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The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios

Satish Bastola *, Conor Murphy, John Sweeney

Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, National University of Ireland, Maynooth (NUIM), Ireland

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ABSTRACT

In the face of increased flood risk responsible authorities have set out safety margins to incorporate climate change impacts in building robust flood infrastructure. Using the case study of four catchments in Ireland, this study subjects such design allowances to a sensitivity analysis of the uncertainty inherent in estimates of future flood risk. Uncertainty in flood quantiles is quantified using regionalised climate scenarios derived from a large number of GCMs (17), forced with three SRES emissions scenarios. In terms of hydrological response uncertainty within and between hydrological models is assessed using the GLUE framework. Regionalisation is achieved using a change factor method to infer changes in the parameters of a weather generator using monthly output from the GCMs, while flood frequency analysis is conducted using the method of probability weighted moments to fit the Generalised Extreme Value distribution to ~20,000 annual maximia series. Sensitivity results show that for low frequency events, the risk of exceedence of design allowances is greater than for more frequent events, with considerable implications for critical infrastructure. Peak flows for the five return periods assessed were found to be less sensitive to temperature and subsequently to potential evaporation (PET) than to rainfall. The average width of the uncertainty range for changes in flood magnitude is greater for low frequency events than for high frequency events. In all catchments there is a progressive increase in the peak flows associated with the 5, 25, 50 and 100-year return periods when moving from the 2020s to the 2080s.

1. Introduction

Projected changes in climate are expected to increase flood risk in north western Europe (e.g., Lehner et al., 2006; Wilby et al., 2008; Murphy and Charlton, 2008). In responding to such risks, responsible authorities have set out design allowances to incorporate climate change impacts in building robust flood infrastructure. Such safety margin strategies aim to reduce vulnerability at null or low costs. When it is cheap, particularly at design stage, Hallegatte (2009) highlights that it is prudent to add security margins to design criteria to improve the resilience of infrastructure to future (expected or unexpected) shocks. This paper sets out to subject such design allowances to a sensitivity analysis of the uncertainty inherent in estimates of future flood risk. We use Ireland as a case study where policy guidance such as the Greater Dublin Strategic Drainage Study (GDSDS) sets out that all new development must allow for a 20% increase in peak flows for all return periods up to 100 years to allow for climate change. Similarly, the Office of Public Works (OPW), the national body responsible for flood risk management in Ireland has advised an allowance of +20% of peak flows under a mid-range future scenario and +30% as a high-end scenario (OPW, 2009). Such decisions are crucial to the protection of lives, livelihoods and critical infrastructure and therefore need to be subjected to sensitivity analysis to demonstrate how robust such safety margin approaches are to uncertainty in future impacts (Prudhomme et al., 2010).

In the past two decades a large body of work has dealt with the application of hydrologic models for assessing the potential impacts of climate change on a variety of water resource issues. Such assessments have predominantly been based on what Wilby and Dessai (2010) term a 'top–down' approach involving the propagation of future climate scenarios through hydrological models (predominantly a single hydrological model) (e.g., Arnell and Reynard, 1996; Xu, 1999; Bastola et al., 2011), to derive an estimate of a future impact metric which is subsequently provided for policy makers to decide on appropriate adaptation options. Despite their widespread application, such approaches have met with limited success (Wilby and Dessai, 2010), in large degree due to the uncertainty in future simulations of relevant impacts.

Within this framework, Global Climate Models (GCMs) have emerged as the dominant tool in producing future climate scenarios through modelling natural processes as closely as possible. However, there are considerable uncertainties associated with the use of GCMs (see Prudhomme et al., 2003), while others (e.g. Kay et al., 2006; Rowell, 2006; Bastola et al., 2011) have shown that GCM uncertainty is by far the largest contributor to the cascade of uncertainty associated with future impacts. Such uncertainties mean that where decisions

* Corresponding author. Tel.: +353 1 7086592.
E-mail address: Satish.bastola@nuim.ie (S. Bastola).

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are made it is imperative that a range of GCMs is included, so that a fuller understanding of the uncertainty space can be developed. Therefore, recent studies have moved towards employing a diverse range of GCMs driven by a number of plausible emission scenarios to generate quantitative measures of uncertainty (e.g., Taye et al., 2010; Bae et al., 2011). In recognition of the considerable uncertainties associated with climate change impact projections the focus of modelling has moved towards decision appraisal rather than top down, predict and provide approaches that have been the mainstay of traditional impact assessment (Prudhomme et al., 2010; Wilby and Dessai, 2010).

Due to the cascade of uncertainty associated with scenario led approaches, the range of impacts and their implied adaptation responses can become impracticable (Wilby and Dessai, 2010). Therefore, the utility of probabilistic based approaches in adapting a risk-based framework for impact assessment has been increasingly advocated by recent studies (e.g., Ra¨isa¨nen and Palmer, 2001; Giorgi and Mearns, 2003). Scenario-led approaches which include only a few scenarios and GCMs are not compatible with the notion of a probabilistic, risk based framework. Furthermore, continuous research in the field of climate change and impact studies is likely to continuously result in new scenarios with new emerging knowledge that adds to the uncertainty cascade. Therefore, the inclusion of new scenarios and GCMs in the analysis, though desirable, will require analyses to be redone with additional scenarios for formulating robust decision making. Consequently, the idea of using the output from a number of GCMs for sensitivity testing and adaptation options appraisal has surfaced more recently as a more cautious approach (e.g. Prudhomme et al., 2010; Hall and Murphy, 2010; Lopez et al., 2009).

