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On the relationship between Probable Maximum Precipitation (PMP), risk analysis and the impacts of climate change to reservoir safety

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1. Background

Defra have recently funded a project entitled 'Reservoir Safety – Long return period rainfall' (WS 194/2/39). This project was led by CEH and involved contributions from the Met Office, the University of Sheffield and the University of Salford. The main output from the CEH team was an extension of the FORGEX statistical methodology for estimating rainfall return periods up to 1 in 100,000. This has involved a revision of the Flood Estimation Handbook (FEH) procedures, which will be published in mid-2009. In addition, work on existing PMP estimation procedures, and the uncertainty of the Flood Studies Report (FSR) PMP estimates has been consolidated.

In parallel with this work, a number of projects being undertaken in the NERC Flood Risk from Extreme Events (FREE) Research & Development programme have a direct relevance for assessing the return periods of extreme events. There remains a need for some clarification of the relationship between the risk based approach of return period analysis now articulated in the revised FEH and within the FREE programme, and techniques of estimating PMP which are still used in engineering practice for dam and spillway design. This short report attempts to provide such clarification and reconciliation. In addition there remains some uncertainty as to how climate change might impact the new FEH procedures, and this topic is also addressed in this report through on-going work in the FREE programme.

2. Joint probability and Depth Duration Frequency analyses

Further research to develop risk analysis to include joint probability analyses is being undertaken in the FREE R & D programme by both CEH Wallingford (Svensson) and Lancaster University (Tawn). Five trial locations have so far been selected with varying soils/geology and climatic characteristics. The CEH work focuses on an event-based joint probability approach, although continuous data series are used to appropriately define the event variables. The characteristics of rainfall events of different durations are being investigated, and some tentative series of monthly rainfall maxima have been derived. Monthly river flow maxima have also been retrieved and plotted together with the associated rainfalls. Convex hull plots have been derived for some of the data, to illustrate the seasonal variation in the dependence between the variables, and in the marginal distributions of the variables. It has been found that independence cannot necessarily be assumed for the flow variables, and serial dependence will have to be incorporated into the joint probability analyses.

Lancaster have concentrated on developing covariate and random effects models for the rate of occurrence of flow events. Covariates used so far include baseflow and a moving average of (lagged) rainfall. The use of random effects was motivated by the observation that the number of events per year is over-dispersed for many UK catchments (even after accounting for covariates). Random effects are useful when there are missing covariates. Investigations of a more theoretical nature have also been made into the effect on the distribution of the annual maxima when different probability distributions are used for the number of events per year and, when included, the random effects. So far efforts have been concentrated on a single site, with considerable time being spent on identifying flow events and their properties. Whilst this work may lead to extensions of the revised FEH approach, it will not provide practitioners with practical tools for some time.

The Flood Estimation Handbook (FEH, 1999) published a growth curve technique (known as FORGEX) for the estimation of rainfall return periods over variable durations. This procedure was developed around a Depth Duration Frequency (DDF) statistical model only applicable for return periods up to about one in several hundred years. Recent work at CEH Wallingford for Defra / EA in the Reservoir Safety-Long return period rainfall Project (WS194/2/39) has presented a new DDF model capable of dealing with return periods of up to one in 100,000 years (Figure 1). This work does not provide estimates of PMP directly, but points the way to a use of a risk-based procedure rather than the current PMP procedure used by reservoir engineers for designing spillways etc. In what follows we suggest how to reconcile initial results from FREE research with this DDF approach. Note that Figure 1 suggests that for some of the stations there might be an asymptotic tendency towards a maximum rainfall for very long return periods.

