BOSCASTLE AND NORTH CORNWALL FLOODS, AUGUST 2004: IMPLICATIONS FOR DAM ENGINEERS.

Dr R. BETTESS, HR Wallingford
V. BAIN, HR Wallingford

SYNOPSIS On the 16 August 2004 over 180 mm of rainfall in 5 hours caused severe flooding in the River Valency and adjacent catchments. Following the flood event, HR Wallingford, CEH Wallingford and the Met Office jointly carried out a study to understand the flood and to determine the peak discharge. The flood in Boscastle was one of the best recorded extreme flood events in the UK and there was good photographic and trash mark evidence from the flood.

The hydrological and hydraulic simulations of the flood showed that the application of standard Flood Estimation Handbook methods did not reproduce the observed flood characteristics very well. A better simulation was provided by assuming high values of the Percentage Runoff and halving the Time to Peak of the unit hydrograph. This modification to the Time to Peak is more extreme than that recommended by the Flood Studies Report for dam studies. This has implications for the methods that should be used when assessing the Probable Maximum Flood for dams on small, steep catchments. The implications for dam engineers are discussed.

INTRODUCTION

Boscastle entered the UK's flood annals, in dramatic fashion, on 16th August 2004. Prolonged heavy rainfall centred over Otterham, on the edge of Bodmin Moor near the North Cornwall coast, led to severe flooding in a number of river catchments. Those most affected were the River Valency and the Crackington Stream, but flooding and damage also occurred on the River Ottery and the River Neet. Mercifully, no one was killed; but the event scarred the landscape, caused damage to buildings and infrastructure.

To understand the event studies were undertaken on behalf of the Environment Agency by a consortium led by HR Wallingford, with a brief to report early findings within a few weeks and considered conclusions within a few months of the event. The work amounted to assembling forensic evidence, reconstructing the characteristics of the event and deducing its causes, on the basis of best available data and methods. The meteorology of the event was analysed by the Met Office; the hydrology by CEH Wallingford; the hydraulics and geomorphology by HR Wallingford. Halcrow and Royal Haskoning undertook post-flood surveys (in the Valency/Jordan and Crackington Stream catchments, respectively), and they and the Environment Agency assembled witness evidence from local interviews. The project team's final report (HR Wallingford, 2005) contains full details of the analyses undertaken and the conclusions reached. The work pointed to shortcomings in the current procedures used to predict extreme floods on small catchments and so has implications for dam engineers concerned with estimating Probable Maximum Floods on such catchments. This paper reflects on the implications of the findings of the studies for dam engineers. Whilst the floods affected both the Valency/Jordan and Crackington catchments, this paper concentrates on the Valency/Jordan catchment only.

THE CATCHMENT

Figure 1 shows the geographical location of the Valency river and its tributaries above Boscastle; the locations shown refer to points at which inflow hydrographs were derived. The catchment is located on the north coast of Cornwall. The catchment area above Boscastle is approximately 20 km^2. The catchment rises to approximately 300m AOD and the main branch of the River Valency is approximately 7 km long. Thus the slope of the river is steep. There are a number of tributaries which are also steep, and some of them are incised as they approach the main channel. The soils are generally thin over impermeable bedrock. The catchment is predominantly rural with much of the land given over to grassland. There are significant areas of woodland adjacent to the main river and its tributaries.

