3 Climate Change and Water Resources

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3.1 Introduction

On every scale, changes in global climate are likely to have significant impacts on hydrology and water resources, with increased energy resulting in an intensified hydrological cycle. Given the complex and fragile interaction between the climate system and land-surface hydrology, any changes in the primary processes of precipitation and evaporation will have considerable knock-on effects for the rest of the hydrological cycle. It is not just surface components of the hydrological cycle that show likely changes as a consequence of global warming, subsurface hydrological processes are also likely to be altered. Previous work (Charlton and Moore, 2003) highlighted the likely changes in effective run-off on a national basis. The major findings from this work showed that:

- A widespread reduction in annual run-off is likely, with reductions most marked in the east and south-east of the country
- Winter run-off is likely to increase in the west
- All areas are likely to experience a decrease in summer run-off, with the greatest reductions in the east of the country
- The frequency and duration of low flows are likely to increase in many areas.

Such changes are likely to increase the pressures placed on water resources in many parts of the country. Therefore, this work aims at refining the impacts of climate change on strategically important catchments. In order to take account of uncertainty, downscaled output from three global climate models (GCMs), forced using two emissions scenarios, is used as input to a rainfall run-off model, which is calibrated for each individual catchment. The uncertainty derived from the use of a particular impacts model is also quantified. Changes in catchment storage, average monthly streamflow, streamflow variability, flow percentiles and the magnitude and frequency of extreme events are assessed for each catchment. Key impacts and areas of future vulnerability are highlighted.

3.2 Uncertainty in Future Hydrological Simulations

When modelling the effects of climate change on water resources there is a cascade of uncertainty that begins when future socio-economic storylines are translated into future emission scenarios and ends with impact modelling (Wilby, 2005). As outlined in Chapter 2, large amounts of uncertainty surround the development of future emissions scenarios, while GCM predictions over the current century are necessarily uncertain, both because the sensitivity of the climate system to changing greenhouse gas concentrations as well as the rate of ocean heat uptake is, as yet, poorly quantified (Stott and Kettleborough, 2002). Furthermore, different GCMs show varying sensitivities to similar greenhouse gas forcing, thus producing wide ranges of model output in terms of future changes in temperature and precipitation. As a result, impact modellers and planners are faced with the use of a wide range of predicted changes from different models of unknown relative quantity, owing to large but unquantified uncertainties in the modelling process (Murphy *et al.*, 2006).

As well as uncertainties cascaded into impacts models, impacts models themselves give rise to uncertainty. Conceptual rainfall run-off (CRR) models have been the most widely applied for climate impact assessment (Cunnane and Regan, 1994; Arnell and Reynard, 1996; Sefton and Boorman, 1997; Pilling and Jones, 1999; Arnell, 2003; Charlton and Moore, 2003). However, 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. Consequently, CRR models incorporate large simplifications in order to represent catchment hydrology. One of the major consequences of such simplifications is the generation of uncertainty within the modelling framework. Such uncertainty is seen in the process of parameter estimation with the inference of values for parameters that cannot be directly measured relying heavily on calibration to an observed time series of river flow. Such calibration is associated with well-known limitations attributable to parameter identifiability, parameter stability, uncertainty and the equifinality of outputs arising from different combinations of model parameters. Wilby (2005) has shown that uncertainty derived from subjective choices in model calibration can be as large as the uncertainty derived from the use of different emissions scenarios. Consequently, there is an 'explosion' or 'cascade' of uncertainty associated with climate impact assessment, with the magnitude of uncertainty being multiplied through each step in the methodology (Jones, 2000). It is therefore desirable to quantify this uncertainty, so that the full range of possible future impacts can be accounted for.

3.3 Research Outline

This research follows a well-established methodology for simulating the impacts of climate change on water resources. The ensembles derived from each GCM run using both emissions scenarios are used to drive a hydrological model representing the catchment system, so that simulations of future changes can be assessed. A CRR model, applied on a daily time step, is calibrated on past hydrological and climatological data for each catchment in the analysis. Central to the use of CRR models in climate impact assessment is their ability to represent the catchment system as a simplified agglomeration of stores representing catchment processes, thus enabling such models to be applied to a wide variety of catchments. Simplification results in the reduction of the amount of data necessary to run the model and, in turn, CRR models tend to contain a small number of parameters, many of which can be measured from physical reality. Consequently, simple model structures and ease of application have led to the widespread use of CRR models in climate impact assessment. Once validated, the rainfall run-off model is used to simulate hydrological conditions over the time period 1961–2099.

By forcing the CRR model with downscaled output, hydrological simulations are derived for four time periods, the control (1961–1990), the 2020s (2010–2039), the 2050s (2040–2069) and the 2080s (2070–2099). Changes in monthly streamflow and catchment storage are derived for each of the ensemble runs by assessing the difference between the control and each future time period. Given the weighted averaging employed for the generation of ensembles, such data are not suitable for the examination of extremes. Therefore the simulated outputs for each GCM and each scenario are run individually in determining changes in future flood frequency and percentile analysis.

In total, nine catchments throughout Ireland are considered. These are shown in Table 3.1. The catchments were chosen so that as broad a range of

Table 3.1. Catchments studied, their location and summary statistics.

Catchment	Area (Km)	Gauge	Data (days)	Mean rainfall (mm)	Mean ET (mm)	Mean discharge (cumecs*)	Land use	Soil texture
Suir	3,556.00	Clonmel	14,610	2.7	1.27	48.2	Pasture	Loam
Blackwater	3,245.70	Ballyduff	14,610	3.1	1.5	62.3	Pasture	Loam
Boyne	2,670.50	Slane	14,610	2.4	1.22	35.4	Pasture	Clay Loam
Moy	1,980.87	Rahans	9,862	3.9	1.22	57.9	Peat Bogs	Loam
Barrow	2,956.00	Levitstown	11,688	2.5	1.27	20.9	Pasture	Sandy Loam
Brosna	1,082.50	Ferbane	14,610	2.4	1.22	17.1	Pasture	Loam
Inny	1,072.50	Ballymahon	10,227	2.6	1.22	18.7	Pasture	Loam
Suck	1,050.00	Bellagill	9,498	2.8	1.22	25.2	Pasture	Loam
Ryewater	213.90	Leixlip	14,610	2.2	1.5	2.3	Pasture	Clay Loam

*1 cumec represents a flow of 1 m^3/s.

hydrological conditions as possible was considered. Furthermore, strategically important catchments, such as the Ryewater, a major tributary of the Liffey, were included. Catchments of varying size are also represented. The largest catchment in the analysis is the River Suir with a catchment area of approximately 3,556 km^2 while the smallest is the Ryewater with an area of just over 213 km^2. The number of days of available data, the mean daily rainfall and evapotranspiration, daily mean discharge, as well as the predominant land use and soil textural properties are presented in Table 3.1. Figure 3.1 provides the location of each catchment. Baseline (1961–1990) precipitation and evapotranspiration data were obtained from Met Éireann, while daily streamflow data for each gauge were obtained from the Office of Public Works (OPW).

3.4 Rainfall Run-Off Model Overview and Application

3.4.1 HYSIM overview

The Hydrological Simulation Model (HYSIM) is a CRR model, which uses rainfall and potential evaporation data on a daily time step, to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. HYSIM has been used for a variety of hydrological applications including assessing the impacts of climate change on the hydrological cycle (Pilling and Jones, 1999; Charlton and Moore, 2003; Murphy *et al.,* 2006). The complete flow diagram of the structure of the model is

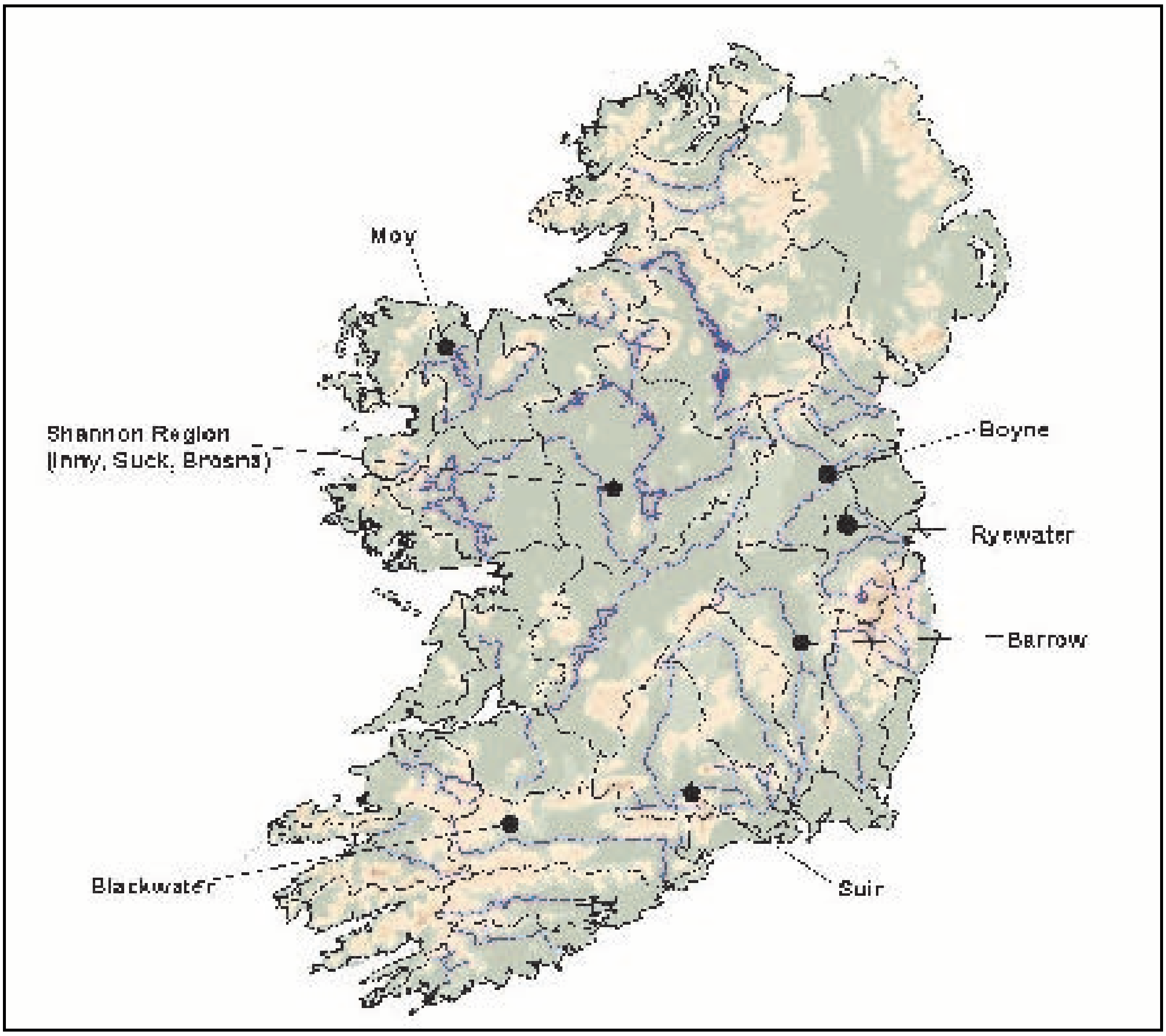

Figure 3.1. Location of each of the study catchments.

given in Fig. 3.2. Seven natural stores are employed to represent catchment hydrology. 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 *et al.* (2006).

Parameters within HYSIM can be broken down into two groups, the physical parameters and the process or 'free' parameters (Sorooshian and Gupta, 1995). The former represents physically measurable properties of the watershed, whereas process parameters represent watershed characteristics that are not directly measurable, such as the lateral interflow rate. There are two approaches to fitting the model: the first involves the specification of the physically measurable parameters, while the second involves the optimisation of process parameters. A split sample procedure was adopted for calibration and validation. The first 30 years of the baseline data set (1961–1990) 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 the global instrumental record. In Ireland, the warmest year was recorded in 1997. Furthermore, the 10 years 1991–2000 present some of the largest flood peaks on record in Ireland, such as the November 2000 floods 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 than at any other period in the baseline data set.

