to three categories. Where more than five events occurred in any category, these were plotted (see Figure 13 for an example). Where possible to do so, contours were drawn on the plots to represent lines of equal flow or level peaks for different rainfall depth and duration.

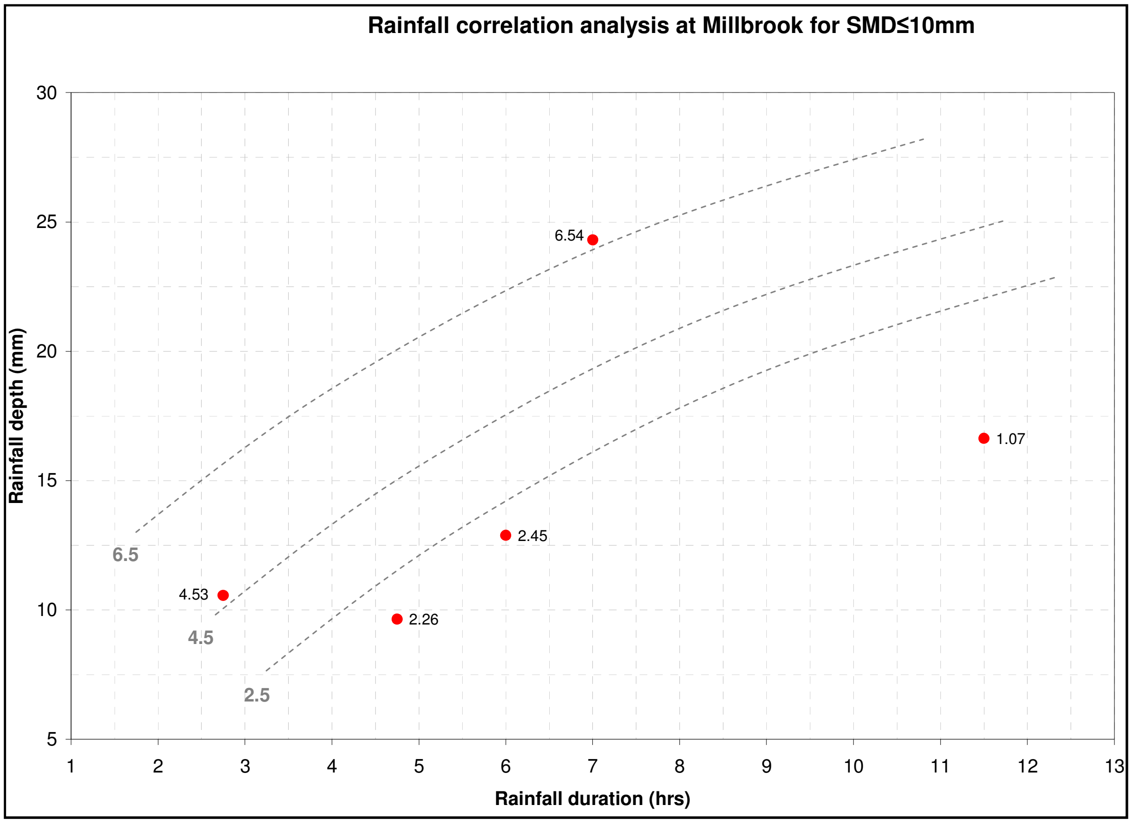

Figure 13 - Example rainfall correlation plot with contours of response

Peak-to-peak correlation

Peak-to-peak correlation relates peak level or flow at a donor station to a forecast point to enable a prediction of level or flow to be made at the forecast point.

The primary requirement for developing a peak-to-peak correlation is that there are sufficient event data at both the forecast point and the donor station. When the data points are plotted on a graph a best-fit line can be fitted through the points to determine if a relationship exists. An example graph is shown in Figure 14.

