CLIMATE CHANGE IMPACT ON CATCHMENT HYDROLOGY & WATER RESOURCES FOR SELECTED CATCHMENTS IN IRELAND.

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ABSTRACT
This paper analyses the likely impacts of changes in climate for nine hydrologically diverse catchments throughout Ireland. When assessing the impacts of climate change on water resources there is a cascade of uncertainty that begins with the establishment of future pathways of development and ends with impact assessment (Wilby, 2005). In order to represent uncertainty in future simulations, statistically downscaled output from three Global Climate Models (GCMs), forced using two emission scenarios is used to force a lumped, conceptual rainfall-runoff model for three future time periods; the 2020s, the 2050s and 2080s. Changes in catchment storage, streamflow and extreme events are assessed through comparison with the GCM modelled control period 1961-1990. Future simulations suggest that reductions in soil moisture storage throughout the summer and autumn months are likely for each catchment. The extent of decreases are largely dependent on the storage potential of individual catchments; the lower the capacity of catchments to store water, the greater the sensitivity to climate change. Reductions in groundwater storage during the recharge period will increase the risk of severe drought, as the failure of winter or spring precipitation may result in prolonged drought periods where the groundwater system is unable to recover. Greatest reductions in streamflow are likely for the autumn months in the majority of catchments, while greatest increases are suggested for the month of February. The magnitude and frequency of flood events are shown to increase, with the greatest increases associated with floods of a higher return period. Uncertainty in future simulations derived from HYSIM parameter uncertainty is found to be more important than uncertainty due to emission scenario.

INTRODUCTION
There is broad agreement that anthropogenic climate change is likely to have a large impact on water resources with the availability of water to meet future demands and the magnitude and frequency of future extreme events being uncertain. Increases in temperature associated with an enhanced greenhouse effect are likely to result in an increase of atmospheric water content, due to increases in surface evaporation and the water holding capacity of the atmosphere. Such a response is liable to lead to an increase of precipitable water in the atmosphere (Douville *et al*., 2002). Given the importance of precipitation and evaporation in driving the hydrological cycle, any changes in these primary processes may have considerable knock on effects for the rest of the system; such as changes in the volume and timing of runoff and streamflow, changes in soil water storage, groundwater-surface water interactions as well as in the variability of hydrological processes, with consequences for extremes of flooding and low flows. This research investigates the likely impacts of climate change on Irish hydrology and highlights the key vulnerabilities of Irish water resources. Uncertainty in future simulations is also accounted for.

OVERVIEW OF METHODOLOGY
In order to obtain the objectives outlined a conceptual rainfall-runoff model is applied to a number of catchments throughout Ireland. Statistically downscaled data from a suite of GCMs, run using a range of emissions scenarios is incorporated to force the rainfall-runoff model for three future time periods, the 2020s, 2050s and 2080s. Changes in catchment hydrology as a result of climate change are assessed for each catchment, with the uncertainty in future impacts derived from different GCMs, emission scenarios and the rainfall-runoff model employed highlighted. The following sections will contend the methodology adopted while section three will highlight the key vulnerabilities to emerge.

CATCHMENTS ANALYSED
Individual catchments were selected to encompass as wide a range of hydrological conditions as possible so as differences in the hydrological response to climate change can be assessed for each. In total nine

catchments were included as outlined in Table 1. For ease of presentation the results from two catchments, the Suir and the Boyne are provided here. Detailed results for each of the remaining catchments will be published shortly in Murphy and Charlton (2006).

Catchment	Area (Km)	Gauge	data (days)	Mean Rainfall (mm)	Mean ET (mm)	Mean Discharge (cumecs)	Land use	Soil Texture
Suir	2173	Clonmel	14610	2.7	1.27	48.2	Pasture	Loam
Blackwater	2338	Ballyduff	14610	3.1	1.5	62.3	Pasture	Loam
Boyne	2408	Slane	14610	2.4	1.22	35.4	Pasture	Clay Loam
Moy	1911	Rahans	9862	3.9	1.22	57.9	Peat Bogs	Loam
Barrow	1660	Levitstown	11688	2.5	1.27	20.9	Pasture	Sandy Loam
Brosna	1207	Ferbane	14610	2.4	1.22	17.1	Pasture	Loam
Inny	1071	Ballymahon	10227	2.6	1.22	18.7	Pasture	Loam
Suck	1184	Bellagill	9498	2.8	1.22	25.2	Pasture	Loam
Ryewater	215	Leixlip	14610	2.2	1.5	2.3	Pasture	Clay Loam