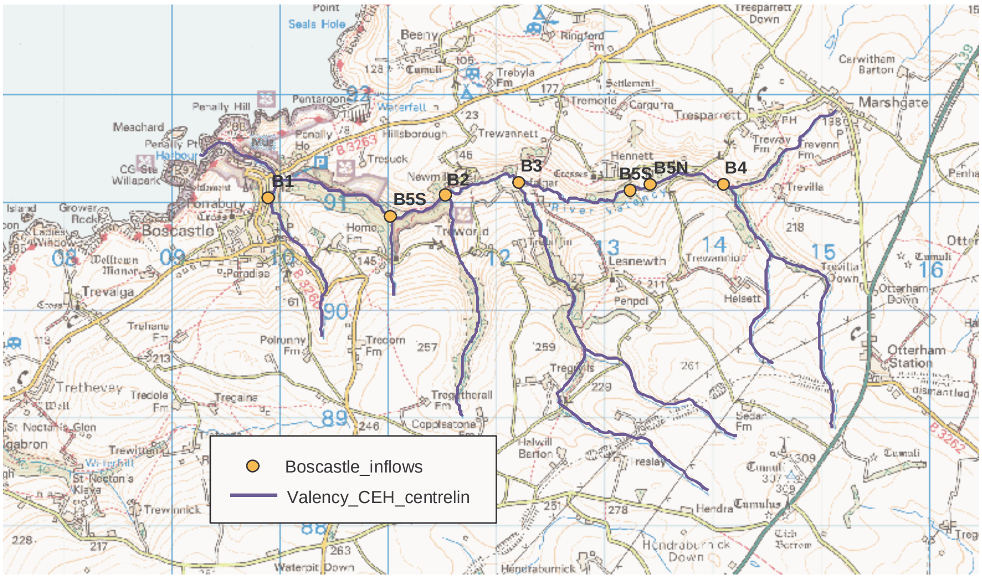

Figure 1 The Valency catchment above Boscastle, showing the river and main tributaries, and points at which inflow hydrographs for hydraulic modelling were calculated.

THE FLOOD EVENT OF 16TH AUGUST 2004, AS WITNESSED

The flooding of Boscastle on 16th August 2004 must be one of the best-recorded extreme flood events in the UK and there is a good photographic record of the event. The evidence indicates that the flood was out of bank for around 5 hours, rising to a peak (from the bankfull stage) in 1.5 hours. As the flood rose, some individuals reported very rapid, short-term rises in water level of 1 to 1.5 metres ("walls of water") in periods of a minute or less.

RECONSTRUCTION OF THE RAINFALL EVENT

The area around Boscastle experienced extreme rainfall accumulations resulting from prolonged intense rain over a four hour period from 13:00 to 17:00 BST (1200-1600GMT) on 16th August 2004. The exact track of the rainfall cells varied slightly during this period, but between the Camel Estuary and Bude the variation was sufficiently small to ensure that the heaviest rain fell into the same coast-facing catchments throughout the period. The intensity of the precipitation was probably enhanced by large-scale uplift associated with larger scale weather troughs.

The Tipping Bucket Rain gauge (TBR) at Lesnewth recorded maximum short period accumulations of 68mm in 1 hour, 123mm in 3 hours, and 152mm in 5 hours. Comparison with the quality controlled check gauge indicates that these should be increased by 20% to 82mm, 148mm & 183mm, respectively, to allow for under-reading by the TBR. The

Lesnewth TBR also recorded a peak rain rate of nearly 300mm/hr at about 16:35 BST (1535 GMT).

Observations of the spatial and temporal pattern of precipitation were well captured by the Cobbacombe and Predannack radars. Maximum values over $4km^2$ pixels differed from those observed by the TBRs due to sampling differences, but the overall pattern was consistent. The highly localised character of the event can be seen clearly in the sharp spatial gradients of the Cobbacombe Cross radar data, in Figure 2. Note the high values around the SW-NE track through Lesnewth and Otterham, and the sharp reductions in rainfall totals away from it.

The FORGEX method (NERC, 1999) was used to assess the probability of occurrence of the observed rainfall. The adjusted, observed maximum one-hour fall at the Lesnewth TBR of 82 mm has an annual probability of occurrence of around 0.13%. The three-hour total, again at Lesnewth, is comparable with the Camelford flood in 1957, and with several events in other parts of the country, most of which were accompanied by large hailstorms. The annual probability of occurrence is about 0.08%. The overall storm has an annual probability of occurrence less than 0.05%, which is larger, that is, less extreme, than that of the 1953 Lynmouth event and the 1955 Martinstown event. It is notable that all three events covered very small areas.