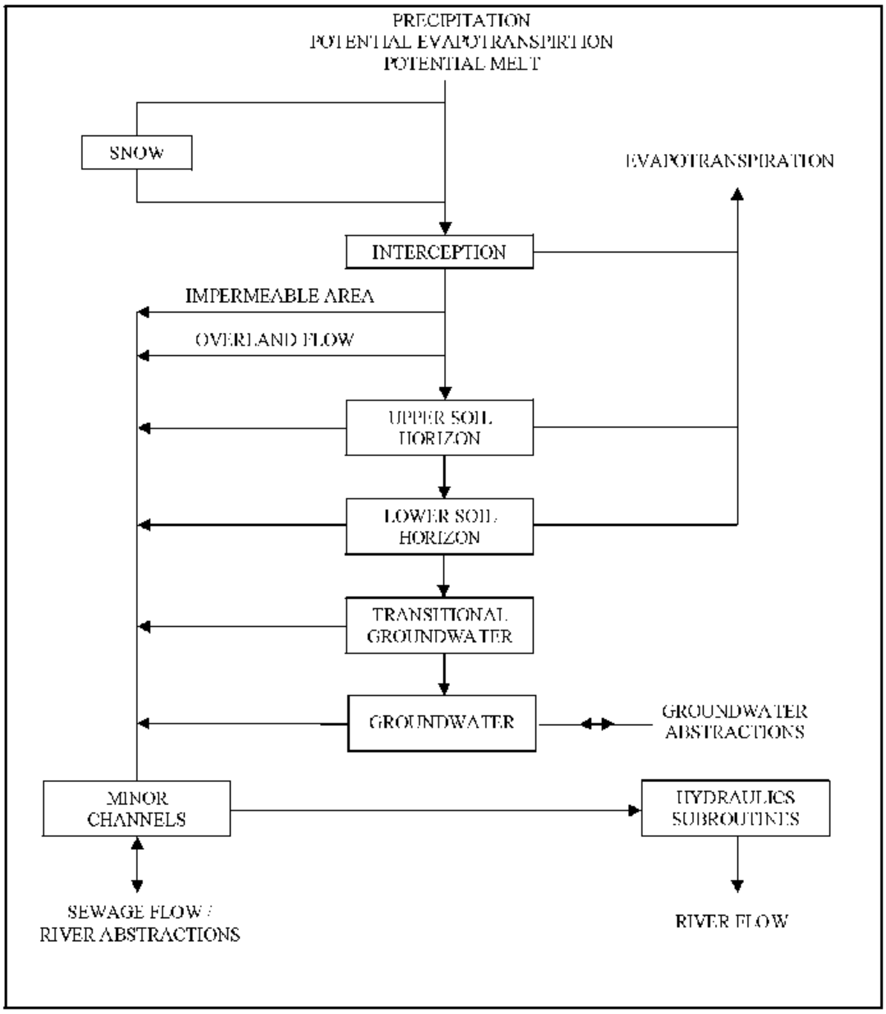

Figure 3.2. Hydrological Simulation Model (HYSIM) structure.

3.4.2 Deriving physical parameters

The first method to consider when parameterising the model was the specification of physical characteristics of each catchment. The incorporation of a Geographical Information System (GIS) has the potential to dramatically increase the speed, accuracy and reproducibility of catchment parameterisation, while in turn reducing the subjectivity of the model user (Pullar and Springer, 2000). Consequently, the use of a GIS was central to the parameterisation procedure. The first task was the delineation of catchment boundaries using the EPA's Digital Elevation Model (DEM). Automated digital terrain analysis methods are available to derive most watershed characteristics that cannot be readily derived using common GIS tools.

Soil hydrological properties were calculated from the General Soil Map of Ireland (Gardiner and Radford, 1980). Once the catchment boundary was delineated it was used to extract the relevant data for each catchment. Each soil association within the catchment was examined and the proportions of the soil type and its location within the catchment were considered. The dominant soil texture was calculated by establishing the percentage sand, silt and clay in each soil association with the derived texture being used to calculate the soil parameters. Vegetation parameters were obtained using the CORINE (Coordination of Information on the Environment) data set (O'Sullivan, 1994). Again the catchment boundaries were used to cookie-cut the desired data (see Fig. 3.3). Due to the

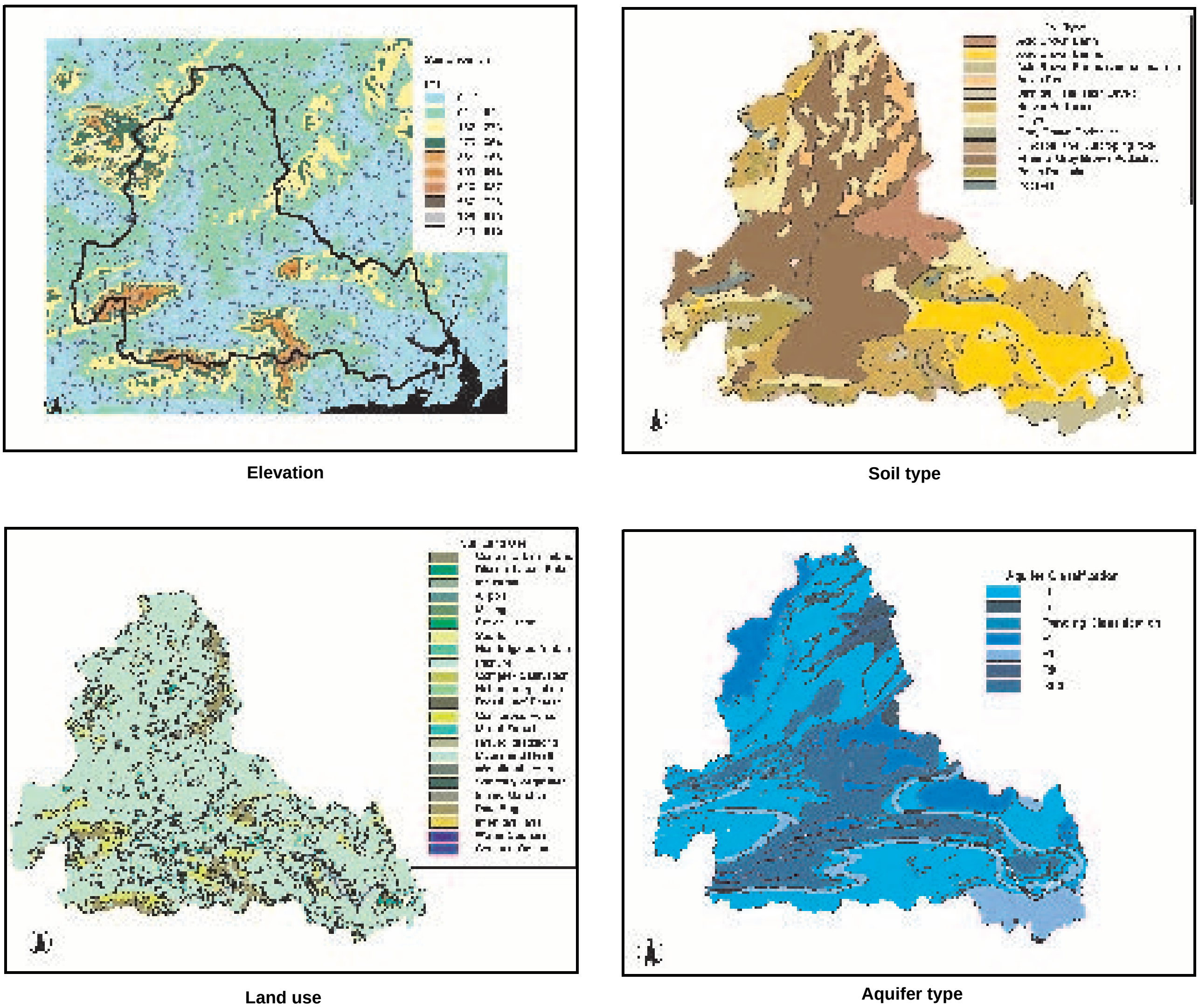

Figure 3.3. Calculation of physical parameters for the Suir catchment through the incorporation of GIS techniques.

lumped nature of the model, the land use with the highest percentage was used to derive the land-use parameters. Many of the groundwater parameters were calculated from flow records while others were estimated using the Aquifer Map of Ireland (Geological Survey of Ireland (GSI), 2003) (Fig. 3.3).

3.4.3 *Process parameter estimation and uncertainty quantification*

Within HYSIM, calibration is catered for by a multi-parameter optimisation procedure. HYSIM employs the Rosenbrock method, a local search algorithm using a direct search method. Blackie *et al.* (1985) provide details on the functioning of the Rosenbrock method. In order to calibrate the model, a number of objective functions were employed. These comprised the Nash–Sutcliffe (NS) efficiency criterion, the Coefficient of Determination (R^2), the Mean Actual Error (MAE) and the Percent Bias (PBIAS). Both correlation and relative error measures were included as the use of correlation-based measures alone can be oversensitive to extreme values and are insensitive to additive and proportional differences between model predictions and observations (Legates and McCabe, 1999). Only results for NS and PBIAS will be given here. For NS, values of 1 indicate a perfect fit while a PBIAS of 0% is ideal. Once the optimum parameter set was realised for each catchment, the Rosenbrock algorithm was restarted using different parameter values in order to establish whether the results relate to a local or global optimum (Blackie *et al.,* 1985). When different starting points were used, different end values were encountered due to problems related to the parameter response surface. Sorooshian and Gupta (1995) highlight a number of difficulties associated with the parameter response surfaces that are common to CRR models. These include the presence of several major regions of attraction into which the search algorithm may converge. Furthermore, where parameters exhibit varying degrees of sensitivity a great deal of interaction and compensation may be evident (Sorooshian and Gupta, 1995). These obstacles make it very difficult for a local search strategy such as the Rosenbrock method to progress towards a global optimum and results in uncertainty in model output.

Therefore, uncertainty is seen in the process of parameter estimation and, as a result, it is necessary to quantify the uncertainty derived from the estimation of the process parameters. Uncertainty evaluation generally holds that all acceptable parameters or models of a system be retained until they are disproved and consists of analysing the range of parameter sets that are acceptable for a specific application (Wagener, 2003). These plausible models are used to construct uncertainty bounds or confidence limits for model output. One established method for uncertainty analysis is the Generalised Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992).

The GLUE procedure starts with the recognition that many model structures or parameter sets within a given model framework will simulate a required output. Given this concept of equifinality it follows that no single optimum set of model parameters can be readily identified (Beven, 1993). Consequently it is only possible to assign a likelihood value to each parameter set, indicating that it can predict the system and that the set of parameters provides an acceptable or behavioural simulation of the observed flow (Beven and Binley, 1992). The GLUE procedure has five main steps (Beven and Binley, 1992):

1. The definition of a likelihood measure, chosen on the basis of an objective function to determine model performance

2. The definition of a prior distribution for each parameter

3. Parameter sets are sampled from the defined prior distributions using sampling techniques such as Monte Carlo Random Sampling and Latin Hypercube Sampling

4. Each parameter set is classified as behavioural or non-behavioural through assessing whether it performs above or below a predefined threshold

5. Predictive model runs generate results from each of the parameter sets that yield acceptable calibration simulations. These combined simulations are in turn used to determine the weighted mean discharge and simulation

probability bounds (Melching, 1995).

In implementing the GLUE procedure for each catchment, the NS efficiency criterion was adopted as the likelihood measure. Behavioural parameter sets were taken as those with an efficiency value above 0.7. A uniform distribution was attributed to each process parameter (as proposed by Beven and Freer, 2001) and values were generated using Latin Hypercube Sampling. For more information on the techniques employed see Murphy *et al.* (2006). Using the example of the Suir catchment, these parameter sets were run for the calibration period 1961–1990 and, of these, 50 were retained as behavioural with efficiency values ranging from 0.701 to 0.825. In order to validate these parameter sets, a blind simulation was conducted on each set for the validation period 1991–2000. From the 50 behavioural parameter sets obtained during calibration, all were retained as acceptable sets in representing the period 1991–2000. For the validation period, model efficiency ranged from 0.702 to 0.852.

In order to ascertain the representativeness and thus the range of conditions provided by the 1961–1990 calibration period, the transferability of parameter sets over wet and dry periods was assessed for the validation years. The ten most skilful parameter sets were extracted and run for both the calibration and validation periods as well as for individual years within the validation period. On a decadal timescale the 1970s are representative of a relatively dry decade while the 1980s are considered to be wet. Therefore, the calibration period provides a wide range of flow conditions on which to train the model. The NS efficiency value and the PBIAS of the ten most skilful parameter sets for each catchment were analysed. Tables 3.2 and 3.3 show the results obtained for the calibration and validation period for each catchment using the NS efficiency criterion. Good results are achieved for each catchment, with efficiency values remaining high when parameter sets are transferred to the validation period. Only four catchments, the Brosna, Inny, Moy and Suck, show a general reduction in model performance during the validation period. However, the reductions in performance are only slight with values always remaining above the 0.7 threshold value. Improvements in model performance are evident for the Barrow, the Blackwater, the Ryewater and the Suir, while performance for the Boyne remains similar during both calibration and validation. Figure 3.4 shows the validation uncertainty bounds for the Suir at Clonmel.