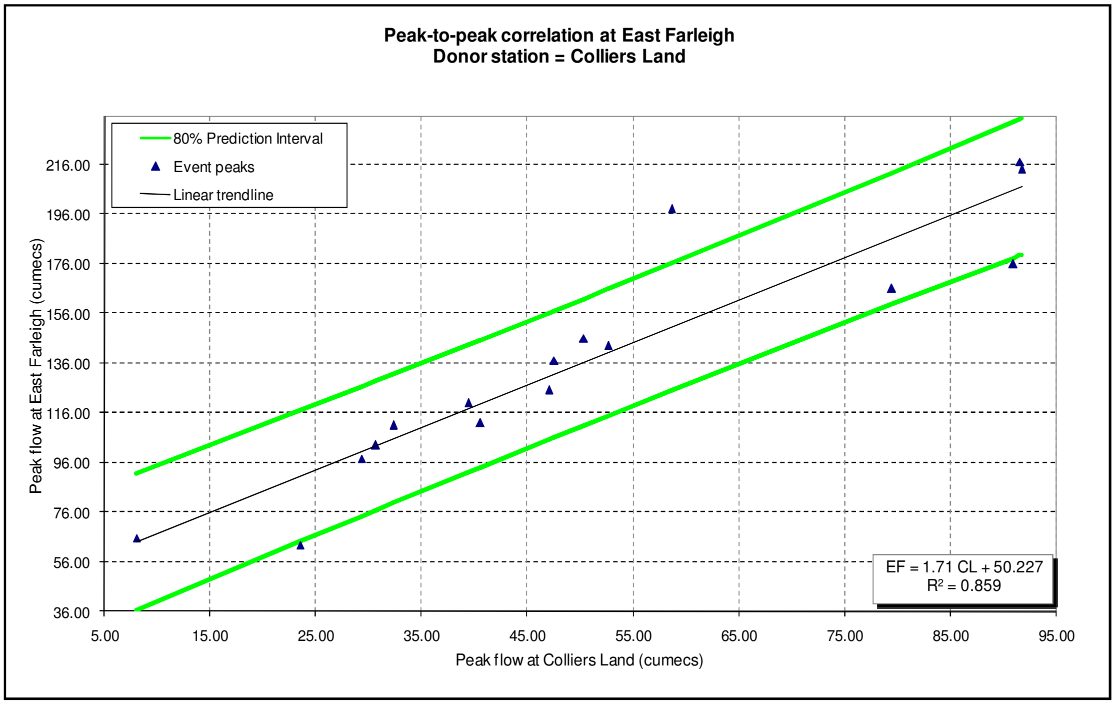

Figure 14 - Peak to peak correlation plot

Confidence in the correlation increases with the number of events that are included within the analysis and the goodness of fit measure (R^2). In this case R^2 is understood as the coefficient of determination of a linear regression and not the Nash-Sutcliffe coefficient of the predictive efficiency of a hydrological model.

Confidence limits can be generated for each regression line to show the range of predictions that could be made with a certain degree of statistical confidence. This helps users assess the level of confidence in the correlation and understand the degree of uncertainty at each site, based on historical events. The green lines on Figure 14 describe the upper and lower bounds of the 80% confidence limits.

Identification of donor stations

A key element in this technique is the identification of suitable donor stations. Donors were selected on the basis of their location relative to the forecast point and data quality/availability. For obvious reasons, it was not possible to develop this technique at the most upstream forecast point in each tributary or for watercourses with only one forecast point. The use of GIS data to understand the spatial relationship between the points is highly recommended.

A further selection criterion was the travel time between the stations, as a short travel time will be of less use than a long travel time for forecasting. Hence, correlations with longer travel times were prioritised. Correlations were not undertaken between two forecast points immediately upstream and downstream of a structure as operationally they were deemed to be of limited use.

Catchment lag analyses

The time between the centroid of the hyetograph and the resultant peak flow in the river (see Figure 15) is referred to as the 'Catchment Lag' in the Flood Estimation Handbook (FEH). It is useful for forecasting purposes as it provides information on the typical response time at the forecast point for a range of events and conditions (antecedent catchment conditions, rainfall duration and rainfall total). During a flood event this information can be used to estimate the time of peak flow at a particular forecast point.