The South West peninsula has been subjected to six extreme rainfall events in the last century, of which three occurred in the decade 1951-60. The point ($1km^2$) probability deduced from an examination of these events indicates a similar annual probability to that derived using the FEH method. Allowing for the sparse observational network, the evidence indicates that an extreme rainfall event will occur somewhere in the South West region once every 20 years, on average.

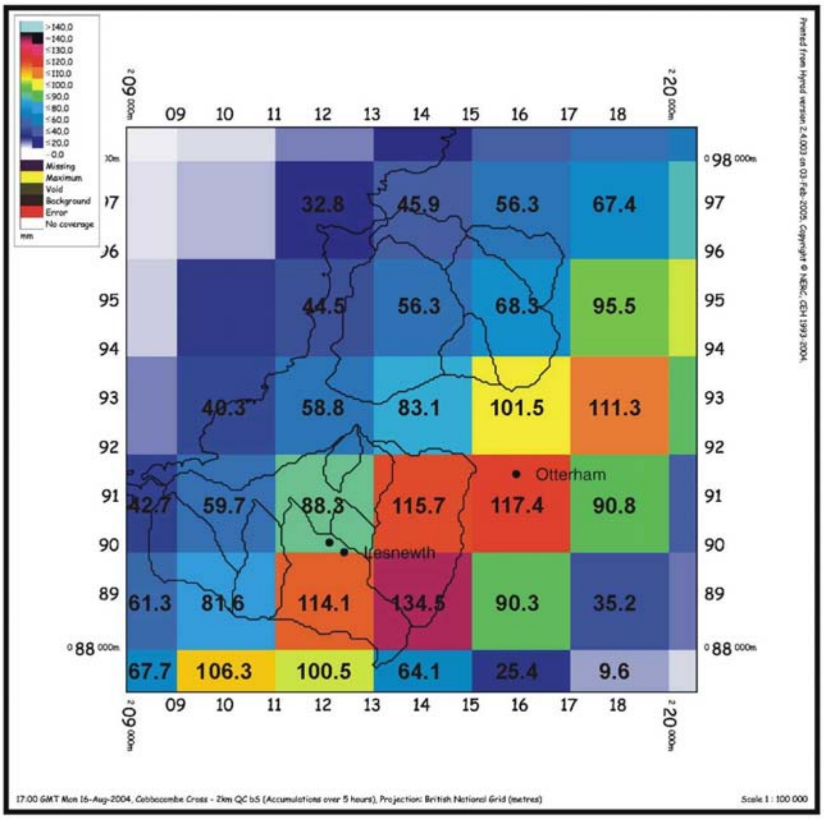

Figure2: 2 km gridded rainfall estimates based on data from the Cobbacombe Cross radar

HYDROLOGICAL & HYDRAULIC MODELLING OF THE FLOOD EVENT

Modelling strategy

Integrated hydrological and hydraulic modelling was undertaken to simulate, and thereby understand, the rainfall-runoff transformation and the development and passage of the resultant flood through the catchment. Using the available rainfall radar data as input, hydrological modelling was used to generate discharge hydrographs for selected sub-catchments of the Valency system. These flows were then routed down the catchment using a hydraulic model to generate discharge and stage hydrographs in Boscastle. Modelled stage hydrographs were compared with wrack mark and eye-witness accounts of flood levels, with the parameters of both the hydrological and hydraulic models being calibrated in reasonable fashion so as to achieve best-possible representation of the characteristics of the flood event by the hydraulic model.

IMPROVEMENTS IN RESERVOIRS

Hydrological modelling

The currently accepted 'best UK methodology' for flood flow estimation is provided in the Flood Estimation Handbook (FEH; Institute of Hydrology 1999). Its focus and methods are geared towards more commonplace floods than those that affected the North Cornwall coast in August 2004, but it remains the only practical tool for modelling flood events on small ungauged catchments in the UK. The flooding at Boscastle from the Valency and Jordan catchments was very severe, and in consequence, difficult to reproduce reliably using FEH methods, as will be clear from what follows.