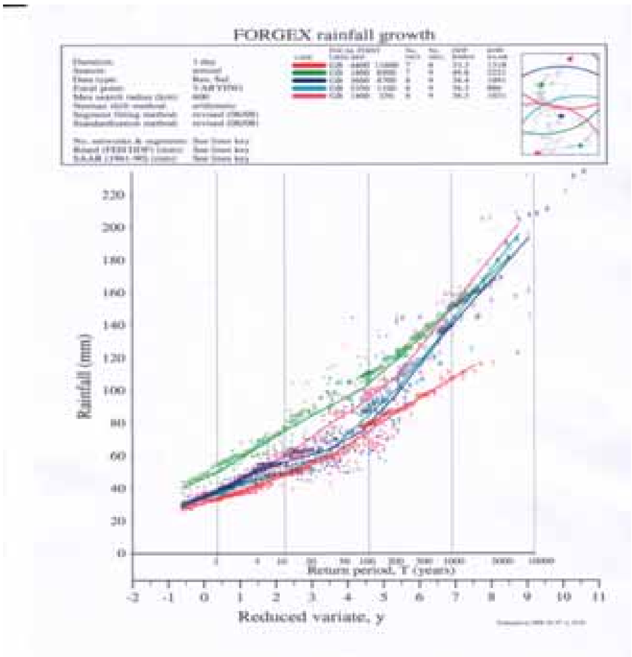

Figure 1: FORGEX growth curves using the new CEH DDF model with a search radius of 600 km around different stations across the UK (1961-1990) (CEH Defra/EA Reservoir Safety Project – Long Period Rainfall Final Report, 2009).

3. PMP and its relationship to risk based statistical analyses of rainfall

By definition the PMP is assumed to be physical upper limit to the amount of precipitation that can fall over a specified area in a given time. One may consider a specific recurrence interval associated with such an amount. Fountaine and Potter (1989) applied a variation of the World Meteorological Organisation (WMO, 1986) approach to a catchment of 220 miles^2 (569.8km^2) in central Wisconsin, USA. An exceedance probability for PMP values ranging from 11 inches to 13 inches was found to be ***3×10^{-5}*** to ***4×10^{-5}*.**

The storm transportation technique remains rather subjective and further work needs to be undertaken. Newton (1980) notes that the probability of a storm producing the PMP over a particular catchment of the Tennessee Valley in the USA has been taken as ***1 in 10^8 years***, with a probability of ***1 in 10^6 years*** defining the upper confidence limit. However, considering a storm antecedent to a storm-producing PMP, given that the total rainfall for the storm sequence should not exceed PMP for that duration, reduced this exceedance probability to about ***1 in 6×10^5 years*** with a probability of ***1 in 2×10^4 years*** defining the upper confidence limit.

With the above in mind one may examine the probability of occurrence associated with PMP implied by the storm model described by Collier and Hardaker (1996). This analysis was reported in the CEH Long return period rainfall project (Collier and Morris, 2008) assuming that the probability of occurrence (frequency) equivalent to the PMP from storms of durations of 10 to 24 hours is likely to be derived from consideration of the storms as Mesoscale Convective Systems (MCSs) (Browning and Hill, 1984). Use of a storm model of such systems reveals that the PMP is associated with a probability of **about 1 to 8×10^5 years.** This is consistent with statistical analyses in the USA and elsewhere, however, these results must be viewed with care as it is not clear how the variables considered are dependent.

Hand et al (2004) have reported depth – durations of all extreme rainfalls in the 20th century. This data set has been extended in the FREE project by digitizing the British Rainfall Archive (McSharry; Hydro-GIS Ltd) and in the DEFRA / EA Reservoir Safety Project by the Met Office (Defra WS 194/2/39 Work Package 1). In the FREE Project all volumes of British Rainfall were obtained, and contact was made with the Met Office regarding the provision of complete digital daily time series for selected rain gauges with records going back to 1860 – the start date of the British Rainfall publication. We discuss this work later.

4. The physical basis of PMP

Work on the development of a hybrid model for predicting the probability of very extreme rainfall is being undertaken in the FREE programme by Imperial College (led by Toumi). Although this research is not yet complete it is already providing useful clarification of the basis of PMP and how it might link to risk analyses. A numerical modelling case study of a very extreme rainfall event is underway. In order to fully understand the response of the model to changes in atmospheric moisture availability, perhaps induced by climate change, a simpler set of idealised experiments are being undertaken. To date, most of the work has concentrated on these idealised experiments.

The US National Centre for Atmospheric Research (NCAR) Weather Research & Forecasting (WRF) model (version 3) is a fully compressible, non-hydrostatic regional atmospheric model that is under constant development through the collaborative efforts of various research and operational institutions worldwide. One of the main advantages it has over other similar models is that it has been developed to enable simulations of a number of atmospheric situations within an idealised framework. This allows the user to fully isolate the effects of changes to any of the forcing mechanisms in the initial conditions or model physics.

