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Regionalisation of climate impacts on flood flows to support the development of climate change guidance for Flood Management.

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Abstract
Current Defra / Environment Agency guidance (FCDPAG3 supplementary note: http://www.defra.gov.uk/environ/fcd/pubs/pagn/climatechangeupdate.pdf) requires all flood management plans to allow for climate change by incorporating, within a sensitivity analysis, an increase in river flows of up 20% over the next 50 years, and beyond. This guidance is the same for all of England and Wales, making no allowance for regional variation in climate change or catchment type. This reflects the lack of scientific evidence to resolve the spatial distribution of potential impacts on flood flows with enough confidence to set such policy regionally. The 20% allowance was first raised in 1999 for MAFF and subsequently reviewed following the release of the UKCIP02 scenarios. Although the 20% figure is a memorable precautionary target, there is the risk that it leads to a significant under- or over-estimation of future flood risk in individual catchments.

Defra and the Environment Agency procured project FD2020 (Regionalisation of climate change impacts on flood flows) to provide a more rigorous science base for refreshing the FCDPAG3: supplementary note guidance. The FD2020 approach is exploring the relationships between catchment characteristics and climate change impacts on peak flows in a "scenario neutral" way. This is done by defining a regular set of changes in climate that encompass all the current knowledge from the new scenarios available from the IPCC Fourth Assessment Report. For each of the 155 catchments included in the research, this broad approach will provide multiple scenarios to produce a "vulnerability surface" for change in the metrics of peak flows (e.g. the 20-year flood flow). Some of the UKCP09 products have also been used to understand what these projections may mean for changes to peak flow. The catchment-based analysis will be used to generalise to other gauged sites across Britain, using relationships with catchment characteristics, providing the scientific evidence for the development of regional guidance on climate change allowances.

Specifically the project is:
- Investigating the impact of climate change on peak river flows in over 150 catchments across Britain to assess the suitability of the FCDPAG3 20% climate change allowance.
- Investigating catchment response to climate change to identify potential similarities such that the FCDPAG3 nationwide allowance could be regionalised.
- Investigating the uncertainty in changes to future peak river flows from climate change.
- Developing an approach that has longevity beyond the project timeframe and the lifetime of the latest generation of climate model results.

RATIONALE

Projected changes in climate are generally expected to increase flood risk across England and Wales (Wilby et al., 2008). Current Defra guidance on incorporating possible changes to peak flows from future climate change is described in the project appraisal guidance (FCDPAG3 supplementary note: http://www.defra.gov.uk/environ/fcd/pubs/pagn/climatechangeupdate.pdf, 2006). This requires all flood management plans to include, within a sensitivity analysis, an increase of up to 20% over the next 50 to 100 years. The 20% sensitivity allowance is kept constant out to 2115, unlike some other variables (Table 1), and is the same across Britain, making no allowance for regional variation in climate change or catchment type. At that time the underpinning science was not available to resolve the spatial distribution of climate change impacts on flood flows with enough confidence to set policy regionally.

Table 1 Defra guidance on climate change from FCDPAG3 (2006)

Parameter	1990-2025	2025-2055	2055-2085	2085-2115
Net sea level rise (mm/yr) SE England	4.0	8.5	12.0	15.0
Peak rainfall intensity	+5%	+10%	+20%	+30%
Peak river flows	**+10%**	**+20%**		
Offshore winds	+5%	+10%		
Extreme wave height	+5%	+10%		

Defra and the Environment Agency have since procured a project (FD2020: Regionalised impact of climate change on flood flows) to provide the scientific evidence to consider whether the guidance within the FCDPAG3 supplementary note can be refreshed. Although the 20% figure is a memorable precautionary target, there is the risk that it could lead to significant under- or over-estimation of the future risk, and as yet there is not the confidence in the science evidence to support significant investment in adapting to future river flows above the current sensitivity approach.

This paper outlines the methods being developed within project FD2020, although at the time of writing this paper the project is still ongoing, so only some sections describe completed work.