In the absence of flow records, the required parameters for rainfall-runoff estimation were determined using the standard FEH procedures for ungauged catchments. The required (spatially complete) rainfall data for the Valency catchment was derived from rainfall radar data, normalised to agree broadly with the adjusted rain gauge data. To obtain agreement with the best indications of water levels at given times and places (as obtained from eyewitness accounts and from wrack mark levels), it proved necessary to make a number of adjustments to parameters in the FEH method. To obtain reasonable agreement with best evidence flood levels, the time to peak had to be reduced by 50%, and the percentage runoff had to be adjusted, iteratively. The FEH constant percentage runoff (PR) was replaced by a time -varying PR related to antecedent and developing conditions. PR at the start of the event was calculated using the FEH methodology, but was then increased as the storm proceeded, according to the formula given below, to reflect the progressive wetting of soils and the expansion of the variable contributing area of the catchment:

$$PR_t = PR_{urb} * (1 + 0.8(\sum P_t/P_{TOTAL})$$

where PR_t is the percentage runoff at time t during the storm, PR_{urb} is the FEH design percentage runoff derived from soil and storm rainfall total, $\sum P_t$ is cumulative rainfall from the start of the storm to time t, and P_{TOTAL} is the rainfall total for the entire storm.

The factor of 0.8 was determined empirically, as that needed to generate the necessary gearing factor to increase PR_{urb} from the FEH initial condition to the 85 to 95% values that probably prevailed towards the end of the storm. The high percentage runoff towards the end of the event, coupled with the steep slopes of the catchment, undoubtedly led to high volumes of fast flow running off from increasing areas of the catchment. The destruction of field walls, the under-mining of roads and tracks, and the washing away of fords in the upper parts of the catchment testify to the occurrence of significant, fast-flowing torrents running overland. The departures required from the standard FEH methodology were, in the circumstances, deemed reasonable and understandable.

Hydraulic modelling

Floodwater flows and levels were simulated with an INFOWORKS-RS model of the Valency river system. The model was constructed using post-flood cross sections and structure survey data. No pre-flood data were available. The observed pattern of flow through the streets of Boscastle was represented as a multiple channel arrangement, with flows through and between the various channels being controlled by appropriate spill structure placements and parameters. The model was calibrated, on water level and timing, by reference to observed wrack marks, photographs, video and eye-witness accounts. As noted earlier, the available degrees of freedom in the hydrological and hydraulic phases of flood modelling were co-varied iteratively, to achieve the net best possible (and believable) end result. In the event, it proved necessary both to vary the standard FEH parameters to produce flows of sufficient magnitude, and to model significant blockage of the bridges in order to match water level predictions from the model to the observed profile of peak water levels.

Figure 3 shows the peak level calibration of the final model in the reach above its downstream boundary. The water level effects of the B3263 road bridge at chainage 350m and the smaller bridge at chainage 170m show clearly.