For the Imperial College experiments the model is run with a horizontal resolution of 1km on a domain that is 800km in the x-direction and 160km in the y-direction. For 3-D simulations. 80 vertical levels are used with a grid spacing of 250m with the model top at a height of 20km. Open lateral boundary conditions are used at the x boundaries and periodic boundary conditions are applied at the y boundaries. For cloud microphysics parameterisation, a Kessler type scheme is used. This is a simple warm cloud scheme that includes water vapour, cloud water and rain. The effects of Coriolis force, surface physics and atmospheric radiative transfer are not included.

The model is initiated with vertical profiles of temperature and water vapour that are based on a typical condition for strong mid-latitude convection. The vertical profile of wind includes strong shear in the lowest 2.5 km of the atmosphere. Squall lines are initiated by a line oriented thermal perturbation with a x-radius of 5km and vertical radius of 1.5 km placed at the domain centre 1.5km above the ground. For the 3-D experiments small random temperature perturbations are added to the thermal in order to accelerate the squall line towards a 3-dimensional structure.

So far a suite of experiments using the WRF (Weather Research and Forecasting) model has been completed. This suite of experiments comprises both 2-D and 3-D simulations of an idealized squall line for a range of temperatures with relative humidity held constant. In this way, the precipitable water (i.e. the atmospheric moisture variability) can be changed while the system remains in dynamic balance. A detailed analysis of the model response to the changes in moisture availability is currently being undertaken.

For constant relative humidity, theory suggests that the amount of atmospheric precipitable water is constrained by the water vapour content of saturation, which is governed by the Clausius-Clapeyron relation. Following the tutorial text of Tsonis

(2002), the Clausius-Clapeyron equation relates the rate of change of the saturated partial pressure of water vapour in the atmosphere as a function of temperature to the latent heat of vaporization multiplied by the inverse of the temperature multiplied by the difference between the specific volumes of water vapour and liquid water. This relationship predicts that there will be a 7% increase in precipitable water per degree of warming.

Fig. 2 shows the peak 1-hour rainfall accumulation from the simulated idealised squall line for a range of initial surface temperatures. It is clear that up to a temperature of about 25C the response of peak hourly precipitation to increased temperature (and therefore moisture as relative humidity is held constant) scales with the Clausius-Clapeyron relation. However, at higher temperatures this scaling diminishes. For the 8-hour accumulation period, the peak accumulation actually decreases with increasing temperature.

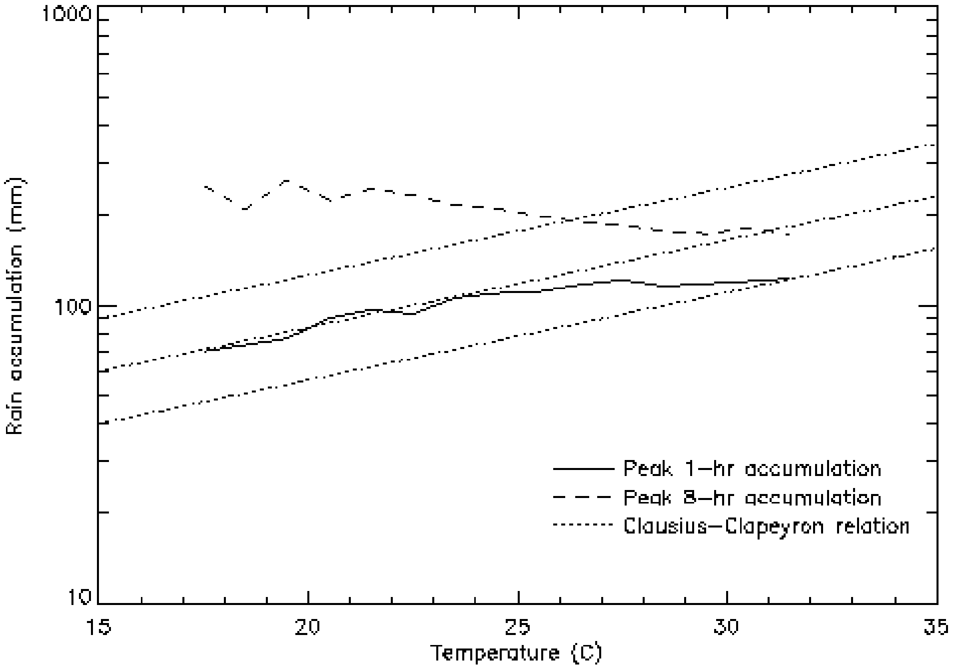

Figure 2: Peak precipitation accumulation on a logarithmic scale as a function of temperature (FREE Progress Report; R. Toumi, 2008).