METHODOLOGY

The project methodology is illustrated in Figure 1 below. The method is based on catchment hydrological modelling, but is not a traditional climate change impact study, which typically take the outputs of one or more global (GCM) or regional climate model (RCM) to perturb the meteorological data that drive a calibrated catchment model so that any changes to river flows under future climates may be derived. This traditional approach has a number of limitations:

- The GCM/RCM output is used to adjust only a single representation of baseline.
- The RCM may not adequately represent the regional and local climate, and particularly the characteristics of extremes needed for modelling peak flows.
- River flow response to climate, and climate change, is non-linear and there may be thresholds that could result in a significant change to river flows that are overlooked.
- The dynamical interaction between the climate and catchments is complex. Changes in many aspects of rainfall (means, intensity, frequency and seasonality), as well as evapotranspiration, soil moisture and temperature all influence river flows. A single set of GCM/RCM outputs will only represent one set of these changes and may not increase our understanding of how these variables interact.

Figure 1. Schematic of project FD2020 (Regionalised impact of climate change on flood flows).

The research community is tackling the first two bullet points in a number of ways. First, the latest generation of climate change scenarios (UKCP09) will be released as probability density functions (pdfs), derived from perturbed parameter experiments of the Hadley Centre RCM (and the optional use of a stochastic rainfall generator). These data can, in turn, be used to drive catchment models and would provide pdfs of change in peak flows. Second, other research supported by the Environment Agency and UKWIR, has used several GCMs to explore different representations of the future climate and hence a range of future impacts on low flows.

However, these approaches are still based on many assumptions and large uncertainties remain, for example, changes in the inter-annual and inter-decadal variability of climate, and the assumption that the future climate lies somewhere within the space described by the scenarios.

The project described in this paper therefore takes a scenario-neutral approach, being based on a broad sensitivity analysis to determine catchment response to changes in climate. These catchment responses are then regionalised so that catchments which respond in similar ways to given climate stimuli are grouped together. The assumptions behind the methodology are investigated through a wide-ranging uncertainty method applied to selected catchments.

Hydrological Modelling

Two hydrological models were used for the analysis: The CLASSIC (Climate and Land-use Simulations In Catchments) model (Crooks and Naden, 2007) and the PDM (Probability Distributed Moisture) model (Moore, 1985; 1999; 2007). Both are conceptual rainfall-runoff models developed for continuous simulation of river flow across the complete flow range. They incorporate soil moisture accounting processes which is the main source of non-linearity between rainfall and the generation of runoff. Smaller catchments are modelled by the PDM, which requires inputs of catchment-average rainfall and potential evaporation (PE), plus flow data for calibration. Larger catchments are modelled with CLASSIC which requires gridded inputs of daily rainfall and PE, as well as land-use, soil and digital terrain data and flow data for calibration.

Many previous studies of the impact of climate change on peak river flows in Britain ignored the role of precipitation falling as snow, and of subsequent snowmelt. However, as this project is *regionalising* the impacts of climate change on flooding, it is important that these processes are included as the winter flow regime of upland catchments can be considerably affected by snowfall and snowmelt, even in the UK (e.g. Archer, 1981; Ferguson, 1984). Therefore, future changes in temperature will almost certainly alter the balance between snowfall and rainfall processes in such catchments. In recognition of this, snowmelt modules have been added to both the PDM and CLASSIC models.

Figure 2 Map showing all catchment boundaries.

River flow simulation is performed at a daily time step except for all but the smallest catchments (less than 50 km^2) where hourly simulation is necessary to represent hydrologically-responsive catchments. While the hourly PDM catchments have been calibrated and run at the hourly time-step, the impact of climate change for these catchments is assessed on statistics derived from daily mean flows, for consistency with the larger catchments simulated using daily data (both PDM and CLASSIC). The 155 catchments considered have been selected to provide a good spatial coverage of Britain (Figure 2) as well as a wide distribution of catchment properties (Crooks et al, 2009). The sample includes 120 catchments simulated by the PDM (including 46 run at an hourly time-step) and 35 by CLASSIC. Further details of the modelling method (including a full list of catchments names and numbers, the development and application of the snowmelt modules and details of the method and results of the calibration procedure) can be found in Crooks et al (2009).

Climate scenario approach

Kay et al (2009) showed that the greatest source of uncertainty in the analysis of future flows is the GCM structure. This project broadened the climate change analysis beyond the reliance on a single GCM or RCM realisation, as previous work underpinning policy development for Defra (and MAFF) had done (Reynard et al, 2001; 2004). Projections from 17 GCMs used in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) were included. They are all considered to provide equally plausible representations of future climates under specified greenhouse gas emissions. More detail on the chosen GCMs can be found in Prudhomme and Reynard (2009).