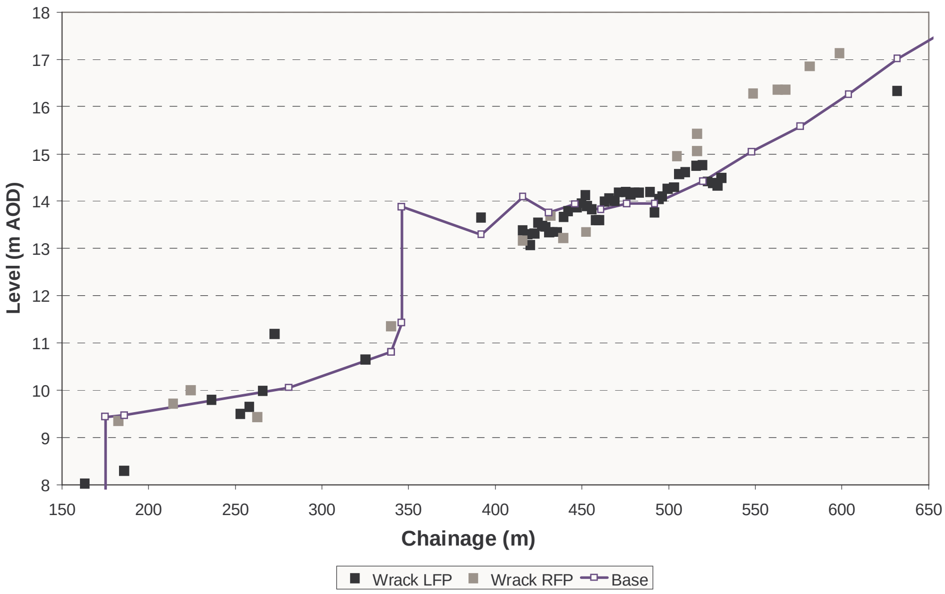

Figure 3 Predicted water levels and observed wrack mark levels in Boscastle. LFP denotes a Left-bank Flood Plain wrack mark. RFP denotes a Right-bank Flood Plain wrack mark.

The predicted peak discharge in the centre of Boscastle was approximately 180 m^3/s. This compares with FEH estimates of the Q_{med} (the median annual flow) at Boscastle of 4 m^3/s and of the 1% annual probability flow from FEH statistical modelling and rainfall-runoff modelling of, respectively, 10.4 m^3/s and of 34.8 m^3/s.

THE EXCEEDANCE PROBABILITY OF THE 2004 FLOOD

The history of flooding in Boscastle and elsewhere in the Valency catchment includes evidence of notable events as long ago as 1824. More recent floods occurred in 1950, 1958 and 1963. A best possible representation of the flood frequency curve of the Valency/Jordan at Boscastle, derived from a combination of FEH statistical and rainfall-runoff methods, supported by historical evidence and considerable judgement, is given in Figure 4. A GEV Type II probability distribution appears to fit the Boscastle data and estimates best. It is clear that the 2004 flood event was a very extreme event. Its estimated annual exceedance probability was 0.30%, the equivalent of a 1 in 350 years return period. The GEV Type II curve indicates that the return period of an event of that magnitude might be as extreme as 1 in 450 years – an annual probability of 0.22%. On the basis of the available data, and recognising the uncertainties involved, it seems reasonable to conclude that the annual probability of a Boscastle-scale flood is around 0.0025.

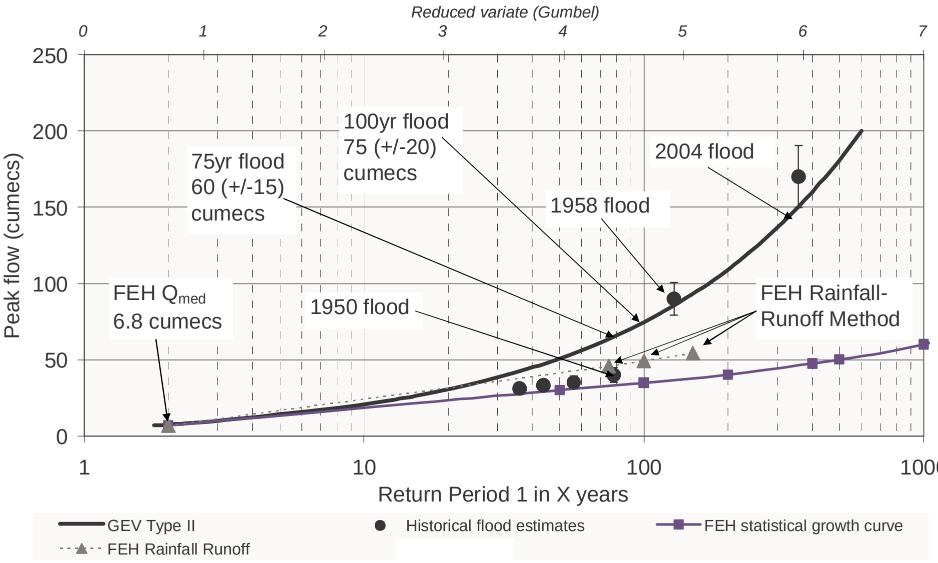

Figure 4 Estimated flood frequency curve for the Valency/Jordan catchment at Boscastle

LIMITATIONS AND UNCERTAINTIES OF DATA, MODELS AND ESTIMATES

The various models used and the various estimates produced with them are based on a set of assumptions and are subject to a range of uncertainties, in both the base data and in the representation of physical processes and conditions within the models.