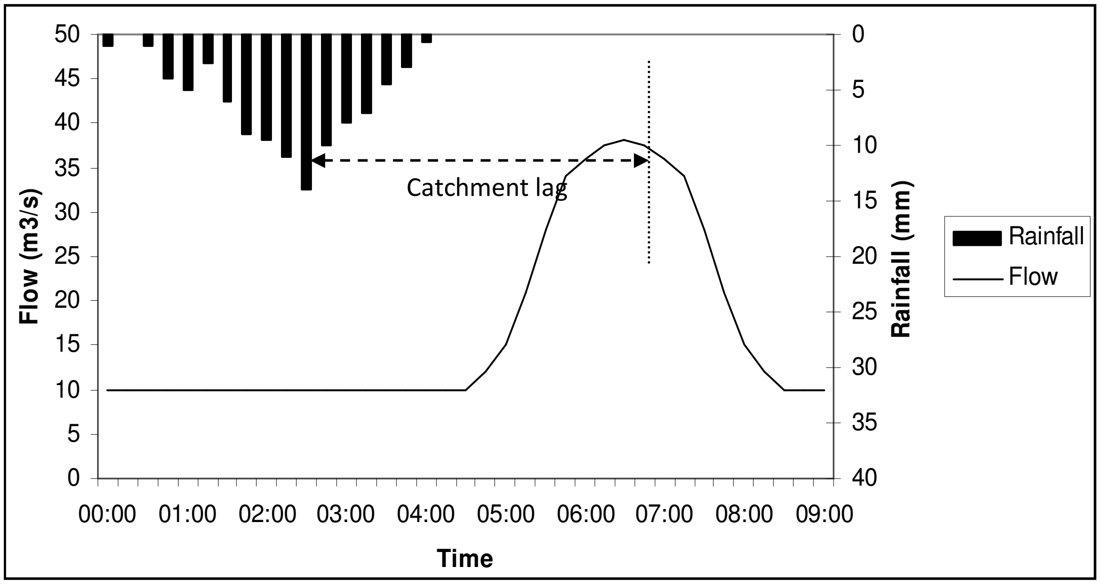

Figure 15 - Catchment lag

Catchment lag analysis was undertaken for up to 15 events per forecast point, incorporating the highest peak events and a wide range of high flow / flood event magnitudes.

The primary criterion for selecting suitable events was that the peak of the hydrograph should be clearly identifiable, allowing the time of peak to be clearly established. Single-peaked events are most appropriate for analysis, as identification of the contributing rainfall for multi-peaked events is ambiguous.

Selection of the start and end times of the contributing rainfall to a hydrograph peak requires hydrological judgement and is necessarily a somewhat subjective task. It is important to have clear records of the assumptions made such that they could be re-examined should the results need repeating or updating in the future.

The results were collated into summary tables that are categorised by SMD, in order to group results into similar catchment wetness conditions. The wetter the catchment the higher the expected level / flow peak would be per unit depth of rainfall as runoff rates are typically higher.

Results

For this technique to be of use operationally at any given forecast point, the variation of the catchment lag should ideally be small. The smaller the variation, the more certain the estimation of when the peak will occur.

For smaller catchments, especially those where there is only 1 forecast point, the confidence that can be placed in these results is lower. However, where there are multiple forecast points in a catchment, a comparison can be made of how the catchment lag increases downstream: this is exemplified by the Meon catchment, as detailed below.

It can be seen from Figure 16 that the forecast point at East Meon has the shortest catchment lag, and Titchfield by far the longest. The other forecast points do not take exactly the order expected mainly due to the already mentioned complex hydrogeology within this catchment.

SMD Range A	Mean catchment lag (hours from centroid of contributing		
Forecast Point	SMD ≤ 10	10 < SMD ≤ 100	SMD > 100
East Meon	3.9	3.4	N/A
West Meon	6.9	9.5	N/A
Mislingford	7.9	4.5	N/A
Wickham	6.1	5.8	N/A
Titchfield	10.5	15.5	N/A

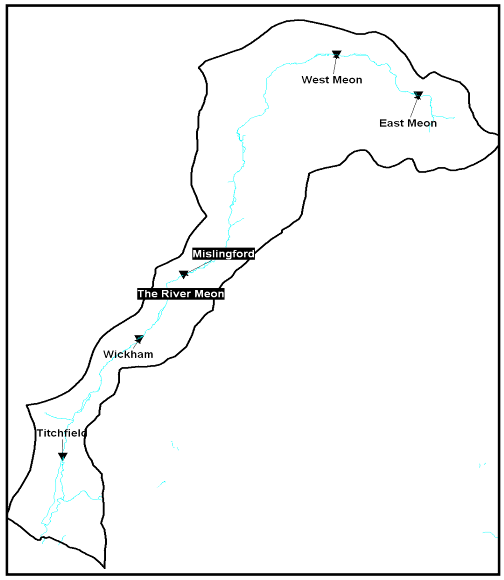

Figure 16 - Illustration of Meon catchment lag work

Travel times analyses

Travel time analysis was undertaken between the forecast points at which peak to peak correlations were developed to provide a method of predicting the expected time of peak when using the peak to peak correlations. This was carried out by using actual event data. The analysis showed that the travel time varies quite widely from event to event between any two forecast points in many of the catchments, with only a small proportion showing consistent travel times.