Table 1 Catchments analysed and their critical characteristics

The Boyne is the largest catchment selected with a catchment area of 2,408 km^2 at Slane Castle (N 949 739). Topography is predominantly characterised as flat to undulating lowland with pasture by far the most abundant landuse. The soils of the Boyne catchment are predominantly composed of Grey Brown Podzolics (52%), Acid Brown Earths (12%) and Gleys (24%), while Basin peat is important in the upper reaches of many of the tributaries, with large areas forming cultivated peat bogs. While acid brown earths and grey brown podzolics are well drained soils, gleys are soils in which the effects of drainage impedance dominate and have developed under the influence of permanent or intermittent water logging (Gardiner and Radford, 1980). Altogether over 35% of the Boyne catchment is comprised of poorly drained soils, which reduce the capacity of precipitation to infiltrate into the subsoil and into groundwater. Subsoils within the catchment are comprised of glacial tills of limestone and shale. Significant deposits of sand and gravel are not widespread. Thus the infiltration of water, its movement through the soils and into groundwater is not as rapid as the Suir catchment where highly porous sand and gravel subsoils are dominant. In relation to underlying geology, by far the most common is the Lucan formation (41% coverage), which is comprised of dark muddy limestone with interbeds of shale and varying amounts of chert. Due to the impurities in formation karstification is inhibited and the transmissivity and thus the aquifer potential of the bedrock are reduced.

The Suir has a catchment area of 2,173 km^2 at Clonmel (S 208 222). The topography is generally low-lying with higher hills and mountains in the south east of the catchment. Soils consist predominantly of acid brown earths and grey-brown podzolics, while subsoils comprise glacial tills and sand and gravels in the higher ground with alluvial deposition around the main channel and its tributaries. In relation to the hydrogeology, large deposits of glacial till and sand and gravels result in many locally important aquifers. Furthermore, these deposits play a key role in the groundwater flow regime within the catchment. High permeability rates associated with sands and gravels allow a high level of groundwater recharge and provide additional storage to underlying bedrock aquifers. In terms of aquifer productivity almost half of the catchment is made up of moderately productive, locally important aquifers. Regionally important aquifers make up approximately 35% of the catchment area. Poorly productive aquifers only comprise about 13% of the catchment.

THE RAINFALL-RUNOFF MODEL HYSIM

Conceptual rainfall-runoff (CRR) models have been the most widely used for climate impact assessment (Wilby, 2005; Arnell, 2003; Charlton et al, 2006, 2003; Pilling and Jones, 1999; Sefton and Boorman, 1997; Arnell and Reynard, 1996; Cunnane and Regan, 1994). Central to the use of CRR models in climate impact assessment is their ability to characterise the catchment system as a simplified agglomeration of stores representing catchment processes, enabling such models to be applied to a wide variety of catchments. The model employed here, HYSIM is a lumped CRR model, which uses rainfall and potential evaporation data to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. Although spatially lumped and hydrologically conceptual in nature, the model contains many parameters that can be measured from physical reality. The model is built around two sub-routines; the first of these simulates catchment hydrology while the second simulates channel hydraulics. In relation to the hydrology routine seven natural stores are represented. The main components of the model are the upper and lower soil reservoirs, with the works of Brooks and Corey (1964) employed to represent the variation of effective permeability and capillary suction with changes in moisture content. A full description of the model and its structure is given in Murphy (2006).

UNCERTAINTY IN IMPACTS MODELS

When modelling the impact of climate change on water resources there is a cascade of uncertainty that begins when future socio-economic story lines are translated into future emission scenarios and ends with impact modelling (Wilby, 2005). Although CRR models have been the most widely used for climate impact assessment, constraints are placed on such an approach by a lack of knowledge of the workings of the hydrological system, a lack of data and by the volume of complex computations required to simulate every process within the hydrological sphere (Wilby, 2005). Consequently CRR models are associated with well-known limitations with respect to parameter identifiability, parameter stability, predictive uncertainty and equifinality of different model structures and parameter sets (Beven and Binley, 1992; Beven, 1993; Jakeman and Hornberger, 1993; Beven and Freer, 2001; Wagener et al., 2001). Therefore all model calibrations and subsequent predictions will be subject to uncertainty (Beven, 2000). Quasi random sampling in the form of Latin Hypercube Sampling (LHS) was employed to examine the uncertainty in HYSIM output derived from problems within the parameter space such as equifinality. This approach has been widely used in environmental modelling studies. (Wilby, 2005, Wilby and Harris, 2006, Uhlenbrook and Sieber, 2005; Sieber and Uhlenbrook, 2005; Christiaens and Feyen, 2001). In order to generate parameter sets that are capable of simulating catchment hydrology, a uniform distribution was attached to each parameter and LHS used to generate samples from each. The Nash Sutcliffe (NS) (1970) non-dimensional efficiency criterion was adopted as a measure of goodness of fit of the modeled hydrograph with the observed, with behavioural parameter sets were taken as those with an NS value of above 0.7 NS is defined as:

$$NS = 1 - \frac{\sum_{i=1}^{n} \left(Q_i - \hat{Q}_i\right)^2}{\sum_{i=1}^{n} \left(Q_i - \overline{Q}\right)^2}$$

where, $\hat{Q}_i$ are the n modelled flows, Q_i are the n observed flows and $\overline{Q}$ is the mean of the observed flows. Based on the analysis of convergence rates 100 different parameter values were generated by dividing each uniform distribution into 100 non-overlapping intervals on the basis of equal probability, with one sample being extracted from each interval. For each catchment the values generated for each parameter were combined randomly to form 100 parameter sets. HYSIM was then run with each of these 100 parameter sets.

In order to generate and test behavioural parameter sets a split sample procedure was employed. Where available, the first thirty years of the baseline data set (1961-90) were used for calibration. This period was selected so that the model could be trained on as much variability in streamflow as possible. Validation was conducted for the period 1991-2000. This decade has been the warmest globally, with 1998 being the warmest year on global instrumental record. Furthermore the ten years 1991-2000 present some of the largest flood peaks on record in Ireland, such as the November 2000 flood in the Suir catchment. Thus the 1990s provide a good test of model performance, with conditions being more akin to those expected under climate change that at any other period in the baseline data set. The generated parameter sets were run for the calibration period. Based on their performance as defined by the NS score obtained, parameter sets were assessed as behavioural or non-behavioural. Those deemed behavioural were further analysed during the validation period, while non-behavioural sets were omitted. Tables 2 and 3 show the NS ranges and the number of behavioural parameter sets obtained for each period. The increase in model skill in many catchments during the validation period highlights both the robustness of the HYSIM model and the representativeness of the calibration data set, as the validation period contains the warmest and some of the wettest years on the instrumental record. The degree of success obtained in testing the model during the 1990s also highlights the transferability of parameter sets to conditions outside those on which the sets were derived. Behavioural parameter sets retained for the period 1991-2000 were used to derive uncertainty bounds. The constructed bounds incorporate the error derived from model structure, data measurement, parameterisation and lack of knowledge in model process parameters and can thus be used to quantify uncertainty in model simulations beyond the baseline period.

	Barrow	B'water	Boyne	Brosna	Inny	Moy	Rye	Suck	Suir
NS Range	.72-.80	.71-.78	.74-.85	.71-.83	.71-.85	.86-.90	.70-.73	.70-.73	.70-.80
No. of sets	44	38	73	77	64	100	56	39	50

Table 2 NS ranges and the number of behavioural parameter sets generated for each catchment during the calibration period.

	Barrow	B'water	Boyne	Brosna	Inny	Moy	Rye	Suck	Suir
NS Range	.70-.82	.71-.80	.70-.85	.70-.82	.70-.78	.83-.87	.70-.76	.70-.78	.70-.82
No. of sets	37	23	69	70	64	100	42	35	50

Table 3 NS ranges and the number of behavioural parameter sets retained for each catchment during the validation period 1991-2000.

UNCERTAINTY IN FUTURE CLIMATE SCENARIOS

Large amounts of uncertainty are associated with the generation of future climate scenarios. Indeed, uncertainty is an intrinsic component in modelling the climate system due to its complex non-linear and often chaotic behaviour. Furthermore, the uncertainties associated with the natural climate system are compounded by external factors such as future anthropogenic greenhouse gas (GHG) concentrations and the role that radiative forcing will play in moderating climate over the coming century. This point has received much attention and the analysis, quantification and management of uncertainty has been the focus of significant research in recent years (Stott and Kettleborough, 2002; Murphy *et al*. 2004; Giorgi, 2005; Wilby, 2005; Wilby and Harris, 2006). As a result of the inherent complexity of the climate system, GCMs differ in their characterisation of important processes and consequently different GCMs show different responses to radiative forcing and thus differences in climate sensitivity are evident. Consequently, Wilby and Harris (2006) highlight the fact that over reliance on a single GCM in impact assessment could lead to inappropriate planning or adaptation responses.

Uncertainties are also present in the determination of future atmospheric concentrations of GHGs. Projections of future concentrations are derived from emissions of GHGs as described by each of the SRES scenarios using process based models representative of the carbon cycle. Each scenario leads to substantial differences in projected CO_2 concentration trajectories with significant epistemic uncertainty introduced as a result of incomplete knowledge in relation to climate sensitivity and the functioning of the carbon cycle. Nevertheless, the results show that higher emissions are always expected to lead to higher projected atmospheric concentrations (Prentice *et al*. 2001).