It is clear from the rainfall radar data that the area of the rainfall event was limited, and that the spatial gradients of rainfall were large. The spatial resolution of the radar is only 2 km, which is coarse in comparison with the spatial gradients of the rainfall. In addition the catchment is near the limit of the area covered by the rainfall radar, and the data from the two rainfall radar stations do not always agree.

Hydrological and hydraulic modelling of such an extreme event is more uncertain still. The FEH method places proper reliance on available hydrological data, but there are little data available from similar catchments within the South West region, and for storms with the rainfall experienced in August 2004. Standard FEH methods had to be varied to simulate the extreme character of the rainfall-runoff processes experienced in the August 2004 event. Thereafter, the hydraulic model had to be constructed using post-event survey data, in the knowledge that wrack marks could not necessarily be relied on as peak water levels in a channel subject to such change as occurred during the flood. The division of flow down the various streets of Boscastle depends upon local features which are difficult to reproduce within a numerical model. The Froude number of the flows through the centre of Boscastle was relatively high, and this introduces numerical uncertainty into the hydrodynamic modelling. A further complication is added by the changes that took place during the event. The blockage of the bridges in Boscastle has already been discussed above. In addition walls and buildings were destroyed during the event. This means that a description of the topography of the floodplain at the start of the event is not appropriate for the end of the event. All these effects add to the uncertainty in the modelling.

EXPLANATION OF LOCAL HYDRAULIC PHENOMENA

Eyewitnesses testified to the occurrence of a number of transient, but significant, rises in water level at various places and times, during the flood. Many observers believe that the rapid increases in water level they observed during the flood event were caused by the rapid and progressive failure of blockage or trash dams in a downstream sequence. The most likely explanations for such local hydraulic phenomena, however, would seem to be blockage of a flow route, with subsequent diversion or failure. Scenario testing with the hydraulic model indicated that rapid blockage of the bridge led to rapid increases in water level upstream of the bridge, and a significant re-distribution of flow into the streets of Boscastle. Thus rapid blockage of the bridge could have led to sudden changes in flow route, and to the observed rapid rises in water level.

ESTIMATION OF THE PROBABLE MAXIMUM FLOOD (PMF)

The Flood Estimation Handbook (FEH) recommends that the estimation of the PMF is determined using the estimated Probable Maximum Precipitation (PMP). The FEH recommendation is then to use a unit hydrograph approach to determine the PMF from the PMP. In carrying out this approach the FEH recommends two modifications to the standard procedure. In determining the unit hydrograph, FEH recommends that the Time to Peak is reduced by one third, that is, the standard value is multiplied by 0.67. This has the impact of increasing the estimated peak discharge by a factor of 1.5 but does not affect the overall volume of water within the PMF. In addition when calculating the PMF, FEH also suggests that an allowance can be made for frozen ground by increasing the standard percentage runoff to 53%.

To get a satisfactory agreement between the modelling and the observations on the Valency a number of changes had to be made to the FEH approach. The Time to Peak was reduced to one half of the value derived from catchment predictors while the Percentage Runoff was increased so that it approached 90% towards the end of the event. If a similar reduction in the Time to Peak was used in estimating the PMF then the peak discharge would be increased by approximately 17% in comparison with the method described in the FEH.

The modelling of the Valency catchment suggested that towards the end of the event the instantaneous Percentage Runoff was high and higher than that which would be estimated for such a catchment using standard FEH methods. If such a Percentage Runoff were used to estimate the PMF then this would have the impact of increasing the overall volume of the flood. The increase in the flood volume depends upon the specific catchment characteristics but could approach 100%.

A study of extreme events in the UK has not shown any detectable variation in the location of extreme rainfall events. This implies that one must assume that a rainfall event of similar severity to the Boscastle event could occur anywhere in the country with the same probability. It has been estimated that the annual probability of a similar rainfall event somewhere in the country is approximately 30%. There is no evidence to suggest that the frequency of such extreme events is changing through time.