It was found that plotting the travel times against the peak flow (or level) at the upstream forecasting point (Figure 17) is the most useful format to derive conclusions.

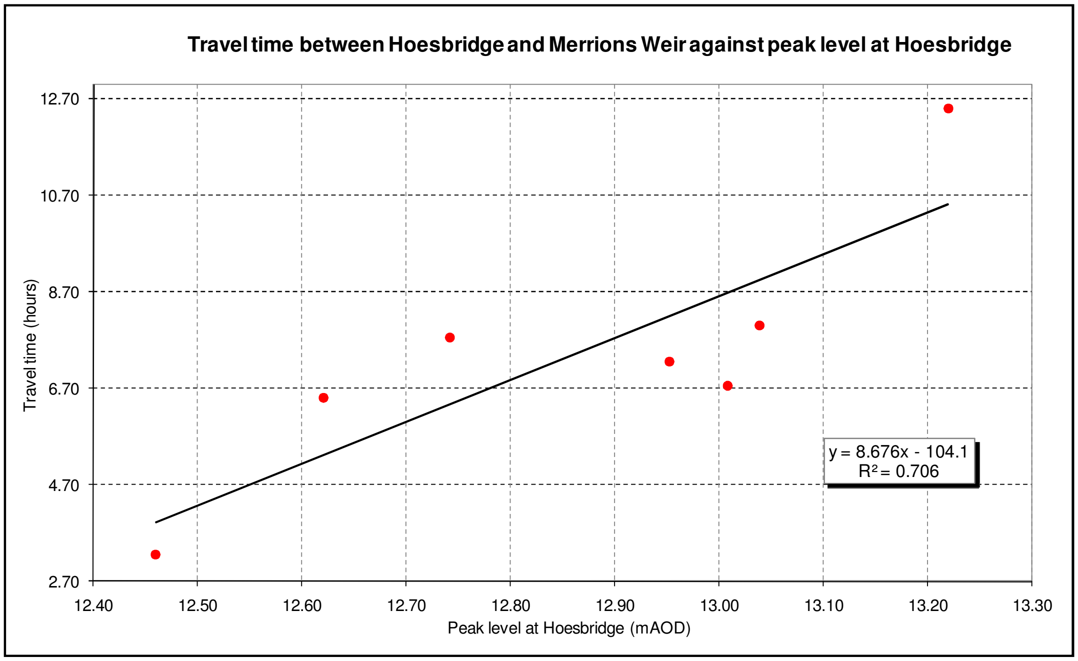

Figure 17 - Plot to show relationship between peak level at upstream donor and travel time

Event rarity analysis

Event rarity analysis provides forecasting duty officers with information on the estimated rarity of a range of historic flood events at each forecast point. The return period of the flow peak is estimated, as is the return period of the contributing rainfall. The rainfall return period is estimated using the depth-duration frequency (DDF) module in FEH. This information helps forecasting duty officers put the current or expected flood event in context with past flood events, which can help determine the likely impact and required resources to effectively manage the event.

An example of the event rarity analysis information collated at each forecast point is presented in Figure 18.

Event rarity analysis

Forecast point	Crowhurst Bridge
Catchment	Rother

Peak flow estimates

Critical Design Storm Duration (hrs) [ReFH only]	13

Return period (years)	Peak Flow (m^3/s)	Source	Rainfall Depth (mm)
5	40.8	ReFH	40.7
10	48.8	ReFH	49.1
25	59.5	ReFH	62.2
50	69.6	ReFH	74.1
100	82.0	ReFH	88.2
200	97.5	ReFH	104.8

Top 6 events				Associated rainfall data		
Date	**SMD**	**Peak flow (m^3/s)**	**Approximate flow return period (years)**	**Depth (mm)**	**Duration (hrs)**	**Approximate rainfall return period (years)**
5/11/2000	0	57	15-25	46.3	10.25	10-15
30/10/2000	1	44.1	5-10	61.5	40.50	05-10
1/12/2000	0	35.2	<5	27.6	14.75	<5
13/01/2004	0	28.9	<5	20.3	20.00	<5
24/10/2006	20	27.3	<5	Rainfall data issues		
26/02/2002	0	27	<5	25.6	15.75	<5

Figure 18 - Example of event rarity analysis at Crowhurst Bridge

Flood warning dissemination

The Environment Agency flood forecasting teams routinely run the forecasting models in real time, running them at least once every six hours. At the same time, river levels & flows and rainfall are remotely monitored. If a pre-determined water level threshold is forecast to be exceeded, a decision regarding whether to issue a flood warning is taken based on guidance in the flood warning procedures. Figure 19 shows the three impact-based warning codes currently used by the Environment Agency.