A final source of uncertainty is associated with the production of regional and localised climate scenarios. Despite the high degree of sophistication of GCMs, their output is generally too coarse to be useful for regional or local scale impacts analysis as important processes which occur at sub grid scale are not at present resolved by these models (Wilby *et al.,* 1999). Therefore regionalisation or downscaling of

GCM outputs is required for meaningful impact assessment. In terms of approach uncertainty two categories of downscaling have come to the fore, namely, dynamic approaches, in which the physical dynamics of the system are solved explicitly, and empirical or statistical downscaling. Although both methods are subject to limitations and assumptions that lead to the generation of uncertainty in downscaling, Gutowski *et al.* (2000) highlight the fact that neither approach consistently outperforms the other. However, because statistical downscaling methods are less costly to implement than dynamical downscaling techniques, they have been most widely employed for climate scenario generation in climate impact assessments, especially in hydrological studies (e.g. Dibike and Coulibaly, 2005).

Given this cascade of uncertainty and the obvious limitations in using a single trajectory for climate impact assessment, recent research has moved towards the quantification of uncertainty through the use of ensembles containing multiple scenarios from multiple GCMs. In line with this, the ensembles produced by Fealy and Sweeney (2006) as highlighted in an earlier paper were used to force HYSIM to produce future hydrological simulations for each catchment. In total three ensembles, an A2 ensemble, a B2 ensemble and a mean ensemble were employed. These ensembles incorporate the uncertainty derived from the use of different GCMs and emission scenarios. Furthermore, uncertainty in future simulations derived from the CRR model is also represented by using all behavioural parameter sets to run each ensemble. The remainder of the paper highlights the salient results obtained for the Boyne and the Suir catchments.

CHANGES IN CATCHMENT STORAGE

In order to assess likely changes in subsurface hydrology, changes in monthly soil moisture storage and monthly groundwater storage are simulated for each time period using the mean ensemble. Figure 1 shows the average changes in storage for each catchment derived from all model runs.

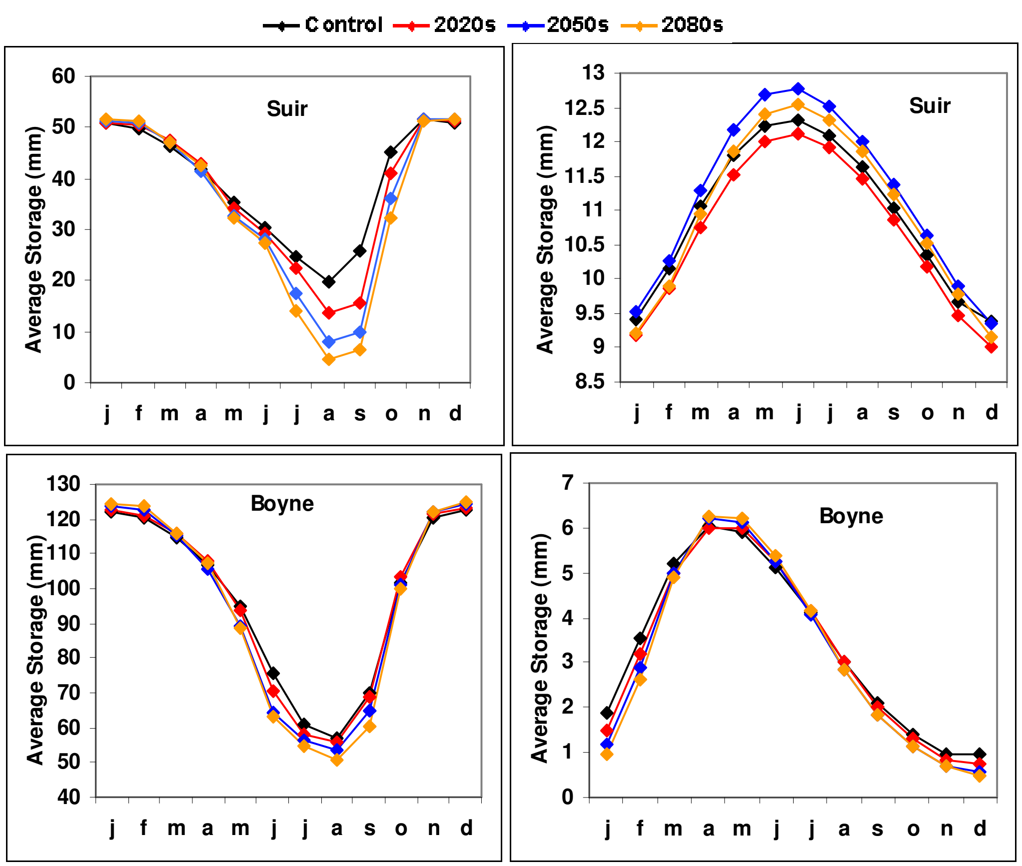

Figure 1 Changes in catchment storage simulated for the Suir and the Boyne catchments using the mean ensemble. Changes in soil storage are shown on the left, while changes in groundwater storage are shown on the right.