The transferability of parameter sets for individual years as well as between wet and dry years in the validation period also proved successful. The inclusion

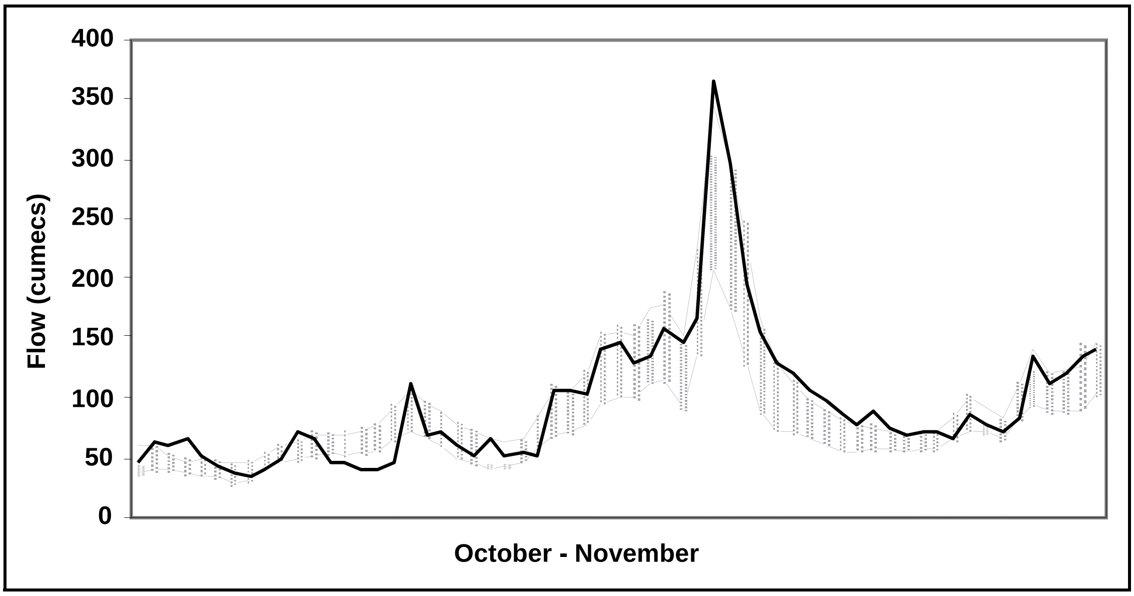

Figure 3.4. Uncertainty bounds generated for the Suir at Clonmel. The peak marks the largest flood in the validation period.

Table 3.2. Top ten Nash–Sutcliffe values obtained for each catchment during calibration.

	Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
Top ten parameter sets	80.1	77.7	85.1	83.0	85.2	89.5	73.5	72.6	79.3
	79.9	77.7	85.0	83.0	85.1	89.5	73.4	72.5	79.3
	79.9	77.6	85.0	82.9	84.9	89.5	73.1	72.5	79.2
	79.8	77.6	84.8	82.9	84.9	89.5	72.8	72.5	78.8
	79.7	77.6	84.7	82.6	84.9	89.4	72.8	72.5	78.8
	79.7	77.3	84.6	82.2	84.5	89.4	72.5	72.5	78.3
	79.6	77.3	84.6	82.0	84.5	89.4	72.5	72.4	78.2
	79.6	77.1	84.5	82.0	84.5	89.4	71.9	72.3	77.9
	79.5	77.0	84.5	81.8	84.4	89.4	71.8	72.2	77.9
	79.5	76.8	84.2	81.6	84.1	89.3	71.4	72.2	77.8

Table 3.3. Top ten Nash–Sutcliffe values obtained for each catchment during validation.

	Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
Top ten parameter sets	81.5	83.2	85.1	82.0	78.4	86.5	80.8	72.3	81.6
	81.4	82.9	84.7	81.9	78.3	86.5	80.4	72.1	81.5
	81.3	82.8	84.5	81.8	78.2	86.5	80.4	71.7	81.3
	81.3	82.5	84.4	81.7	78.2	86.5	78.3	71.5	80.2
	81.2	82.4	84.4	81.5	78.1	86.4	77.9	71.5	80.1
	81.2	82.1	84.3	81.4	78.0	86.4	77.7	71.4	80.1
	81.1	82.1	84.2	81.1	77.8	86.4	77.6	71.3	80.0
	81.1	81.8	84.0	81.1	77.8	86.4	77.5	71.3	79.9
	81.1	81.6	84.0	80.8	77.8	86.4	77.1	71.2	79.7
	81.1	81.4	83.9	80.7	77.7	86.3	76.9	71.2	79.5

of these results is beyond the scope of this report and interested readers should refer to Murphy *et al.* (2006). Given that the 10 years used for validation (1991–2000) comprise the warmest decade on the instrumental record and provide the best available surrogate for expected future conditions as a result of climate change, the results achieved indicate that the calibration period provides a representative sample of the range of hydrological conditions for the Suir.

3.5 Future Simulations

The use of different objective functions in assessing model performance results in the extraction of different optimum parameter sets for each function. Unfortunately, it is not yet clear how populations of parameter sets should be selected for operational use (Wagener, 2003). In order to overcome this, a combination of the top parameter sets, as defined by each objective function, was retained and run using the downscaled GCM data. For each catchment HYSIM was run for each GCM using both scenarios and all of the derived parameter sets. Consequently, future simulations capture a degree of the inherent uncertainty derived from data measurement, parameterisation, the use of different objective functions, GCM climate sensitivity and uncertainty due to different emissions scenarios.

3.5.1 Changes in catchment storage

Changes in temperature and precipitation will alter subsurface hydrology, with significant changes in soil moisture storage, groundwater recharge and groundwater storage likely. Gregory *et al.* (1997), show that a rise in greenhouse gas concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers, while Scibek and

Allen (2005) indicate that reductions in baseflow are anticipated due to the lowering of groundwater gradients in many aquifers. Peters *et al.* (2005) contend that decreases in precipitation and increases in evapotranspiration cause low soil moisture content, which in turn causes low groundwater recharge. 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. It is important to recognise that in terms of groundwater storage, each aquifer is unique in its geology, its geometry and the nature of its connection with surface waterbodies. Given the lumped conceptual nature of HYSIM, only an indication of large-scale changes in catchment storage can be made; however, these are extremely important in highlighting the direction and magnitude of future change, as well as areas where further research is required. Figure 3.5 depicts changes in storage simulated for each catchment.

3.5.1.1 Inny

Soils within the Inny catchment include Gleys, Grey Brown Podzolics, Minimal Grey Brown Podzolics and substantial amounts of Basin Peat. Due to the greater amount of summer precipitation in the midlands and west under the current climate, the seasonal variations in soil moisture storage are not as pronounced in the Inny catchment as they are in eastern catchments such as the Ryewater. This is evident under the control period where the transition from winter to summer storage levels is quite gradual. However, this is likely to be altered as a result of climate change with decreases in spring, summer and autumn becoming more pronounced. By the 2020s, slight reductions in soil moisture storage are evident for many of the summer and autumn months; however, reductions are only in the range of –5%. By the 2050s, the greatest reductions are suggested for August (–19%) and September (–20%). By this time, 7 months show a reduction in storage, from April through to October. Reductions in soil moisture storage in the Inny catchment are likely to be most severe by the 2080s with decreases of approximately –30% likely for August and September. Substantial reductions are also evident for the summer months of June (–12%) and July (–15%).

The Inny catchment has abundant groundwater resources, with extensive faulting and karstification greatly influencing permeability. The vast majority of the catchment (75%) is comprised of locally important aquifers. Although these are less transmissive than the regionally important aquifers, they are very permeable along faults and fractures (GSI, 2003). Under the control period, groundwater storage in the Inny reaches a maximum in the months of April and May and gradually decreases through the summer and autumn months as the importance of baseflow to sustaining streamflow increases. The minimum storage is recorded in November; thereafter the amount of water in storage begins to increase. By the 2020s, there is little change in groundwater storage with slight increases and decreases evident. By the 2050s, however, there is a substantial increase in storage from March to July as a result of increased precipitation. Little change is suggested for the summer and early autumn months; however, reductions are simulated during the recharge period with reductions likely for November (–10%), December (–18%) and January (–7%). By the 2080s, increases in groundwater storage are evident from February to September, with a maximum increase of +12% in April. Again decreases are likely during the late autumn and winter with reductions of –9%, –22% and –11% in November, December and January, respectively.

3.5.1.2 Brosna

Due to its similarity in terms of physical characteristics, climatic regime and close geographical proximity, the response of soil moisture storage in the Brosna is very much similar to that in the Inny. By the 2020s, slight reductions are evident for 5 months, beginning in May and ending in September. Greatest reductions by the 2020s are likely for August with a reduction of –7% relative to the control period. By the 2050s, substantial reductions are suggest throughout the summer months and for the early to mid-autumn. Reductions in the order of –20% to –25% are suggested for August and September. Again the greatest decreases are likely by the 2080s. By this time it is likely that reductions in storage will be experienced for 6 months of the year, beginning in May (–7%) and continuing until November (–5%). Most significant by the 2080s are the simulated reductions for August (–39%) and September (–32%).

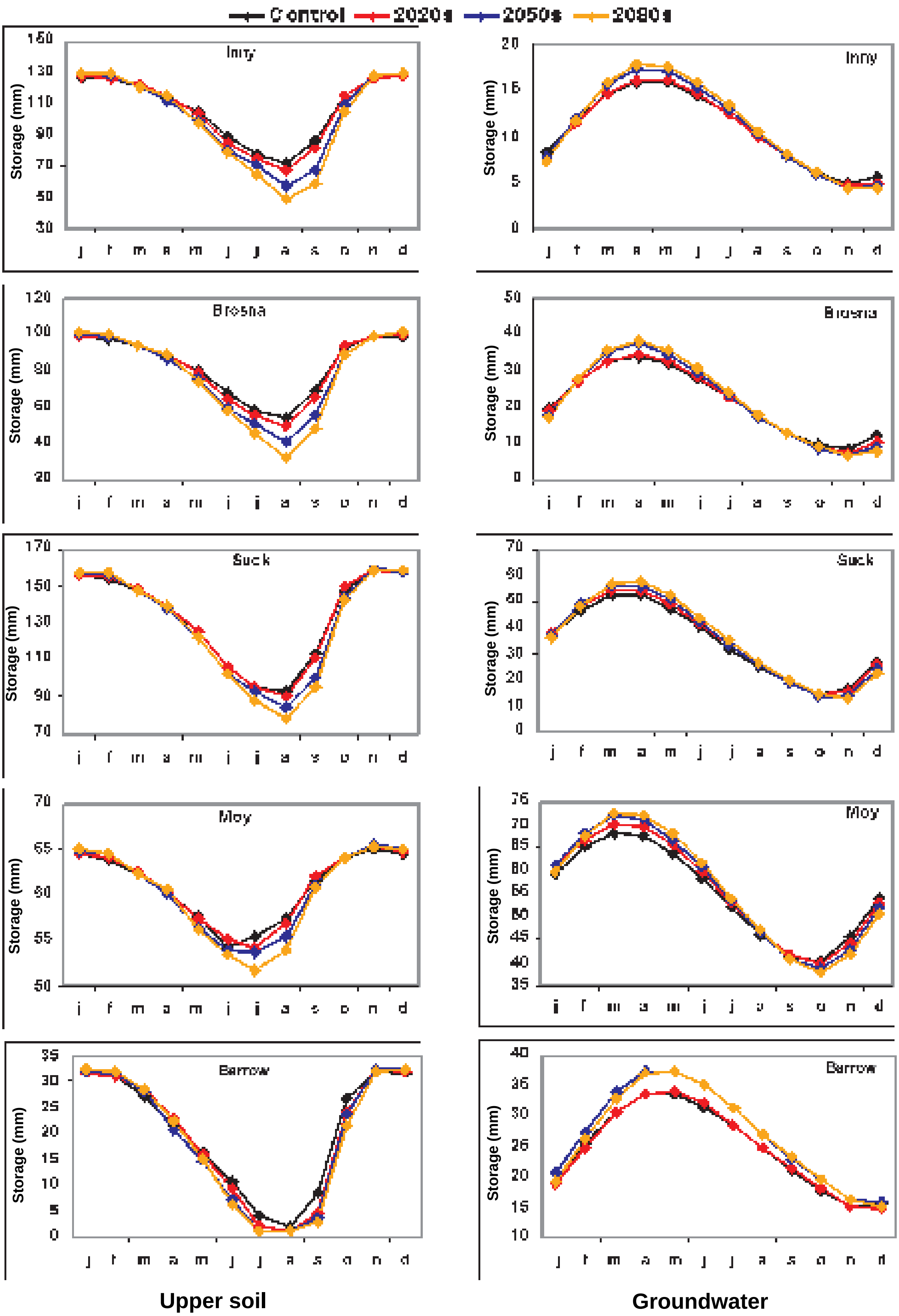

Figure 3.5. Changes in catchment storage for each future time period under the mean ensemble.