Figure 19 - Flood warning codes used in England and Wales

Level thresholds relating to Flood Alert, Flood Warning and Severe Flood Warning conditions are usually defined at river monitoring stations. Accurately forecasting the time of exceedance of the flood warning thresholds is important to ensure that flood warnings are issued in a timely manner. Real time forecasts from the National Flood Forecasting System are the primary source of quantitative forecasts, supported by the contingency methods described previously.

Potential inundation areas for a range of 'design' events are determined 'off line' using hydraulic models such as TUFLOW and ISIS. This mapping data is combined with receptor data (properties) and level data to define flood warning zones and to help with the development of flood action plans, including evacuation procedures, for the different risk areas. Figure 20 shows an example of a flood map that has been delineated into different risk areas, which has then been used to help plan evacuation procedures.

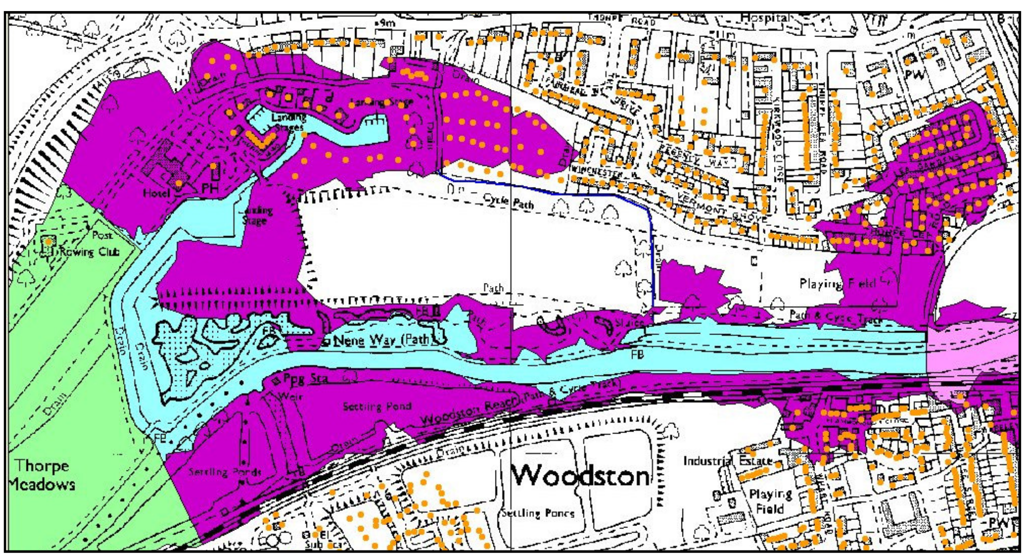

Figure 20 - Example of flood warning zones (coloured polygons) and properties at risk

Flood warnings are issued to those at risk in the flood warning zones using the Flood Warnings Direct service. The automated message provides details of the flood warning, including sources of further information and recommended actions. The flood warnings are also disseminated to the emergency services and local authorities. Emergency plans may then be instigated in order to mitigate the impacts of flooding.

Conclusions

Significant investment has been made in real-time flood forecasting in the UK over recent years. Compared to more traditional measures of flood risk management, such as constructing flood defences, flood forecasting and warning can provide a cost-effective method of mitigating the impacts of flooding. This also reflects the fact that it is not cost-effective to build flood defence schemes at all locations where there is a risk to people and property from flooding.

The examples of hydrodynamic flood forecasting modelling described in this paper are typical of the standard approaches used in the UK. The outputs of these models provide forecasting duty officers with the key evidence to inform the issue of flood warnings (especially when supported by information on the expected performance of the models at different lead-times).

Although the current effort on improving the forecasting capability in the UK is focussed on hydrodynamic modelling and use of probabilistic analysis methods, there remains the need to develop and maintain contingency flood forecasting techniques for use in case of failure of the primary methods. This paper has presented a set of simple but effective contingency tools, based on simple empirical forecasting techniques, which can readily be used by forecasting duty officers.

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