GCMs typically provide information about changes in monthly mean climate, and the range of projections can be wide and vary by region. Subsequent impacts on flood flows are also highly variable due to the non-linear and catchment-specific hydrological processes, as well as their representation by different hydrological models (Wilby, 2005). In order to understand the role of the catchment type on the response to change in climate, the same climate driver changes (specifically precipitation and temperature) were applied to the entire range of catchments over Great Britain.

Although most GCMs agree that Britain will experience increasingly mild and wet winters, and warm, dry summers, the precise changes vary both seasonally and between GCMs. A shift in the rainfall distribution between seasons would have important consequences for the seasonal distribution of soil moisture, and hence the capacity of a catchment to either absorb some of the rainfall or, alternatively, to be closer to saturation with the potential to generate quicker and larger floods. It is thus essential that the range of scenarios tested incorporate the uncertainty in the seasonal variation and mean climate, as well as any possible spatial variations in climate change signals.

Analyses of available projections for the UK showed that average changes in precipitation are generally positive in winter and negative in summer, but temperature does not show this same fixed seasonality of change. The inter-annual distribution of such changes can be summarised by the change in mean annual average, and a maximum deviation from this changed mean, which also represents the seasonality of the changes. Using this simplifying assumption, changes in monthly mean precipitation can be represented by a smooth harmonic function, with the peak in January and the trough in July. To capture the inconsistent seasonal pattern seen in temperature projections across Britain, a similar function was also considered to represent possible warming scenarios. Details of the climate change projections and harmonic function analysis can be found in Prudhomme and Reynard (2009). These monthly changes are then used to perturb observed rainfall, temperature and PE time series

Analytical framework

In order to distinguish the role of catchment characteristics in the changes to flood peaks under climate change, and thus identify more vulnerable catchment types, a sensitivity analysis was undertaken, where the same climate change drivers were applied systematically to all catchments. This analytical framework is scenario-neutral, as the tested scenarios are not uniquely representing future projections that are specific to a given location, GCM or emission scenario.

Assuming that changes in precipitation in the UK have a harmonic peak in winter (as indicated by most of the GCM projections for which we had data), the two main components of a rainfall scenarios are the mean annual change from current baseline, and the maximum seasonal deviation from this mean annual change. The sample domain was bounded by mean annual changes varying from -40% to +60%, and additional seasonal variation up to 120%. This rainfall domain is larger than current GCM and RCM projections suggest for the 2080s, but helps cope with later generations of climate model projections that could show even larger departures from the baseline than current models. The domain was sampled at 5% steps for both mean annual and seasonality changes, and every combination tested, producing 525 different rainfall change scenarios applied to each catchment. In addition, 8 different scenarios of changes in temperature and PE were considered, each to be combined with the rainfall scenarios. A total of 4200 scenarios were thus applied for each catchment.

The hydrological models were run for the 155 catchments to simulate flows under current conditions and for the 4200 futures to produce the sensitivity domain. Changes to three flood indices were calculated: the 2, 10 and 20-year return period flows. Figure 3 illustrates changes in the 20-year return period peak flood for the Wharfe at Addingham, assuming an annual warming of 2.5℃, with an additional seasonal variation of +0.8℃ in January and -0.8ºC in August. Decreases in peak flows are in light grey, and white represents an increase between 0 and 10%. Each subsequent band represents a further increase of 10% with the top right-hand area indicating a 100% increase. The shaded area to the bottom right indicates the part of the domain where the amplitude of the seasonal change reduces the summer rainfall to zero.

Having performed the sensitivity analysis it is then possible to overlay combinations of mean annual change and seasonality projected for the 2080s by individual GCMs and RCMs. The dots, triangles and squares are for individual GCMs and the inverted triangles are the Hadley Centre RCM used to drive the UKCP09 scenarios. These points provide an indication of where the current scenarios sit within the overall sensitivity space. For example, most current scenarios for this catchment show changes in the band representing a 0-10% increase. In this case, Defra's existing 20% precautionary allowance would be deemed robust under the majority of climate change scenarios.

Figure 3. Sensitivity domain for the Wharfe at Addingham showing the change in the 20-year flow under annual temperature increase of 2.5℃, with an additional seasonal variation of +/-0.8℃, with a peak change in January. The grey area is a decrease in flow, with the bands representing increments of 10% in this indicator flow. The symbols represent where individual GCM projections lie in the space.

Eight vulnerability plots (one for each temperature scenario) were produced for each of the 155 catchments. The patterns of change were then used to regionalise, or group the catchments that respond to changes in climate in a similar way.