By the 2020s in the Suir reductions in soil storage are likely from late spring (May) through to mid-autumn (October). The greatest reductions by this time are suggested for the months of August and September with maximum decreases of –39% and –42% respectively. By the 2050s reductions in soil storage are likely from April to October, with the most substantial reductions again likely for August (-64 to -52%) and September (-64 to -60%). The most extreme reductions in soil storage are likely by the 2080s with reductions evident for seven months of the year, commencing in May and persisting until November. Average reductions in the order of –75% are likely for August and September, with maximum reductions of -80% in August. In terms of groundwater storage for the same catchment, the 2020s show slight reductions in storage for all months with greatest reductions likely for the important recharge months. By the 2050s slight increases of up to +4% are suggested for the majority of months as a result of increased precipitation. However, increases are marginal and the direction of change in the winter months is uncertain. By the end of the century greatest reductions are likely during the current recharge period, with reductions reaching a maximum of -4% during the winter months. Increases in groundwater storage of up to +3% are suggested for the rest of the year.

In the Boyne catchment reductions in upper soil storage are likely for five months of the year by the 2020s, beginning in May and persisting until September. Greatest reductions early in the century are suggested for June with an average reduction of –6% in upper soil storage. By the 2050s the number of months showing a reduction in storage increases to six (April to October) with reductions of –16 to -14% and –5 to -12% likely for June and July. Due to increased precipitation earlier in the year and the ability of soils in the Boyne to retain moisture, the number of months recording a reduction in storage by the 2080s is reduced to six. Greatest average reductions by this time are likely for the summer months with average changes of -16%, -10% and -10%. The greatest amount of uncertainty is associated with September where simulations suggest reductions ranging from -20 to -8%, while the direction of change on October is uncertain. Under the control period groundwater storage in the Boyne catchment reaches a maximum in April, while minimum storage levels are recorded in November and December. By the 2020s slight increases are simulated for May, June and July, the direction of change in April is uncertain, while decreases are suggested for the remaining months. The most significant decreases are likely for the winter months with reductions of -26 to -23%, -31 to -13% and -19 to -3% for December, January and February respectively. By the 2050s slight increases are again likely for the spring and early summer, however, by mid-century reductions become more extreme. During the autumn, reductions range from -30% to -10%, while winter decreases are in the order of –46% to –38%, -55 to -22% and -38 to -3%. The direction of change in groundwater storage is uncertain from March through to July. By the end of the century this trend becomes more pronounced. Again the direction of change is uncertain for spring and much of the summer, with simulations in March ranging from -26 to +9%. Most problematic are the reductions simulated by this period. Average reductions in autumn range from –12% to –30%, while reductions of –55 to -49%, -65 to -31% and –49 to -6% are suggested for the winter months. Once again the most significant reductions are likely to occur during the important recharge season.

When all catchments are considered, the impact of climate change on subsurface hydrology presents results that vary much between catchments and are largely driven by individual catchment characteristics, with infiltration rates and the ability to hold water limited by the infiltration capacity, the porosity and the type of subsurface material. Reductions in soil moisture storage throughout the summer and autumn are simulated for each catchment. The extent of decreases in storage are largely dependant on the soil characteristics of each individual catchment with the water-holding capacity of soil affecting possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. The highly permeable soils of the Suir, the Barrow, the Blackwater and the Ryewater all experience substantial reductions in storage, while reductions are not as pronounced for the less permeable Boyne and Moy catchments.

CHANGES IN MONTHLY STREAMFLOW

For each catchment the percent change in monthly streamflow derived from the A2, B2 and mean ensemble runs are presented, however only the results from the mean ensemble are discussed here.

Uncertainty bounds are constructed for the mean ensemble results using all of the selected behavioural parameter sets. In the graphs produced in Figures 2 the columns represent the average results obtained using the mean ensemble, with the error bars represent the range of uncertainty derived from the HYSIM model. Percent changes are calculated for each future time horizon through comparison with the 1961-1990 control period. Seasonal changes are defined as winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