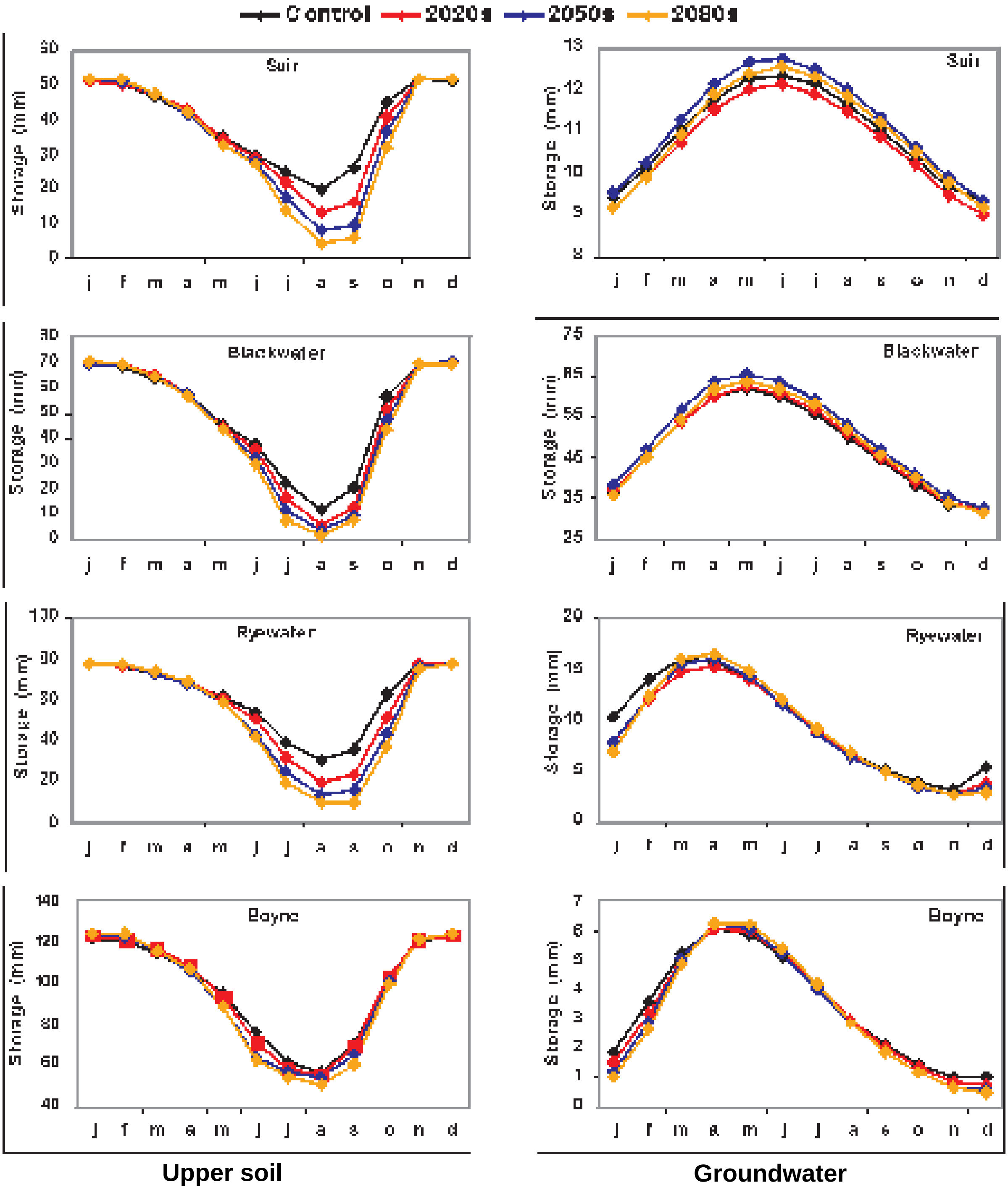

Figure 3.5 ***contd.***

The remainder of the summer months also shows substantial reductions in storage of –15% and –20% in June and July, respectively.

In terms of aquifer potential, over 20% of the Brosna is comprised of regionally important aquifers. Much of the catchment is covered by limestone glacial till and morainic gravels. The dominant rock units within the catchment are pure bedded and unbedded Dinantian limestones. Under the control period, storage reaches a maximum in April and gradually decreases thereafter through the summer and early autumn, with a minimum storage reached during November. By the 2020s, there is little change in groundwater storage for the majority of the year. However, there are substantial decreases at the end of autumn and early winter, with decreases of –14% and –15% suggested for November and December, respectively. By the 2050s, increases in storage of +10% are likely during the spring and early summer. By this time, decreases are likely from August through to February, with greatest reductions again likely at the end of autumn and the beginning of winter, with the months of November and December showing decreases of –23% and –25%, respectively. Greatest change in groundwater storage is likely by the 2080s with increases of between +10% and +13% likely for the spring months. Little change is likely for the summer; however, substantial decreases are likely during the important recharge period with reductions of –25%, –33% and –11% likely for November, December and January, respectively.

3.5.1.3 Suck

Predominant soil types in the Suck are poorly drained and heavily textured. During the 2020s, slight reductions are evident for only 3 months of the year (July, August and September). By the 2050s, reductions in storage are extended to 7 months, beginning in April and extending to October. Greatest reductions are likely for the month of September, with a reduction of approximately –12% evident by this period. For the remainder of the months, reductions are all less than –10%. By the 2080s, reductions are slightly greater; however, the greatest reductions only reach –15% in August and September.

The dominant hydrogeological characteristics of the Suck catchment are the widespread coverages of Dinantian pure bedded limestone and limestone glacial tills. Almost 75% of the catchment consists of regionally important aquifers with the potential for groundwater storage being the largest among the Shannon sub-catchments considered. Under the control period, greatest groundwater storage is achieved in March and April. In the summer and early autumn, storage levels are shown to decrease more rapidly than in the Inny and the Brosna, with minimum storage reached earlier in the year (October). By the 2020s, a slight increase in storage is suggested for the majority of months, with slight decreases likely for the last 3 months of the year. By the 2050s, decreases of between –10% and –15% are likely for November and December. By the 2080s, increases in storage of approximately +10% are suggested from March to July. By this time, minimum groundwater storage is likely to occur in November with reductions of –20%. Substantial reductions are also likely for December.

3.5.1.4 Moy

Soils within the Moy are poorly drained with significant deposits of Blanket and Basin Peat. During the control period, soil storage reaches a minimum in June and increases thereafter. The timing of minimum storage is delayed until July by mid to late century as a consequence of climate change. By the 2020s, only slight reductions (all less than –3%) are suggested for the months of May, July, August and October. More consistent drying is likely by the 2050s with reductions suggested from May to October. However, these reductions remain minimal when compared to other catchments. By the 2080s, drying persists for these months with greatest reductions of –6%. The ability of soils within the Moy catchment to retain moisture may be the cause of reductions being less pronounced than in other catchments. Increases in evaporation are not as strong for the west of the country, while more energy is required to remove water from the soil due to the increased forces of capillary suction in the heavily textured soils.

The geology of the Moy catchment is extremely complex with the groundwater storage potential of rock varying hugely. In terms of aquifer potential, almost 30% of the catchment is underlain by poorly productive bodies. Subsoils within the catchment are largely comprised of limestone and sandstone glacial till. Under the control period, groundwater storage reaches a maximum in early spring, reducing thereafter to an October minimum. By the 2020s, slight reductions are likely for October, November and December. By the 2050s, the same general trend is maintained although both increases and decreases are slightly more pronounced. Greatest change is simulated for the 2080s, with increases reaching a maximum of +7% in March and April. Decreases in storage of between –5% and –7% are likely for the last 3 months of the year. It is interesting to note that the Moy catchment exhibits the most conservative changes in both soil and groundwater storage and serves to highlight the importance of catchment characteristics in determining a catchment's response to climate change.

3.5.1.5 Barrow

Soils in the Barrow catchment are permeable, well-drained mineral soils and are among the most heavily cultivated soils in the country. In terms of future changes in soil storage, little change is likely for the winter and spring months due to the suggested increases in precipitation. Substantial reductions in storage are likely by the early summer with reductions of –11% likely for June. During the 2020s, the greatest decrease in soil storage is evident for the month of July with reductions of –50% simulated, while decreases are likely to persist until October. By the 2050s, reductions in soil storage are further pronounced with maximum reductions of –65% likely for July. Reductions in storage are also evident earlier in the year than simulated for the 2020s, commencing in April and persisting until October. The most dramatic changes in soil storage are suggested for the 2080s with reductions of –39%, –75% and –51% simulated for the summer months. It is worth noting that decreases are simulated from May through to November by this time. Given the increases in evaporation and the decreases in precipitation during the autumn months, reductions in the order of –65% and –18% are suggested for September and October.

Geology in the Barrow catchment is diverse and includes fine-grained well-bedded limestones and medium- to coarse-grained sandstones, siltstones and shales. Subsoil deposits consist of sands, gravels and clays of variable extent and thickness. These deposits play a key role in the groundwater flow regime with highly permeable sands and gravels allowing a high level of recharge and additional storage to underlying bedrock aquifers. Under the control period, maximum groundwater storage occurs in March and April and gradually decreases to a minimum in November. By the 2020s, slight decreases in storage are likely for all winter and the majority of spring months, while slight increases are likely from late spring until the end of autumn. By the 2050s, increases in storage of between +6% and +10% are simulated for all months as the large storage capacity of the underlying geology offsets the reductions in precipitation in the summer and autumn. By the 2080s, increases are maintained for the majority of months with increases in the order of +10% likely from May to November. Slight decreases are suggested for December and January by this time.

3.5.1.6 Suir

Like the Barrow catchment, soils within the Suir are generally classified as highly permeable and well drained. By the 2020s, 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 decreases of –31% and –39%, respectively. By the 2050s, reductions in soil storage are likely from April to October, with the most substantial reductions again likely for August (–59%) and September (–62%). The most extreme reductions in soil storage are likely by the 2080s with reductions evident for 7 months of the year, commencing in May and persisting until November. Reductions in the order of –75% are likely for August and September.

Subsoils within the Suir catchment comprise glacial tills and sands and gravels. As with the Barrow, high permeability rates associated with sands and gravels allow a high level of recharge and provide additional storage to underlying bedrock aquifers. The bedrock geology of the catchment is extremely diverse. In terms of aquifer productivity, almost half of the catchment is underlain by moderately productive, locally important aquifers. Regionally important aquifers make up approximately 35% of the catchment area and, of these, diffuse karst aquifers are the most common. Under the control period, June is the month of maximum groundwater storage, while minimum storage occurs in December. A distinct lag between maximum precipitation and maximum groundwater storage is evident, while a large proportion of groundwater is contributed to streamflow as baseflow due to diffuse karstic conditions. By the 2020s, slight reductions in storage are evident for all months with greatest reductions likely for the important recharge months. By the 2050s, slight increases are suggested for the majority of months as a result of increased precipitation. However, increases are marginal. By the end of the century, greatest reductions are likely during the current recharge period, while December becomes the month when groundwater storage is at a minimum.

3.5.1.7 Blackwater

The predominant soil types within the Blackwater are relatively permeable. Under the control period, soil water storage is at a minimum during August and September. By the 2020s, there is a reduction in soil storage for 6 months of the year, with the greatest reduction likely for the month of August (–51%). Substantial reductions are also likely for July (–27%) and September (–41%). By the 2050s, the rate of decrease between the spring and summer is much more rapid, with further reductions in storage evident for 7 months of the year, beginning in April and persisting until October. The greatest reductions are likely for the late summer and early autumn months, with a reduction of –47% in July, –67% in August and –54% in September. By the 2080s, 8 months show reductions in soil storage with reductions being extended into November. Of these, 5 months, June to October, show reductions of more than –20%. Again the greatest reductions are evident for July (–65%), August (–82%) and September (–63%).