Regionalisation

At the time of writing, the regionalisation work is still to be completed, along with the uncertainty analysis and interpretation of results. A clustering method is being used to group catchments according to the response surface obtained for the different return periods. Changes in peak flows, for each return period, are compared catchment-by-catchment, and groups formed with similar responses, and for each; the average (or composite) sensitivity pattern is being derived.

Uncertainty Analysis

A number of assumptions are made when implementing the analytical framework. The uncertainty analysis will be undertaken for one catchment from each group, in order to provide further insight to the implications of some of our assumptions, in particular:

- The use of a first order harmonic function to summarise change in mean monthly precipitation and temperature changes in RCM/GCM scenarios.
- The use of a peak change in January (fixed phase) and a first order harmonic (symmetry in the gradual decrease and increase around the peak and troughs).
- The effect of using the simple "delta change" method for creating future daily rainfall scenarios. This will involve using alternative time series of statistically and dynamically downscaled climate scenarios to drive hydrological models for representative catchments.
- The method of estimating changes in return periods higher than 20 years? The limited availability of long time-series of observed rainfall and PE data to drive hydrological models (and of concurrent flow data for model calibration) means that the return period to which flood frequency can be reasonably derived is limited. Plots will be produced of the changes at various return periods up to 20 years, for catchments within each of the groups, to determine whether indicative guidance can be issued for higher return periods.
- The extent to which estimates of current natural variability might bracket future changes in peak flows.
- Hydrological modelling uncertainty (structure and parameterisation) is obviously important and certain assumptions have been made for this project. These issues will be discussed as part of the overall discussion of uncertainty

DISCUSSION

This paper describes the methodology developed by project FD2020, for the hydrological modelling of changes in peak flows under climate change. This is based on the modelling of 155 catchments and a new sensitivity methodology for climate change scenario analysis. From within each group a representative catchment has been selected for detailed uncertainty analyses to help explore the effect of different modelling assumptions.

The project will deliver:

1. Response surfaces for each catchment, with individual GCMs and RCMs overlain;
2. For each individual catchment the vulnerability plots will be analysed to provide an assessment of the current 20% guidance. This will be in the form of the proportion of the GCM/RCM dots that lie within, or below, the 20% band;
3. The regionalisation will produce response groups, each group having a set of “composite” vulnerability plots, one for each of the eight scenarios of change in temperature and PE ;
4. For selected catchments, the uncertainty analysis will show the range of changes in peak flows that can result from the various assumptions made within the project methodology, and from using alternative scenario data sources;
5. A methodology (decision-tree), based on catchment characteristics, for estimating climate change impacts for gauged catchments not used in the original analysis.

The results of the regionalisation of changes in flood frequency, as typified by the response groups, will be discussed in the context of the interaction of the seasonality of changes in climate (precipitation, temperature and potential evapotranspiration) with physical catchment properties.

Implementing this method for a new target location (i.e. not modelled as part of FD2020) would require a baseline flood frequency analysis and a set of catchment descriptors fro the new location. With this information, the target catchment could be placed within one of the FD2020 response groups through the use of the decision tree (project deliverable number 5 above). For this group the appropriate climate change guidance can be read-off, in terms of a percentage change to the indicator return period flows (2, 10 and 20-years), with an indication of uncertainty determined from the group-based uncertainty analyses. The precise figures for each group will be developed by Defra and Environment Agency once the research is completed and the scientific evidence presented.

Next steps: Application for Policy

This project has been undertaken to support the development of updated Defra policy on guidelines for incorporating the potential changes in flood flows due to climate change. The methodology and results described in this paper provide an evidence base to support policy. It is likely that the blanket 20% sensitivity allowance currently enshrined in flood management policy and practice will be updated based on the evidence from this regional study. For example, the new guidance might first require the user to determine the type of catchment being considered for flood management, which in turn might lead to a sensitivity range of flood flows to use in appraisal and decision making. Defra and the Environment Agency, along with key stakeholders, will be considering an updated guidance note, which will embrace: 1) wider findings from UKCP09 publication, including the latest science on sea level rise and surge, to consider; 2) emerging Treasury Green Book supplementary guidance on adapting to climate change; 3) emerging research findings from R&D project FD2617 Economic Appraisal of Adaptation options. The combination of 1, 2 and 3 will input into the policy work. The science will also feed into a supporting document to the Environment Agency’s new Project Appraisal Guidance for Flood and Coastal Risk Management.

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