The solid line in Figure 1 shows the peak 1-hour precipitation, the dashed line shows the peak 8-hour accumulation and the dotted lines show the Clausius-Clapeyron relation (7% increase per degree C). The decrease in peak 8-hour accumulation and diminishing increase for the 1-hour accumulation with increasing temperature is due to an increase in the speed at which the squall line moves.

Fig. 3 shows Hovmöller diagrams (time versus distance; see legend) for squall lines with initial surface temperatures of 22C, 25C and 28C. From Fig. 3 it is clear that as the temperature is increased, the heaviest rainfall moves more rapidly to the east. At this stage, the team believe that this is due to increased latent heat release as a result of a warmer moister atmosphere. This energy is converted to momentum that increases the strength of the rear-to-front flow in the squall line thus accelerating the system. A full momentum analysis has been undertaken in order to test this hypothesis. The results suggest that, at least for the case of an idealised squall line, increased moisture availability does not necessarily result in an increase in point rainfall accumulations, particularly for warmer temperatures and longer accumulation periods. This means that rainfall extremes, which are typically associated with convective rainfall, may not be governed by moisture availability alone. Indeed, no robust relationship between temperature and rainfall accumulation has been found. However, one of the key factors of an extreme rainfall event is stationarity of the system. The team has found that an approximate Claussius-Clapeyron scaling of about 1.5 i.e. about 10% increase per degree C exists for maximum rainfall accumulation in a grid square over accumulation periods of 1 minute to 8 hours. Further idealised experiments are planned that will help to clarify the role of other influences on extreme rainfall for squall lines such as vertical wind shear and topography.