Subsoils within the Blackwater are diverse, with deposits comprised predominantly of sandstone and limestone glacial tills. Dominant bedrock consists of Old Red Sandstone, undifferentiated Namurian deposits and unbedded Dinantian limestones. The vast majority of the catchment is underlain by moderately productive aquifers, while regionally important aquifers make up over 16% of the catchment area. Under the control period, the groundwater storage regime is similar to that of the Suir. By the 2020s, there is little change evident for the winter and spring months, while only slight increases are suggested for the remainder of the year. By the middle of the century, increases are simulated for all months, with results ranging from +4% to +6%. By the 2080s, reductions in storage are likely for each of the winter months, most pronounced in December with a reduction of –5%. Increases in the order of +1 to +3% are likely for the remaining months.

3.5.1.8 Ryewater

The majority of the Ryewater catchment comprises soils having a heavy clay loam texture. In terms of soil storage during the control period, there is a gentle reduction throughout the spring and into the summer. As is evident in other catchments, the rate of drying during the spring and summer becomes more pronounced during future simulations for the Ryewater. By the 2020s, 7 months show a reduction in storage with the greatest changes once again evident during August (–32%) and September (–35%). By the 2050s, the reductions become more pronounced, with 7 months experiencing reductions in storage by mid-century. Five months, from June to October, suggest substantial reductions of over –20%, with August and September showing reductions of –54% and –55%, respectively. By the 2080s, further reductions are likely for all of the summer and autumn months, with major reductions in June (–22%), July (–50%), August (–68%), September (–70%) and October (–40%).

Within the Ryewater, subsoils largely comprise glacially deposited till derived from the Irish Sea, while the underlying geology is predominantly made up of impure limestone. Consequently, aquifer productivity is largely refined to being moderately productive. Under current conditions, groundwater storage reaches a maximum earlier in the year than many of the other catchments analysed, with storage peaking in March. By the 2020s, decreases in storage are simulated for each month, with substantial decreases in November (–14%), December (–28%), January (–24%) and February (–13%). By the 2050s, slight increases are simulated for April and May; however, more pronounced decreases are likely for the rest of the year. The most severe decreases are likely for December and January, with reductions of –37% and –26% simulated. By the 2080s, 5 months show an increase in storage, with greatest increases in April and May of approximately +5%. The most dramatic changes by the end of the century are the significant reductions in storage during important recharge months, with the months from November to February showing reductions of –15%, –45%, –33% and –12%, respectively.

3.5.1.9 Boyne

In relation to the other catchments involved in this analysis, the Boyne is one of the catchments with the greatest amount of soil water storage. When examining the results, it is evident that least change is shown in terms of simulated future soil moisture storage for the Boyne catchment. Over 35% of the Boyne catchment comprises poorly drained soils, which reduce the capacity of precipitation to infiltrate into the subsoil and into groundwater. By the 2020s, reductions are likely for 5 months of the year, beginning in May and persisting until September. Greatest reductions by the 2020s are suggested for June, with a 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 –14% and –8% likely for June and July. Because of 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 reductions by this time are likely for the summer months of –16%, –10% and –10%.

Subsoils within the Boyne catchment are complex with important deposits of glacial tills of limestone and shale and till of Irish Sea origin. On the catchment scale, the infiltration of water, its movement through the soils and into groundwater, is not as rapid as in the Suir catchment where highly porous sand and gravel subsoils are dominant. Due to the impurities in limestone formation, karstification is inhibited and the transmissivity and thus the aquifer potential of the bedrock is reduced. Under the control period, groundwater storage 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, while decreases are suggested for the remaining months. The most significant decreases are likely for the winter months with reductions of –26%, –21% and –10%. 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 –12% to –27%, while winter decreases are in the order of –19% to –42%. By the end of the century, this trend becomes more pronounced. Again, only slight increases are simulated for late spring and early summer, with a maximum increase of +5% in May. Most problematic are the reductions simulated by this period. Reductions in autumn range from –12% to –30% while reductions of –51%, –50% and –27% are suggested for the winter months. Once again the most significant reductions are likely to occur during the important recharge season.

3.5.2 Changes in monthly streamflow

Changes in monthly streamflow are predominantly driven by changes in precipitation and temperature as well as changes in catchment storage, with the latter dependent on processes such as the infiltration capacity, the porosity and the type of subsurface material. Therefore the effects of climate change on river flow depend not only on the extent of change in climatic inputs, but also on the characteristics of the catchment itself (Arnell, 2003). In order to account for the response of basins with similar characteristics, catchments are grouped so that similarity in response is highlighted. In total, four groups of catchments are analysed:

1. The Suir, the Barrow and the Blackwater form the first group, as their response is determined by the influence of groundwater on monthly streamflow

2. The second group includes the eastern catchments of the Boyne and Ryewater

3. The third group is formed by the Shannon sub-catchments of the Inny, the Suck and the Brosna

4. The final catchment, the Moy, is analysed separately.

For each catchment the percentage change in monthly streamflow derived from the mean ensemble run using all of the behavioural parameter sets is presented (Figs 3.6–3.8). The columns represent the average results obtained using the mean ensemble, with the error bars representing the full range of uncertainty analysed. Percentage changes are calculated for each future time horizon through comparison with the 1961–1990 control period. Appendix 3.1 shows percentage changes and uncertainty ranges simulated for each catchment in tabular form for the 2020s, 2050s and 2080s. The significance of changes in monthly streamflow is calculated using the Student's *t*-test (Appendix 3.2). Figure 3.9 maps seasonal changes in streamflow for each catchment. Seasonal changes are defined as winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

The percentage change derived from the A2 and B2 ensembles is presented for illustrative purposes and is not discussed in the text due to the fact that the mean ensemble is a weighted average of both. In general, the B2 scenario suggests more substantial increases in streamflow for the majority of months during the 2020s, while decreases are generally less pronounced during the summer and autumn periods. On the other hand, the A2 scenario shows more pronounced decreases during summer and autumn than the B2 scenario. While increases in spring under the A2 scenario are less pronounced than the B2, there are a number of catchments in which winter increases are more significant under the A2 scenario. In many cases, the mean ensemble changes do not lie within the ranges simulated by the A2 and B2 ensembles. This is due to the thresholds and feedback present in determining a catchment's response to climate change.

3.5.2.1 The Suir, the Barrow and the Blackwater

Simulations conducted for the 2020s suggest little change for the winter months. Increases of approximately +3% are likely for December streamflow in the Blackwater, while slight decreases are suggested in the Suir for the same month. Under the mean ensemble, March and April are the months that show the most substantial increases by the 2020s in each catchment. A maximum increase of +9% in March is likely for the Blackwater, with the Suir and Barrow showing similar increases, although slightly less pronounced. In terms of streamflow response during the summer months, both the Suir and the Barrow show only slight reductions (between –1% and –8%). When the uncertainty bounds are accounted for, the direction of change in summer months in the Blackwater is uncertain with slight increases and slight decreases simulated. In each catchment, the greatest reductions by the 2020s are simulated for the autumn. The largest reduction in September streamflow is shown for the River Suir, with reductions ranging from –5% to –12%. In each catchment, decreases are most pronounced for October, with average results showing a reduction of between –20% and –23%. Significant reductions are also suggested for November. In the Blackwater and Barrow catchments, average November streamflow decreases by approximately –10%, while average decreases in the Suir approach –20%. The greatest amount of uncertainty is also evident for changes in autumn streamflow in each of the catchments.

By the 2050s, significant increases in streamflow are suggested for the winter months. In both the Suir and the Barrow, greatest increases in streamflow are likely for the month of February by this time, with increases in the order of +15% to +18% likely. Although the average response suggests a slight increase in December streamflow in the Suir, when all model runs are accounted for the direction of change becomes uncertain. In the Blackwater catchment, March remains the month displaying the greatest increase in streamflow, with an average increase of +13%. The response of summer months in each of the catchments remains conservative, with slight increases and slight decreases suggested. In all of the catchments, reductions are not as pronounced as in the 2020s due to increases in precipitation earlier in the year and the role of groundwater in each of the catchments. Indeed, slight increases in streamflow of between +2% and +3% are likely for summer months in the Blackwater catchment under the mean ensemble. As with the 2020s, the autumn months display the greatest reductions. For each catchment the month of October remains the month with most pronounced decreases. The greatest decreases are experienced in the Suir, with average October reductions reaching –27%. Reductions consistent with those simulated for the 2020s are maintained for both the Blackwater and Barrow by the 2050s. Significant decreases in streamflow are also likely for November, with reductions in the Suir ranging from –11% to –44% when the model is run with all parameter sets. Average decreases become more pronounced in November in both the Suir (–22%) and the Barrow (–12%), while they remain the same as in the 2020s for the Blackwater.

The most significant changes in streamflow are likely by the end of the century. During the winter, further increases are likely for the months of January and February by the 2080s, with February displaying the greatest percentage increase in streamflow in all catchments (Suir +22%, Blackwater +13%, Barrow +25%). Increases in December streamflow become

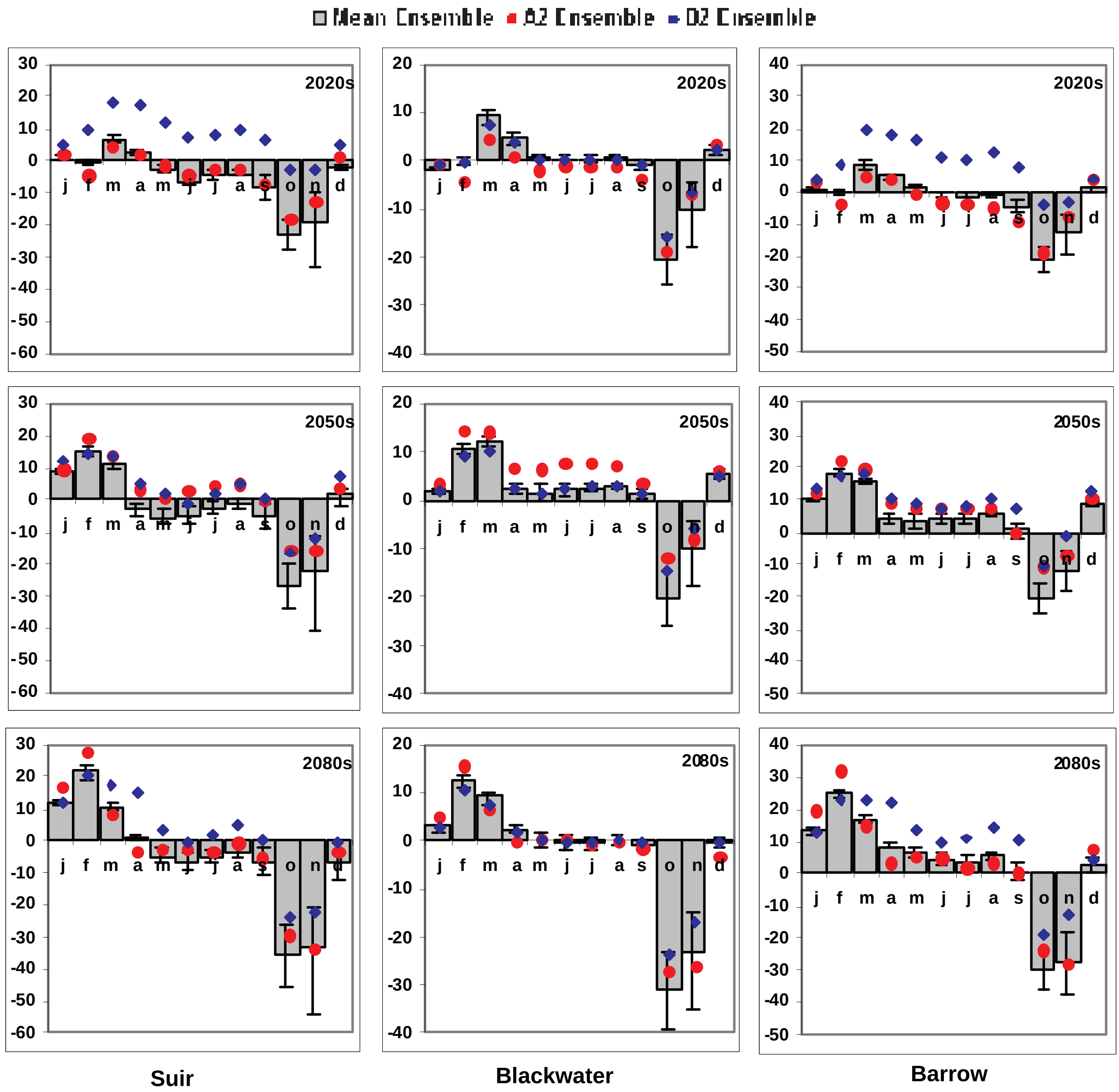

Figure 3.6. Percentage change in monthly streamflow in the Suir, Blackwater and Barrow catchments for each future time period.

less marked by this time in the Barrow while decreases are simulated for both the Suir and Blackwater. In the Suir and Barrow, spring changes remain similar to those simulated for the 2050s, while increases are not as pronounced in the Blackwater. In terms of changes in the summer months, slight decreases are suggested for the Suir (–3% to –7%), the direction of change in the Blackwater becomes uncertain, while slight increases are simulated for the Barrow (approximately +4% in June, July, August). Reductions in autumn streamflow are also greatest by this period. Reductions in both October and November become more pronounced in each of the catchments. For the Suir, average reductions of –36% and –33% are likely. In the Blackwater, October and November streamflow is suggested to decrease by –31% and –23%, while reductions of –38% and –28% are simulated for the Barrow. Again, uncertainty bounds are also greatest during the autumn with reductions of up to –54% simulated for November in the Suir catchment.