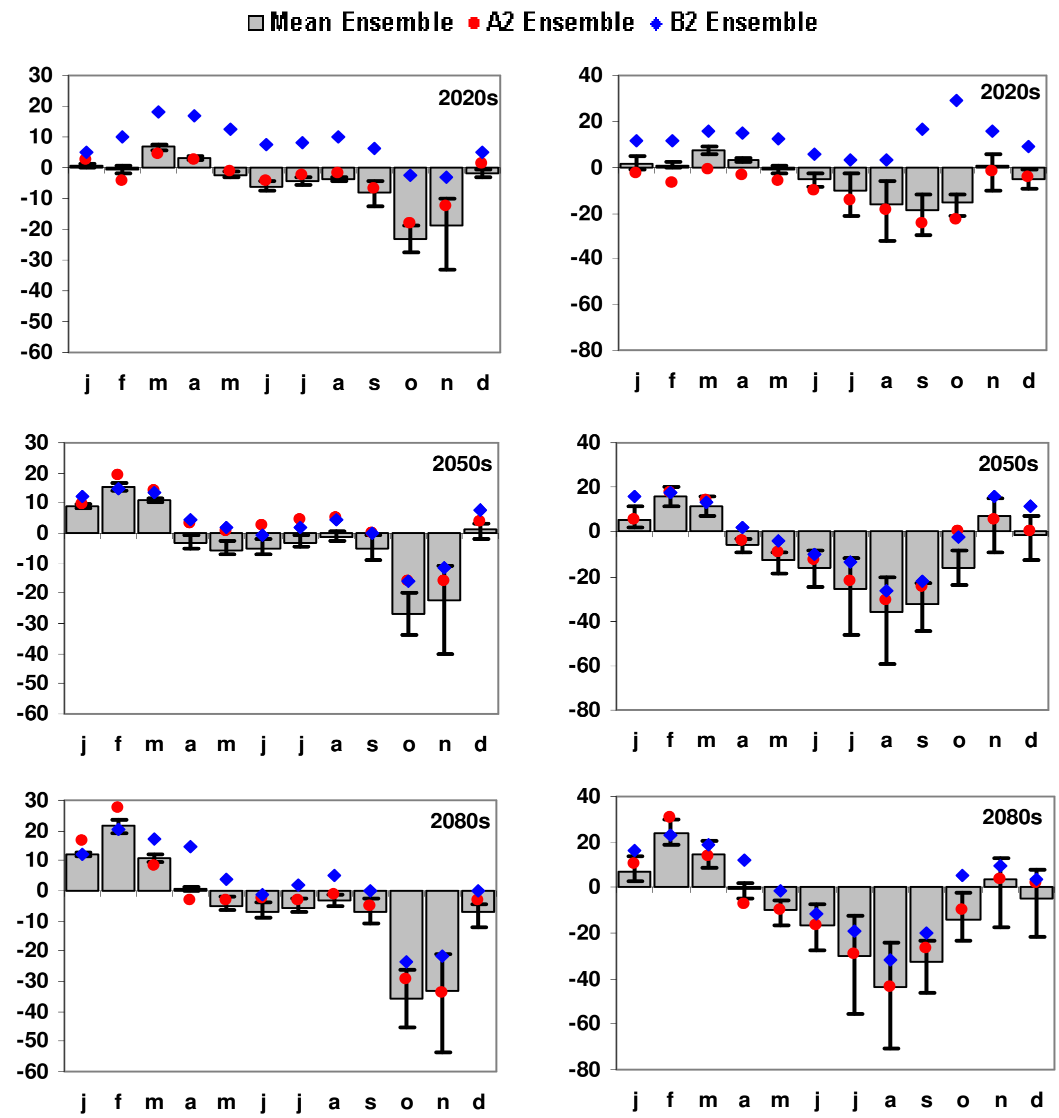

Figure 2 Changes in monthly streamflow for the Suir (left) and Boyne (right) under each of the ensembles constructed by Fealy and Sweeney (2006). Error bars show the uncertainty in future simulations derived from equifinality.

From the results obtained in the analysis of all catchments, the impact of climate change on streamflow is largely determined by catchment characteristics. In general there are two types of response evident, with the main distinction drawn between catchments with high infiltration rates, where the impacts are dampened by large groundwater storage capacities, and catchments with prevailing surface runoff. Similar results have been highlighted by Arnell (2003), Boorman (2003) and Gellens and Roulin (1998). Characteristic of groundwater-dominated catchments are the small changes in summer streamflow simulated for the Barrow, the Blackwater, the Suir and to lesser extent the Shannon sub-catchments. In catchments where surface runoff is more dominant (The Boyne and the Moy) reductions in summer are much more pronounced. In each of the catchments the greatest reductions in streamflow are likely for the autumn months and are thus consistent with changes in precipitation and evaporation. Although the pattern of change is similar in each of the catchments there are large differences in the magnitude of change between catchments. The month of February shows the most significant increases. As a result, flow seasonality is suggested to increase with higher flows in winter and spring, while extended dry periods are likely for summer and autumn. Furthermore, changes in precipitation tend to be amplified within the catchment system with larger percent changes suggested for streamflow due to the non-linear nature of catchment response. Considerable uncertainty ranges, where in some cases percent changes were shown to span a sign change, were found for future simulations of monthly streamflow and catchment storage.