In understanding local scale impacts the direct application of GCMs is difficult given their coarse spatial resolution, which typically requires some form of downscaling. Regional climate models (RCMs) use a dynamic, physically based approach to downscale the larger resolution GCM variables to a higher resolution (typically 50 km) over a limited area. Such techniques are computationally expensive as they explicitly describe the physical properties affecting climate. Additionally, the output from regional climate models often require further downscaling if they are to be applied for hydrological simulation at the catchment scale. With the inclusion of more GCMs the computational cost required to better characterise the outputs from these models is immense. A computationally cheap alternative for downscaling is the statistical approach where empirical relationships are typically established between GCM-resolution climate variables and local climate. Such techniques offer the possibility of including a larger number of GCMs in the analysis. Climate change scenarios generated from statistical downscaling (e.g., using a stochastic weather generator) offer a significant computational advantage over dynamical downscaling methods in sensitivity testing and adaptation options appraisal where the focus is on populating the uncertainty space, with less emphasis placed on the precision of single scenarios.

In facilitating the inclusion of output from a large number of GCMs one of the simplest of the statistical methods is the perturbation method (e.g., Prudhomme et al., 2002). In this method, the change factor derived from the control and future GCM simulation is used to adjust the observations in an additive way for temperature and in a multiplicative way for precipitation. Alternatively, the GCM-derived changes have also been used to infer changes in the parameters of a weather generator, which are then used to simulate rainfall timeseries under current and future climates for use as input to continuous hydrological models (Schreider et al., 2000; Tung, 2001; Fatichi et al., 2011).

In moving this area of work forward, Prudhomme et al. (2010) presented a framework for a scenario neutral approach in testing the effectiveness of UK government safety margins for flood protection under a wide range of climate change scenarios. In their method, instead of using time varying outcomes for individual scenarios, the sensitivity analysis relied upon plausible ranges of climate changes making it neutral to the scenario used. The key advantage of such an approach as outlined by the authors is that the sensitivity domain can cover the entire spectrum of the latest IPCC-AR4 GCMs outputs, while it can also be adjusted to include additional values at both ends of the spectrum to plan for surprise and potential new extreme projections by adjusting the sensitivity domain. Such an approach is compatible with a probabilistic framework by combining knowledge of hazard likelihood with the sensitivity of a catchment (discussed further in Prudhomme et al., 2010).

A potential approach for conducting a sensitivity analysis is to use a full factorial experimental design, in which the model is solved for all possible combinations of the parameters. While this is desired, if there are a large number of parameters to analyse, the number of model solutions which must be obtained can be a limiting factor. In overcoming this, the dimensionality of the sensitivity matrix can be reduced by reducing the number of parameters. For example, Prudhomme et al. (2010) synthesised the monthly change factors from a large number of GCMs using a three parameter harmonic function. Sensitivity analysis shows the effect of varying these parameters over the range of uncertainty that the decision maker has about the exact values of those parameters. Such analysis demonstrates how robust the decision recommended by the models is to the imprecision of knowledge about the uncertainty domain.

The aim of this paper is to analyse the sensitivity of fluvial flood risk to the uncertainty in climate change by incorporating different sources of uncertainty and utilising key features of an ensemble of climate models. In addition to uncertainties in emission scenario and climate model selection, uncertainties arising from hydrological model structure and parameters are also incorporated for four case study catchments. In doing so the safely margin allowances for food infrastructure suggested in Irish policy guidance will be stress tested. Such an analysis will question the allowances made for climate change in critical infrastructure, enable more robust adaptation decisions and exemplify a case study for the analysis of adaptation decisions. The remainder of the paper is structured as follows; first the general steps of the methodology are laid out and information is provided on the study catchments and future changes in temperature and rainfall likely for the study region. Section 2.2 details the generation of climate data using the change factor approach coupled with a stochastic weather generator. Section 2.3 outlines the hydrological models used and their application, while Section 2.4 details the application of the flood frequency analysis. The inclusion of natural variability is discussed in Section 2.5. Finally, the uncertainty of future changes in flood peaks associated with current return intervals and the sensitivity testing of design allowances are demonstrated for the case study catchments.

2. Material and methods

The methodology used to assess the impact of climate change on the frequency of extreme events and their sensitivity to future change is based on the idea of a scenario neutral approach proposed by Prudhomme et al. (2010). Here, however, the change factor approach is used to inform the parameters of a weather generator to produce continuous time series of change and the uncertainty space includes the uncertainty from rainfall runoff models and their parameters. While hydrological model uncertainty is not as large as that from GCMs it has been shown to be a significant contribution to the total uncertainty envelope (Bastola et al., 2011) and also interacts differently with the same scenario input. The steps adopted in this study are as follows (also shown schematically in Fig. 1):

(1) Select a wide range of GCMs developed by various climate centres and a number of plausible emission scenarios that provide output on the future climate for the selected region. In this study we use the IPCC AR4 scenarios (17 GCMs × 3 SRES emission scenarios).