Changes in streamflow of the magnitude simulated (Fig. 3.6) would have significant implications for water resources and flood management in each of the catchments. Surprising from the analysis are the conservative changes in summer flows, as these catchments are located in the south and south-east of the country. This finding highlights the important role that catchment storage plays in offsetting the response to precipitation changes. It is also interesting to note that the greatest reductions in streamflow are likely when storage levels reach a minimum. Although increases in precipitation are simulated for December, more rainfall is diverted to storage than at present and thus a reduction in streamflow compared with the control period is likely, especially in the Suir catchment.

3.5.2.2 The Moy

The Moy catchment is the most westerly of the catchments analysed. By the 2020s, the largest changes in streamflow are likely to occur in late summer and early autumn, with average reductions of –10% in August and September (Fig. 3.7). Decreases are also simulated for the remaining summer and

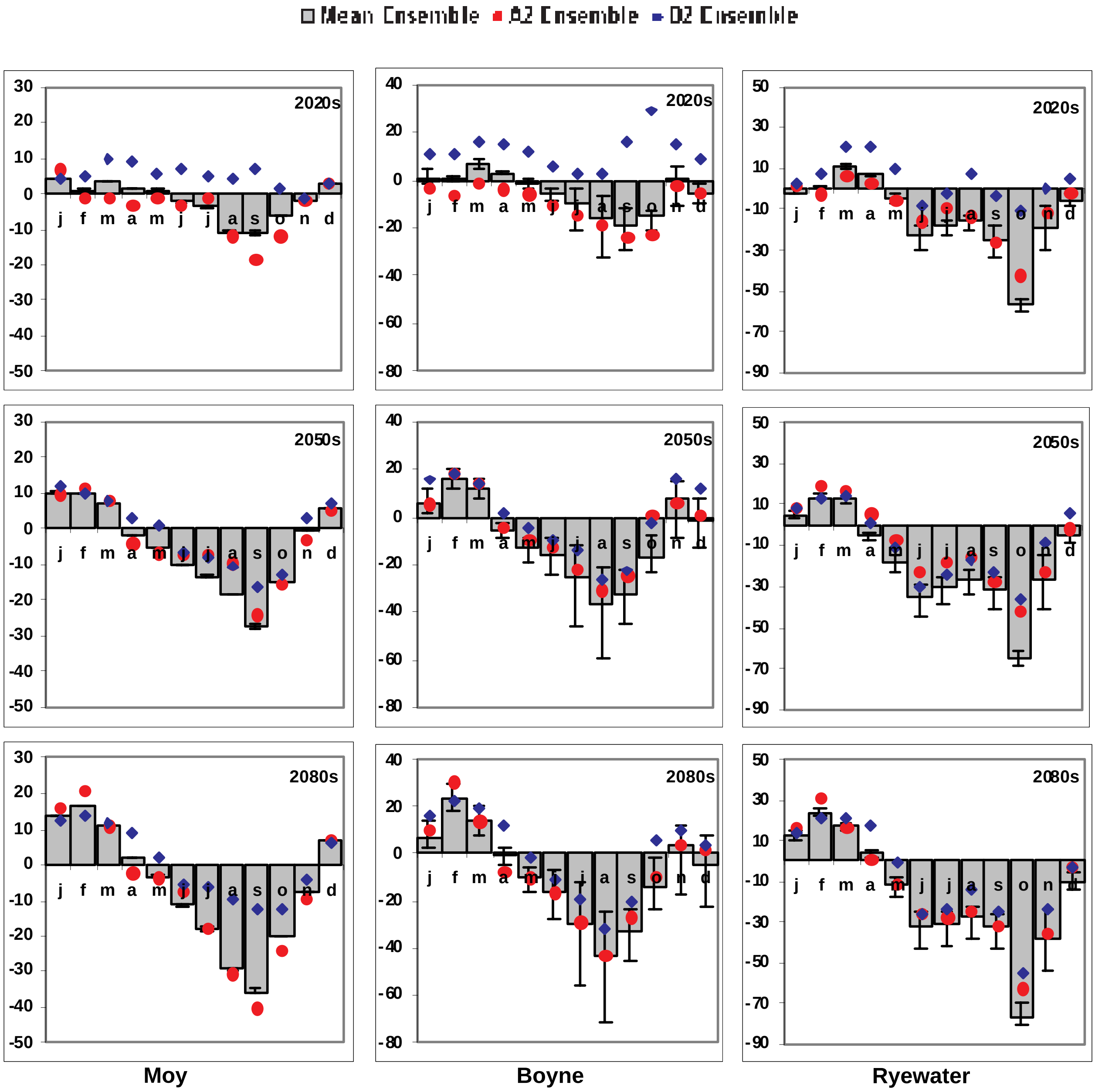

Figure 3.7. Percentage change in monthly streamflow for the Moy, Boyne and Ryewater by each future time period.

autumn months but these are only marginal. Slight increases in the order to +2% to +5% are simulated for the winter and spring months. The decreasing trend in summer and autumn streamflow is likely to continue into the 2050s, with more substantial average decreases simulated for June (–10%), July (–13%), August (–19%), September (–27%) and October (–15%). For the winter months, there are further increases suggested, with December showing an average increase of +6%, while January and February display average increases of +10%. By this time, the direction of change of some of the spring months is altered, with April and May showing decreases in streamflow. Simulations for the 2080s suggest continued increases in flow throughout the winter months, with average increases for December, January and February reaching +7%, +14% and +16%, respectively. Further reductions in flow are also suggested during the summer and autumn with reductions in July, August, September and October extending to –18%, –30%, –36% and –20%, respectively.

3.5.2.3 The Boyne and Ryewater

The Boyne and the Ryewater are located in the east of the country and are the most heavily populated of the catchments considered. While the response of each of the two catchments to climate change is quite different, they are analysed together due to their comparable strategic importance. By the 2020s, little change is suggested for the winter months in either catchment. Indeed simulations for both (Fig. 3.7) suggest slight decreases in December flow. Greatest increases in streamflow are likely for March, with an average increase of +11% in the Ryewater; increases for the same month are not as large in the Boyne. Significant reductions in summer flow are simulated for both catchments. In the Ryewater, greatest summer reductions are likely in June (–22%), while in the Boyne the greatest decreases are likely in August (–16%). In both catchments, the uncertainty bounds are greatest during the summer months. During the autumn, reductions in flow reach a maximum in both catchments. In the Boyne, September streamflow is likely to reduce by –19%. In the Ryewater, greatest average reductions are likely in October (–57%), while substantial reductions are also likely in September (–25%) and November (–19%).

By mid-century, increases in flow are likely for January and February. In both catchments, February displays the greatest change, with increases of +13% to +16%. In the Boyne, the direction of change in December streamflow is uncertain, with simulations ranging from +7% to –13%. Slight decreases are likely for December flow in the Ryewater. By the 2050s, reductions in spring streamflow are also likely. While increases in March streamflow remain largely the same as suggested for the 2020s, reductions in April (–6% and –5%) and May (–13% and –18%) are likely in both catchments. By the 2050s, the greatest reductions in the Boyne are simulated during the summer months, with average reductions of –16%, –25% and –36% in June, July and August, respectively. Uncertainty bounds are large with reductions reaching up to –60% in August. Significant decreases are also likely for the summer in the Ryewater with average reductions of –35%, –30% and –27% in June, July and August, respectively. However, greatest average reductions in the Ryewater are suggested for the autumn, with reductions of –32%, –65% and –27% in September, October and November, respectively. Uncertainty bounds are largest for November with simulations ranging from –15% to –41%.

By the 2080s, further increases are likely during the winter months, especially in February with increases of over +23% in both catchments. During the spring, increases in March become more pronounced, especially in the Ryewater where an average increase of +17% is suggested. In both catchments, decreases in streamflow for April and May are not as pronounced as in the 2050s due to increases in precipitation earlier in the year. In the Boyne, decreases in June remain the same as simulated during the 2050s. However, reductions become more pronounced during July and August with likely average reductions of –30% and –43%, respectively. Uncertainty bounds are also large for these months with streamflow reducing by as much as –56% in July and –71% in August when all simulations are accounted for. During the summer months in the Ryewater reductions are consistent, with average decreases of between –28% and –32% in

June, July and August. Unlike the Boyne, the greatest reductions in the Ryewater are displayed in autumn. Average reductions of –32% and –38% are likely for September and November, respectively. However, the greatest reductions are evident for October with an average reduction of –76% suggested by the 2080s. In the Boyne catchment, significant reductions are likely in September (–33%); however, reductions become less pronounced in October (–14%). By the end of the century, the direction of change in November streamflow is uncertain with simulations ranging from +5% to –24%.

3.5.2.4 The Inny, Suck and Brosna

The Inny, Suck and Brosna are important tributaries of the Shannon catchment. Both the Inny and the Brosna are eastern tributaries, while the Suck joins the main river from the west. Each of the catchments are similar in terms of their physical and meteorological characteristics. By the 2020s, slight increases in streamflow for winter and spring months are suggested for all three catchments (Fig. 3.8). However, these increases are all less than +6%. During the summer months no change, or very slight reductions are likely. In each of the catchments, the greatest changes by the