The greatest amount of uncertainty in future streamflow simulations was shown to be derived from the use of different GCMs, with uncertainty ranges increasing with time. Uncertainty due to emission scenarios is found to be small in comparison to GCM uncertainty, especially by the 2050s and 2080s. Wilby (2005) highlights that uncertainty due to equifinality in rainfall-runoff model parameters is comparable to the magnitude of uncertainty due to emissions scenario. However, this research suggests that equifinality is a more important source of uncertainty, resulting in greater ranges of change in simulated flow than emissions scenario. Uncertainty due to equifinality also increases with time, with the greatest uncertainties associated with end of century results. Furthermore the magnitude of uncertainty for each of the sources analysed is shown to change with catchment characteristics. By comparing results for a runoff dominated catchment and a groundwater dominated catchment, uncertainty ranges were found to be more pronounced in the former.

CHANGES IN THE MAGNITUDE OF FLOOD EVENTS

In order to assess the impact of climate change on the magnitude of flood events, changes in the flow associated with selected return periods under the control period were analysed for each future time period. In total four flood events were chosen; the flood expected every 2, 10, 25 and 50 years. Therefore flood events ranging from fairly frequent (2-year) to moderately infrequent (50-year) are analysed. One of the key assumptions of flood frequency analysis is that the return period of a flood peak of a given magnitude is stationary with time (Cameron et al., 2000). In dealing with non-stationarity in the flood series Prudhomme et al. (2003) contend that it is possible to assume stationarity around the time period of interest (i.e. the 2020s, the 2050s and 2080s). Under this assumption, standard probability methodologies remain valid and are thus considered representative of the flood regime of the time horizon considered (Prudhomme et al., 2003). Similar assumptions are made in this work.

Simulations of changes in the magnitude of flood events were conducted using each GCM and both emission scenarios run with the best NS parameter set derived for each catchment. For each model run the maximum annual flood series was extracted for each future time period. The Generalised Logistic distribution was fitted to each series using the method of L-moments described in the Flood Estimation Handbook (FEH) (Robson and Reed, 1999). The short time series and corresponding limited number of flood events sampled make it difficult to identify the true underlying distribution of the flood regime in each of the catchments. Prudhomme et al. (2003) highlight that flood statistics estimated from such short records involve considerable sampling errors. In order to account for sampling uncertainty, confidence intervals were derived for calculations of flood magnitude for the control period simulations in each catchment using a balanced bootstrap approach. Prudhomme et al. (2003) also contend that these confidence intervals can be used to quantify the effect of natural variability on the flood distribution. For ease of presentation Figure 3 presents changes in the magnitude of flood events in the Boyne and the Suir as an average of results obtained for each GCM for both the A2 and B2 scenarios. The significance of changes are represented by the confidence intervals derived using the balanced bootstrap for the control period of each climate scenario.

In the Suir catchment while increases in the magnitude of selected flood events relative to the control period are simulated for each future time period under both the A2 and B2 emission scenarios, increases are within the range of natural variability. In the Boyne however, significant increases in the flow associated with each return period are suggested for the A2 scenario for mid and late century. Under the B2 scenario increases in the magnitude of all flood events are shown for each future time period. When the analysis is extended to all of the catchments analysed there is a consistent indication that the magnitude of future flood events will significantly increase in the majority of catchments. Generally, there is little regional variation present in the results with changes driven by increases in precipitation and individual catchment characteristics. However, the greatest increases in flood magnitude are suggested for the two most westerly catchments analysed, the Moy and the Suck, where by the 2080s under the A2 scenario, the magnitude of the 50-year flood is suggested to almost double. Greatest change in flood magnitude is associated with the largest floods, while the smallest changes are associated with the more frequent 2-year flood. Furthermore, for all catchments the range of uncertainty is proportional to the frequency of the flood event, with largest uncertainty ranges shown for rarer events