The FEH method is based on extensive data sets containing thousands of records and so there is a danger in drawing conclusions from just a single event. The implication of the modelling of the North Cornwall, however, would suggest that the present methods for estimating the PMF when applied to small steep catchments may underestimate the peak discharge and overall volume of the flood. Until such times as these issues are resolved, it would appear to be prudent for dam engineers to be aware that using the presently recommended FEH methods to determine the PMF from the PMP may underestimate both the peak discharge and flood volume.

From the above the issue arises as to how small and how steep a catchment has to be before there is a significant impact on the predicted PMF. The Valency catchment has an area of 20 km^2. Within the FEH database approximately 15% of catchments have an area smaller than 40 km^2. It would seem prudent that special attention is given to any catchment with an area less than 60 km^2. Within the FEH the average slope of the catchment is represented by the parameter DPSBAR which is the average slope of the channel network. The value of DPSBAR for the Valency catchment is 115m/km. This value is exceeded by more than 20% of the catchments within the FEH database. It is tentatively suggested that the values of Time to Peak and Percentage Runoff determined from FEH are modified for any catchment with both an area less than 60 km^2 and a DPSBAR value greater than 110m/km. This is based purely on the experience from the Boscastle event and needs to be confirmed by the collection of additional data of extreme events in small steep catchments.

CONCLUSIONS

Evidence and analyses indicate that the Boscastle flood of 16th August 2004 was unusual in origin, highly localised in extent and extremely rare in occurrence.

The rainfall event of the 16 August 2004 was brought about by an extremely unusual combination of circumstances, none of which are rare but their combination is extremely so. Using FORGEX, it has been estimated that the annual probability of occurrence of the rainfall event is less than 0.05%. The South West peninsula has been subjected to six extreme rainfall events in the last century, of which three occurred in the decade 1951 to 1960. Allowing for the sparse observational network, the evidence indicates that an extreme rainfall event will occur somewhere in the South West region once every 20 years, on average. There is at present no clear-cut evidence to suggest that long-term climate change may be affecting the probability of such extreme events.

IMPROVEMENTS IN RESERVOIRS

The flood event on the Valency was modelled using a combination of hydrological and hydraulic models. A number of changes had to be made to the standard FEH methodology in order to simulate the hydrological processes. The Time to Peak had to be reduced to 50% of that predicted by using standard catchment descriptors. In addition a variable Percentage Runoff regime had to be used, which increased from an initial value determined through the standard soil and storm rainfall total calculated, but which then grew to 95% as the catchment wetted up and its effective contributing area expanded.

Modelling suggested that the rapid blockage of the main bridge in the centre of Boscastle would have led to large and rapid increases in water level upstream as a result of changes to flow paths, which is a likely explanation of the reported rapid increases in water levels that occurred during the rise of the flood. The best estimate of the peak flow of the flood in Boscastle is 180 m^3/s.

The implication of the modelling of the North Cornwall would suggest that the present methods for estimating the PMF when applied to small steep catchments may underestimate the peak discharge and overall volume of the flood. Until such times as these issues are resolved, it would appear to be prudent for dam engineers to be aware that using the presently recommended FEH methods to determine the PMF from the PMP may underestimate both the peak discharge and flood volume. It is tentatively suggested that the values of Time to Peak and Percentage Runoff are varied from the FEH predicted values for catchments both with areas less then 60 km^2 and DPSBAR values greater than 110 m/km

ACKNOWLEDGEMENTS

The contents of this paper are based on a study carried for the Environment Agency by a team led by HR Wallingford. Other members of the team were the Met Office and CEH Wallingford. Halcrow undertook the post-flood surveys in the Valency and Jordan valleys, and Royal Haskoning undertook those in the Crackington Stream catchment. The contributions of all parties and individuals involved, including those received from the people of Boscastle and Crackington Haven, are gratefully acknowledged.

REFERENCES

HR Wallingford (2005) Flooding in Boscastle and North Cornwall, August 2004. Phase 2 Studies Report. HR Wallingford Report.

Institute of Hydrology (1999) The Flood Estimation Handbook.