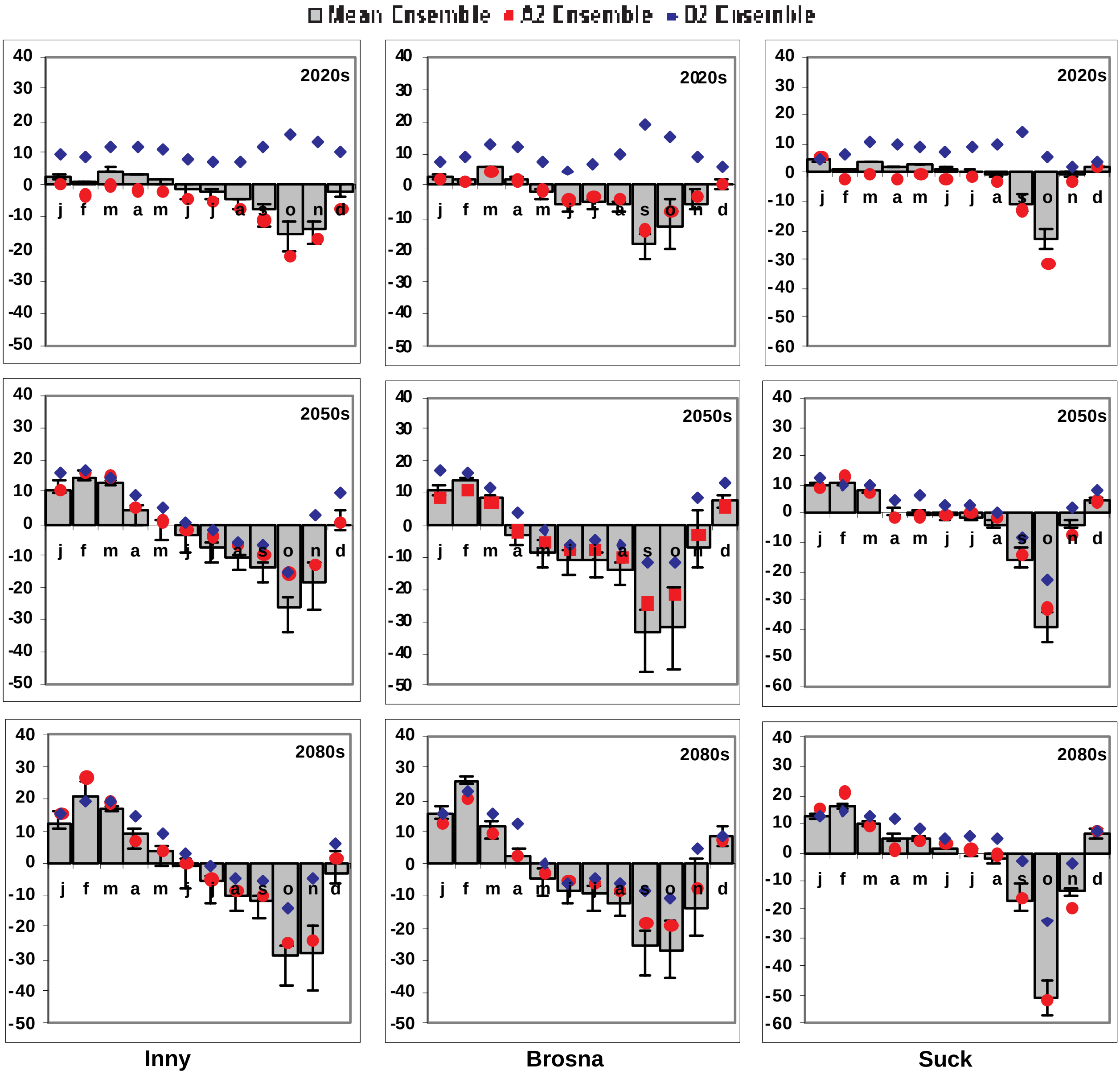

Figure 3.8. Percentage change in monthly streamflow for the Inny, Brosna and Suck by each future time period.

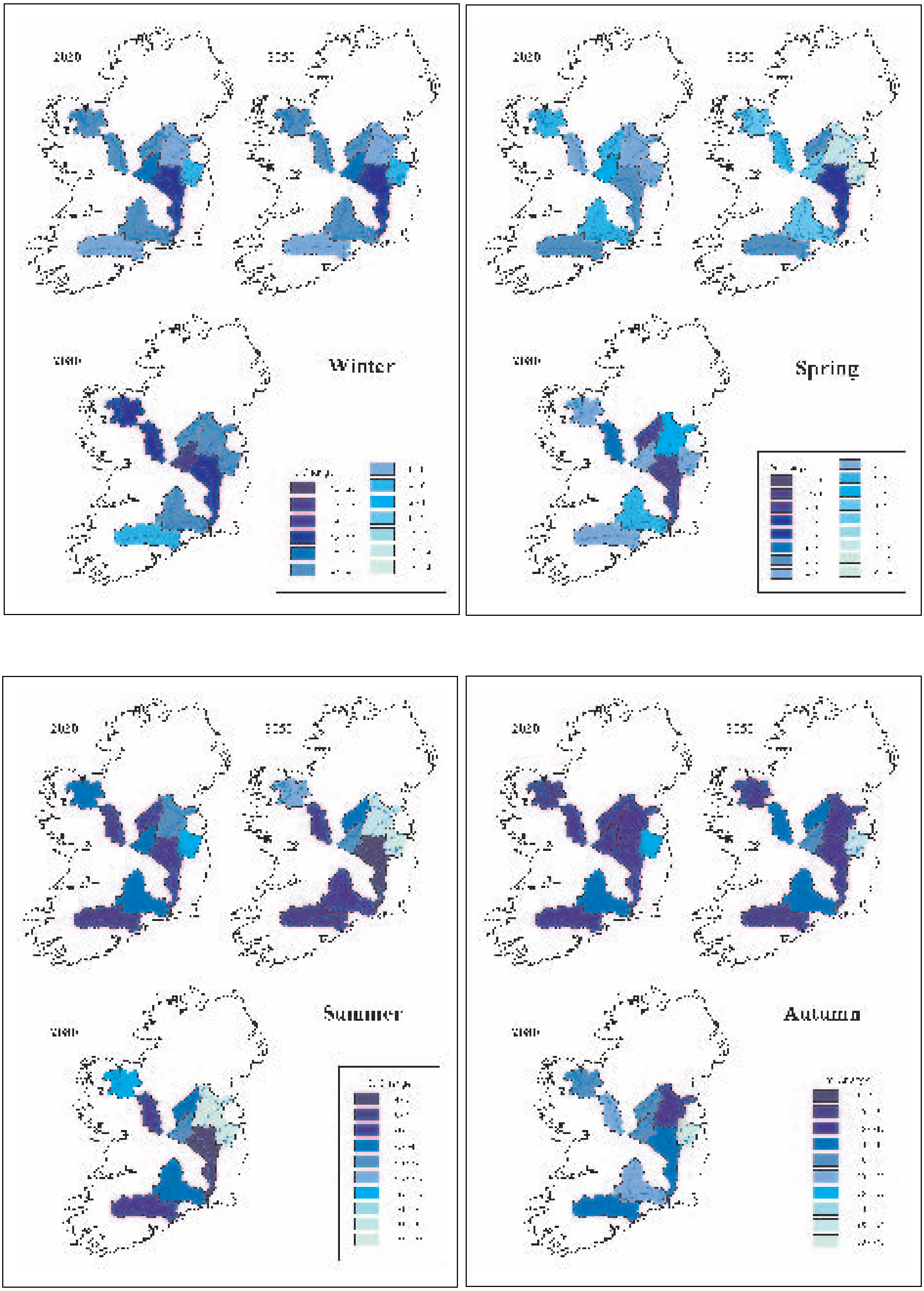

Figure 3.9. Seasonal changes in streamflow for each of the catchments analysed.

2020s are likely for the autumn months. For the Inny, average reductions of –8%, –16% and –14% are simulated for September, October and November, respectively. In the Brosna, the largest reductions are likely for September (–18%) with decreases of –13% and –6% in October and November, respectively. October shows the greatest decrease in the Suck (–22%), while little or no change is suggested for November.

By the 2050s, significant increases are likely for winter months. For each of the catchments, average increases in January approach +10%. In both the Inny and the Brosna, the greatest increases are likely in February (approximately +14%), while increases in the Suck for the same month are not as large. It is worth noting that the direction of change in December flow in the Inny becomes uncertain by the 2050s. In terms of spring streamflow, increases of between +8% and +13% are suggested for March in all of the catchments. However, for the late spring months, especially May, decreases in flow are simulated, with greatest decreases in the Brosna of –8%. Reductions in streamflow during the summer are suggested for both the Inny and the Brosna. In the Inny, minimum average summer reductions are shown for June (–4%) and extend to –11% in August. In the Brosna, average reductions of –11% are likely for June and July, with reductions slightly more pronounced in August (–14%). Only minimal decreases are simulated for the Suck catchment during the summer months. Once again, the greatest reductions in streamflow in all three catchments are likely for the autumn months. In the Inny, average decreases of –14%, –26% and –18% are suggested for September, October and November, respectively, while in the Brosna average decreases for the same months are –33%, –32% and –7%, respectively. When uncertainty ranges are accounted for, the direction of change for November in the Brosna is uncertain. Error bars are also large for September and October, with reductions reaching –45% in both months when all simulations are analysed. In the Suck, greatest decreases are again suggested for October, with an average reduction of just over –39% by mid-century.

By the end of the century significant increases are simulated for winter months. In each of the catchments, February shows the greatest increase in streamflow, with average increases of +21% in the Inny, +26% in the Brosna, and +17% in the Suck. During the winter, the smallest increases are shown for December, where in the Inny the direction of change by the 2080s is uncertain. Greatest increases in the spring are again likely for March with average increases ranging from +10% in the Suck to +17% in the Inny. Increases are not as pronounced during April and May. In the Suck catchment, little change persists in the summer months, while in the Inny and Brosna the greatest summer decreases occur in August with average reductions of –10% and –12%, respectively. Decreases in autumn streamflow are extended into the 2080s for all catchments. In the Inny, average reductions of –12%, –29% and –28% (September, October and November) are simulated, while in the Brosna reductions for the same months extend to –26%, –27% and –13%. In the Suck, average reductions of –17% and –14% are suggested for September and November, respectively. However, greatest reductions are shown for October streamflow with an average reduction of –51%. When uncertainty ranges are accounted for, reductions in October in the Suck are likely to range between –45% and –58%.

3.5.3 Changes in the variability of streamflow

The changes in precipitation highlighted in Chapter 2 are also likely to result in changes in the variability of daily streamflow. Figure 3.10 shows the likely changes in the variability of daily streamflow for each future time period. Changes are calculated as a percentage difference from the 1961–1990 control period. The columns represent the average change for each catchment, while the error bars represent the uncertainty ranges from each ensemble run using all behavioural parameter sets. By the 2020s, the majority of catchments are likely to experience a decrease in the variability of daily streamflow, with greatest average reductions suggested for the Barrow, the Blackwater and the Suir. By the 2050s, increases in variability are simulated for the majority of catchments, with greatest increases in the Brosna and Inny; slight reductions in variability are likely for the Blackwater. Uncertainty bounds are also large, with variability increasing by up to +60% in Inny and Brosna. By the end of the century, further increases in the variability of

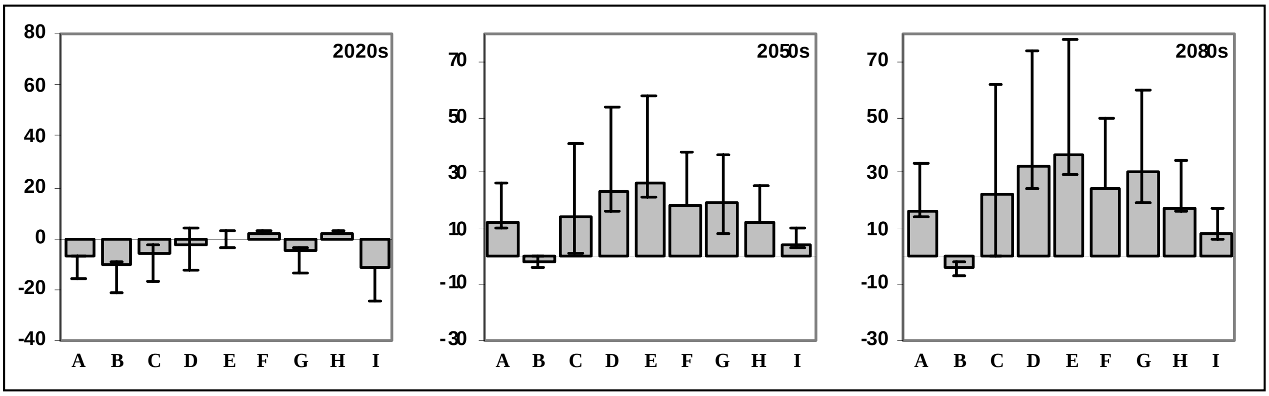

Figure 3.10. Percentage change in the variability of monthly streamflow in each catchment for each time period. A, Barrow; B, Blackwater; C, Boyne; D, Brosna; E, Inny; F, Moy; G, Ryewater; H, Suck; I, Suir.

daily streamflow are likely. The catchments showing the least change in variability are the groundwater-dominated catchments: the Barrow, the Blackwater and the Suir. Indeed, slight reductions in variability are simulated for the Blackwater by the 2080s. The catchments likely to experience the greatest increase are the Brosna, the Inny, the Ryewater and the Boyne.

3.5.4 Changes in selected flow percentiles

As a result of changes in both the variability of daily streamflow and the simulated changes in average monthly streamflow, changes associated with important flow percentiles are assessed for each catchment (Fig. 3.11). These include Q5, the flow that is exceeded 5% of the time, Q50, the flow exceeded 50% of the time and Q95, the flow exceeded 95% of the time. The latter is an important low flow statistic in water resources management. Each statistic is calculated from the full flow record in each time period considered. The changes presented are relative to the control period 1961–1990.