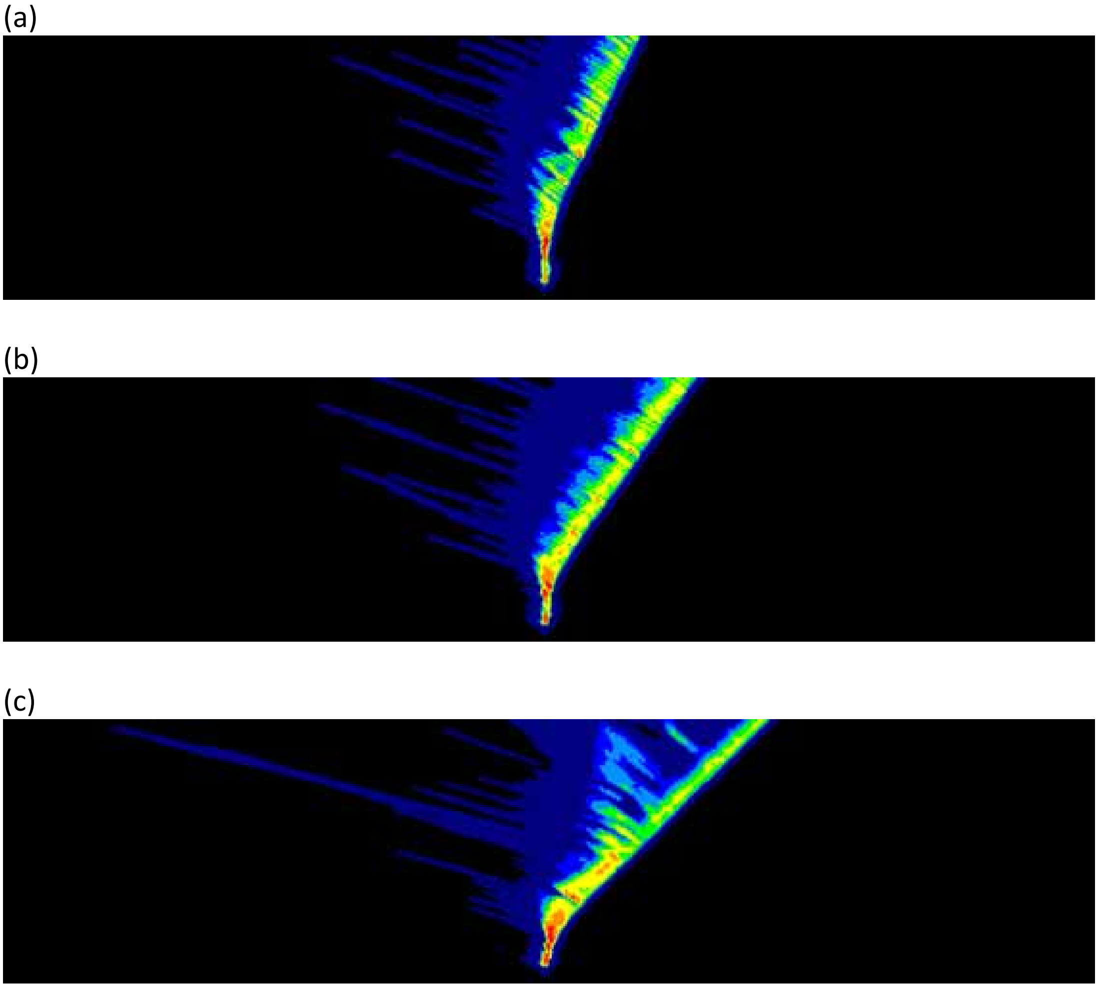

Figure 3: Hovmöller plots of 5-minute rainfall accumulations for different initial surface temperatures for 2-D squall line simulations: (a) 22C, (b) 25C, (c) 28C. The y-direction is time from 0 to 8 hours with a resolution of 5 minutes, and the x-direction is distance along the domain with a resolution of 1km (FREE Progress Report; R. Toumi, 2008).

Initially the plan was to use the Met Office Unified Model (UM) to study the July 2007 extreme rainfall event. However, for consistency with the idealised experiments, it was decided to use the WRF model. In addition, it was felt that the WRF model provides a much more user-friendly solution to performing the sorts of experiments of interest.

A control run to simulate the July 2007 event has been carried out using the WRF model with initial and boundary conditions provided by analyses from the Global Forecasting System. The model is run in nested configuration with the highest resolution nest having a grid length of 3km. At this grid length it is expected that the model will be able to explicitly resolve convective processes, so no cumulus parameterisation is employed. An initial examination of the model output suggests that WRF does a reasonable job in simulating the rainfall extremes observed in this event, although there are some small errors in the timing and location of the extreme rainfall. For this project interest is focused on the effects of increasing atmospheric moisture availability on the extreme amounts of rainfall rather than timing and location of these extremes, so it was felt that such errors would not affect the interpretation of the results. Modifications have been made to the WRF code to allow the temperature in the initial and boundary conditions to be increased whilst keeping the relative humidity fixed in a consistent manner. Simulations are ongoing.

This work has considerable relevance to the CEH risk analysis work for long return period rainfall being undertaken for the Defra / EA Reservoir Saftety Project discussed earlier in this report. In the work being undertaken at CEH as mentioned earlier there is an indication, see Figure 1, that as return period increases there may be an asymptotic tendency for some of the stations towards a maximum possible rainfall. In Figure 1 the different curves relate to different locations in the United Kingdom where red indicates a station in the Orkney Islands. These curves could also relate to changes in maximum temperature occurrence with the red curve and points representing the lowest maximum temperature of about 23^{o}C (Climate of Scotland, 1989). For this temperature Figure 2 suggests a maximum 8 hourly rainfall accumulation of about 200 mm consistent with the daily rainfall for a 1 in 100,000 year return period indicated in Figure 1.This might be consistent with the preliminary findings of the Imperial College work.

5. Impacts of climate change

Climate change may impact both PMP and risk based analyses in two ways. Firstly, as temperature increases, the capacity of the air to hold water vapour changes, and secondly the frequency of occurrence of extreme events changes. In the previous section the work being undertaken at Imperial College is clarifying the first impact.