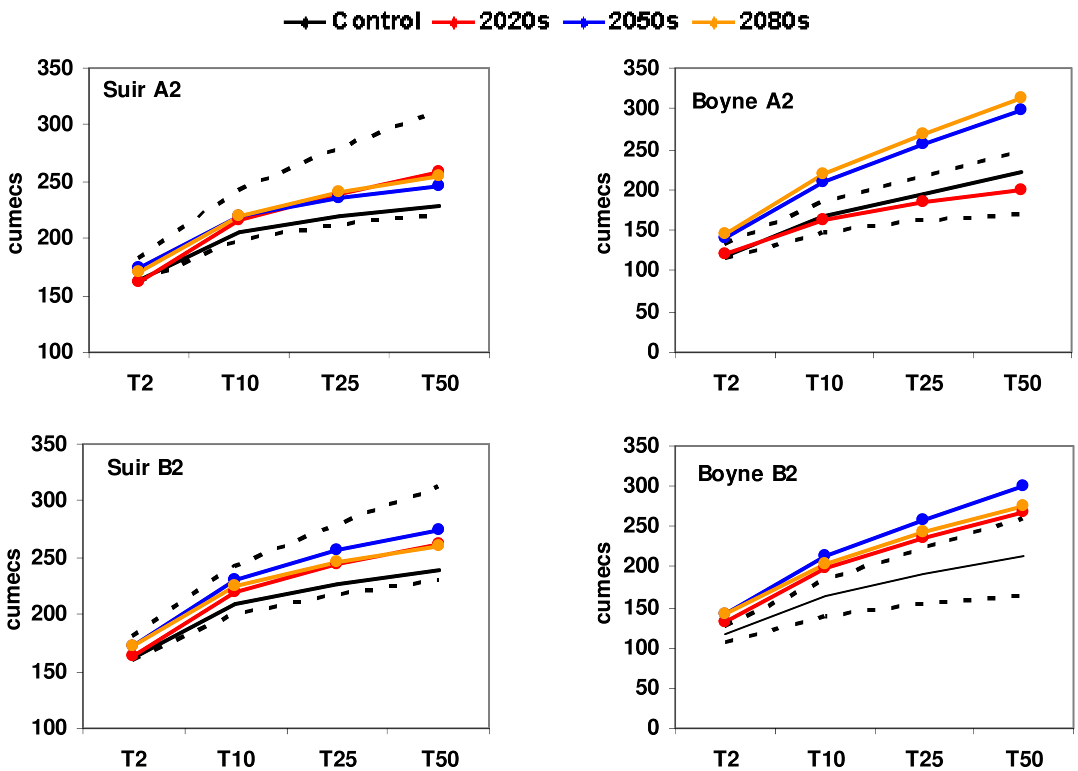

Figure 3 Changes in the magnitude of selected flood events in the Suir and the Boyne under the A2 and B2 emission scenarios. Changes are represented as the average change simulated by each GCM.

KEY VULNERABILITIES

From the above analysis a number of key vulnerabilities come to the fore. Reductions in soil moisture of the scale simulated in many of the catchments will have huge implications for agricultural practices, while increased winter and spring precipitation as well as more frequent wetting and drying may affect the nutrient status of many soils. From the results obtained it can be inferred that soil moisture deficits will become more pronounced, as well as begin earlier and extend later in the year than currently experienced. In terms of groundwater storage, lower levels of recharge and thus lower groundwater levels are likely to result in a shift in the nature of groundwater-surface water dynamics for entire rivers (Scibek and Allen 2005). By mid to late century significant reductions in storage during the recharge period will increase the risk of severe drought as the failure of winter or spring precipitation may result in prolonged drought periods where the groundwater system is unable to recover from previous dry spells. Such impacts would be greatest in catchments where groundwater attenuation is greatest.

The most notable reductions in surface water are simulated for the Ryewater and Boyne. These catchments are the most heavily populated in the analysis and comprise a substantial proportion of the Greater Dublin Area (GDA). Taking account of projected population growth, with the population of the region projected to double by 2031, existing primary sources of water supply are likely to become further stretched over the coming years. The suggested increases in the magnitude and frequency of flood events may have significant impacts in a number of areas such as property and flood plain development, the reliability of flood defences, water quality and insurance costs. Locating development in areas that are susceptible to flooding has lead to property damage, human stress, and economic loss in the past. Increases in flood frequency and magnitude in areas currently prone to such damages is likely to increase in the future. Furthermore, given the scale of changes that are suggested, it is likely that areas that are not presently prone to flooding may become at risk in the future, especially areas that are located close to the confluence of major rivers.

In light of these vulnerabilities, adaptation to climate change presents new challenges to water resources management requiring innovative approaches to complex environmental and social problems. In Ireland there are a number of opportunities for efficient adaptation, some of which are already at the initial stages of implementation and others for which the capacity to adapt is greatly aided by the institutional structures already in place. Over the coming decades, the management of future water resources and the capacity to adapt to a changing climate is dependent on the ability to incorporate both technological and scientific advances into decision-making processes in an integrated and environmentally sustainable fashion. With this in mind, adaptation should be focused on reducing the sensitivity and increasing the resilience of water resources systems, as well as altering the exposure of the system, through preparedness, to the effects of climate change (Adger et al., 2005) In doing this, while the role of integrated assessment is indispensable in adapting to climate change, critical gaps still exist between environmental assessment and the provision of robust information for decision makers and risk managers with much work required for dealing with large uncertainty ranges.

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