Secondly, work within the FREE programme is being undertaken at UEA (Osborn) to study the relation between air flow indices and precipitation extremes in the UK. Recent results from this project published by Maraun et al (2008) support the existence of a long-term increase in winter precipitation intensity, although the summer rainfall intensity has exhibited changes that are more consistent with inter-decadal variability than with any overall trend (Figure 4).

VGAM (Vector Generalised Additive Models) statistical models have been developed that describe the relationships between airflow indices and the probability distribution of monthly precipitation maxima across the UK. The spatial and seasonal variations in the statistical model parameters have been visualized, and physical explanations for these variations, including elevation and exposure to prevailing winds, have been sought. These statistical models have been used to identify time-variations in UK precipitation extremes that can be explained by time-variations in the air flow characteristics over the UK, and

New work has been begun during this period to extend the analysis of the relationships between air flow and UK precipitation extremes to simulations with the HadRM3H regional climate model.

Knowledge about the covariates is important to identify physical drivers of extreme precipitation. These links are now being used to evaluate the performance of regional climate models. Knowledge about their future behaviour will also help to better predict changes in extreme precipitation.

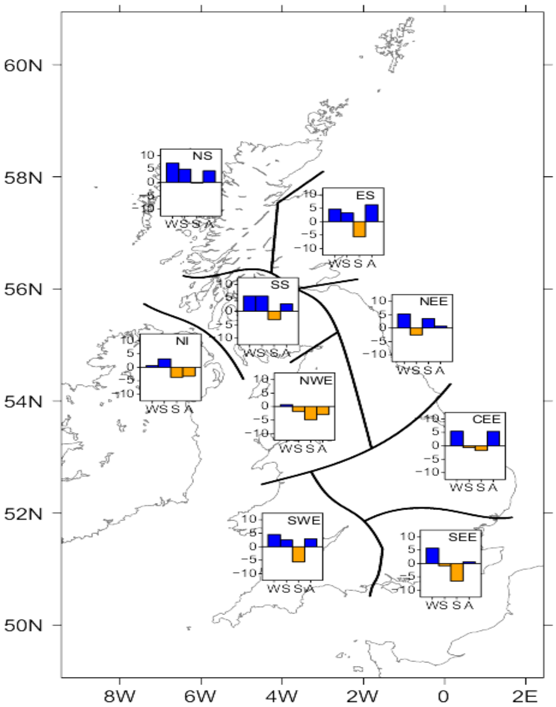

Figure 4: 961-2006 trends of category 10 (heavier events) contributions for winter, spring, summer and autumn. The results are given as the absolute contribution change in percent over the whole period (from Maraun et al., 2008).

6. Interim conclusions

It is now clear that the frequency of occurrence of extreme rainfalls is likely to increase as our climate changes. For example the 100 year return period storm is likely to become the 50 year return period storm (see for example Senior et al., 2002). However, whether the maximum amount of rainfall of a given duration will increase remains unclear. Theoretical considerations suggest that as the climate warms the air can hold more moisture, but there is evidence that this increase does not continue beyond temperatures of around 25 deg C due to a concomitant increase in the speed of movement of atmospheric systems. Unfortunately if systems become stationary the increase in precipitation could continue.

Little work has been carried out on the relationship between surface atmospheric temperature and atmospheric synoptic type and movement. Hand et al (2004) found that most extreme events were associated with stationary or very slow moving systems, but did not link stationarity to temperature and rainfall totals. The maximum rainfall accumulations which have been observed (Hand et al., 2004; Hydro-GIS, 2008 in the FREE programme), and the PMP values estimated by Collier and Hardaker (1996) for durations of one, eight and twenty four hours may be compared. These durations are associated with isolated thunderstorms (e.g. the Hampstead storm in 1975) and Mesoscale Convective Systems (e.g. the Lynmouth storm in 1952). The correspondence between the observations, the theoretical (Clausius Clapeyron equation) and model estimates is striking, and leads to an **interim** conclusion that as the climate warms current estimates of PMP (such as those reported by for example Collier and Hardaker, 1996 and Clarke and Pike, 2007) remain valid. However, further detailed analysis is urgently needed to confirm this conclusion.

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