3.5.4.1 Q5

Q5 is a high flow statistic referring to the flow that is exceeded only 5% of the time. By the 2020s, all simulations range from +12% to –7%. The greatest increases are suggested for the Boyne under the CCCma (Canadian Centre for Climate Modelling and Analysis) B2 run, while the greatest reductions are likely for the Blackwater under the CSIRO (Commonwealth Scientific and Industrial Research Organisation) B2 run. By the 2050s, increases in Q5 are simulated for all catchments under the vast majority of model runs. The greatest increases are likely for the Boyne and the Inny under the CSIRO B2 run, with increases in Q5 of approximately +30% in both catchments. In each catchment, the smallest changes are associated with the Hadley Centre A2 run. By the 2080s, more significant increases in Q5 are simulated for each catchment. Three catchments, the Boyne, the Inny and the Brosna, show maximum increases of between +20% and +30%. In each of the catchments, the majority of model runs indicate an increase in Q5 with the greatest increases simulated under the Hadley and CSIRO A2 runs, while the smallest changes are likely under the CCCma A2 and B2 simulations. Slight decreases in Q5 are likely for the Blackwater (maximum decrease of –8%), with only the Hadley runs suggesting an increase.

3.5.4.2 Q50

Q50 refers to the flow exceeded 50% of the time. For the 2020s, there is a distinct difference between the results obtained using each of the scenarios. Reductions in Q50 are simulated under the A2 scenario while increases are generally associated with the B2 scenario. In terms of GCM, greatest reductions are simulated using the Hadley model, with the Boyne, Inny and Ryewater showing reductions of –25% under the A2 scenario. The greatest increases are simulated by the CCCma and the Hadley Centre (HadCM3) models using the B2 scenario. By the 2050s, changes in Q50 are not as pronounced in each of the catchments, with the majority of runs clustering between +10% and –10%. However, increases in the Boyne and Inny under the CSIRO B2 run are more

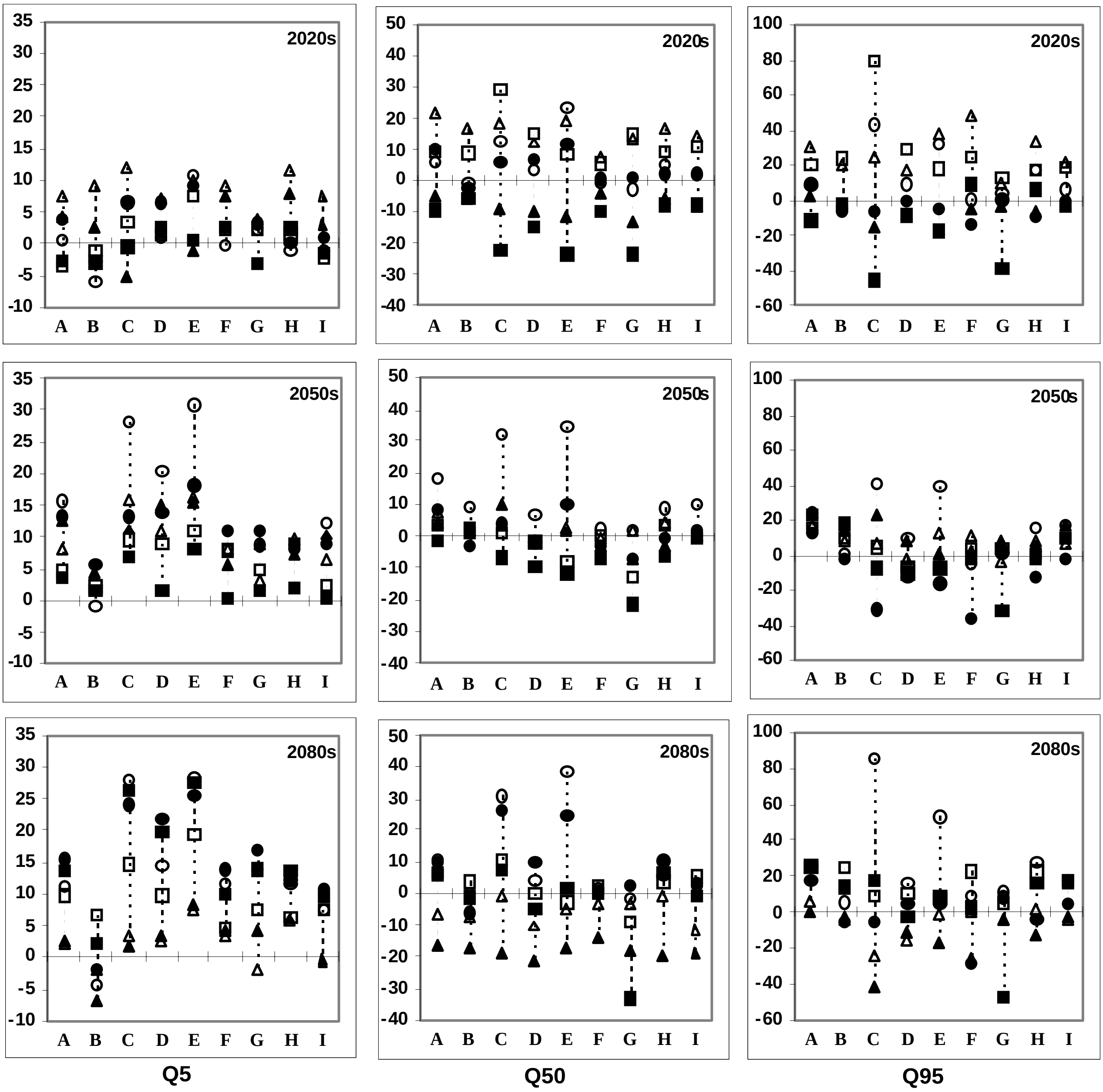

Figure 3.11. Percentage change in important flow percentiles for each catchment by the 2020s, 2050s and 2080s. A, Barrow; B, Blackwater; C, Boyne; D, Brosna; E, Inny; F, Moy; G, Ryewater; H, Suck; I, Suir.

pronounced (+35 to +40%). Again, the greatest reductions in each of the catchments are associated with the Hadley A2 run. By the 2080s, each catchment experiences decreases in the order of –20% in Q50 under the CCCma A2 run. Apart from the Ryewater, little change is likely under the Hadley runs (±10%). The greatest increases in Q50, especially in the Boyne and Inny, are associated with CSIRO A2 and B2 runs.

3.5.4.3 Q95

Q95 is an important low flow statistic referring to the flow that is exceeded 95% of the time. For the 2020s, reductions in Q95 are simulated under the majority of A2 scenario runs while increases are likely under the B2 runs. Largest increases are generally around +35% to +40% under the CCCma and HadCM3 B2 runs. However, an increase of +80% is suggested for Q95 in the River Boyne under the HadCM3 B2 run. In the majority of catchments, the greatest decreases in Q95 are simulated using the HadCM3 A2 run. In all catchments, except the Boyne and Ryewater, reductions of approximately –20% are likely. In the two eastern catchments, reductions of approximately

–40% are simulated by the 2020s under the HadCM3 A2 run.

By the 2050s, results from the A2 and B2 scenarios become more clustered. In the majority of catchments, the greatest reductions are shown for the CSIRO A2 run, while the greatest increases are evident for the same GCM under the B2 scenario. Increases in Q95 are simulated for the Barrow, Blackwater and Suir by the 2050s. By the end of the century, the greatest decreases in Q95 are suggested for the Boyne (–40%) and Ryewater (–50%). However, results are subject to large uncertainty ranges, depending on the GCM and scenario used. For the majority of catchments, the greatest reductions are likely under the CCCma A2 run. The direction of change obtained under the HadCM3 A2 run varies between catchments.

Taking account of the changes in Q95 suggested above, the total number of days with a total streamflow equal to or less than Q95 is adopted as an index to analyse the impact of climate change on low flows. Using the threshold defined under the control period, the number of low flow days in any given year is calculated for the mean ensemble run using all behavioural parameter sets for each future time period. The results are presented in Table 3.4.

By the 2020s, there is a reduction in the number of days when streamflow is less than or equal to the control Q95 in the majority of catchments. For example, in the Suir there is a reduction of between 9 and 11 days in any year when streamflow falls below Q95. The Ryewater is the only catchment to show a likely increase in the number of low flow days by the 2020s, with an increase of 3–5 days simulated. By the 2050s, only the groundwater-dominated catchments show a decrease in low flow days.

The most significant changes are suggested for the Suir, with annual low flow days decreasing by 13–15 days. The greatest increases in frequency of low flow days are simulated for the Boyne and Ryewater, with increases of between 3 and 12 days in the Boyne and 12 and 15 days in the Ryewater. This trend is continued into the 2080s, with groundwater-dominated catchments showing further reductions in low flow days, while catchments in which surface run-off plays a more important role in streamflow generation show further increases in the number of low flow days in any given year. Again, the Ryewater and the Boyne show the most significant increase in low flow days.

3.6 Flood Frequency Analysis

Increases in greenhouse gas concentrations are likely to result in increased temperatures, changes in precipitation patterns and increases in the frequency of extreme events due to an enhanced hydrological cycle. Increased winter rainfall implies an increase in winter flooding, while more intense convectional summer rainfall suggests an increase in the occurrence of extreme summer flooding (Arnell, 1998). Sweeney *et al*. (2002) show under the current climate that indications of increases in average monthly rainfall amounts are particularly strong during the winter months of December and February, while maximum 24-hourly receipts appear to be rising in October and

Table 3.4. Change in the average number of days in the year when flows are less than or equal to Q95.

	2020s		2050s		2080s	
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Barrow	–7	–6	–13	–11	–16	–15
Blackwater	–10	–9	–11	–10	–12	–9
Boyne	–7	1	3	12	7	20
Brosna	–5	–5	3	6	2	8
Inny	–6	–4	1	6	–1	5
Moy	–6	–6	3	3	12	13
Ryewater	3	5	12	15	12	17
Suck	–10	–8	–4	–2	–5	–3
Suir	–11	–9	–15	–13	–17	–13

December. This section accounts for the impacts that climate change is likely to have on future flooding in each of the selected catchments. Changes in the flood regime are characterised in two ways. Firstly, changes in the magnitude of a flood event of a given frequency or return period are analysed. Secondly, changes in the frequency of floods of a given magnitude under the control period are assessed for each future time period. In total, four flood events are analysed: 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. Due to the limited years of data, more extreme return periods were not included. Given that the ensembles are averages of each model run and not suited to extreme value analysis, flood frequency analysis is conducted using each GCM model run for each scenario. In total, six GCM runs 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.*, 1999). However, recent studies (Arnell and Reynard, 1996; Hulme and Jenkins, 1998) have demonstrated the variability of climate characteristics, with such variability having serious implications for statistical methods used in flood frequency analysis. Consequently, assumptions regarding the stationarity of the flood series are made. 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 considered time horizon (Prudhomme *et al.*, 2003). Similar assumptions are made in this work.

In conducting a flood frequency analysis for each catchment, the maximum annual flood was extracted from each time period. In total, 30 maximum annual floods comprised each flood series. An extreme value distribution (Generalised Logistic) was fitted to each series using the method of L-moments following the methodology described in the *Flood Estimation Handbook* (Robson and Reed, 1999). The relatively short time series sampled makes it difficult to identify the true underlying distribution. Thus, confidence intervals were calculated to reflect the sampling error and the effects of natural variability on the flood distribution. For each catchment, bootstrapping was undertaken to produce a set (199) of randomly sampled flood series and the Generalised Logistic distribution was fitted to each series. The 95% confidence interval was derived from the ensemble of the resulting 199 flood frequency distributions (Prudhomme *et al.*, 2003). The 95% confidence intervals describe the limits within which the true curve is expected to lie at the 95% confidence level. Confidence intervals were calculated for the control period only and are used to assess the significance of likely future changes.

3.6.1 Changes in flood magnitude

Figures 3.12 and 3.13 present the simulated changes in flood magnitude under each emissions scenario for each of the return periods analysed. For ease of presentation, the weighted average of the results from each model run is illustrated. Due to the performance of the HadCM3 model in replicating current conditions, especially during periods of high flow, greatest weight is therefore attributed to results derived from these runs. Table 3.5 highlights the percentage change in flood magnitude compared with the control period for each future time period; changes that are significant at the 0.05 level are shaded. For each of the catchments analysed under the A2 scenario, there is a consistent signal that the magnitude of flow associated with each return period will increase for each time period.

Only two catchments, the Boyne and the Inny, suggest a decrease in flood magnitude by the 2020s; however, reductions are not significant when sampling error and natural variability are accounted for. The period in which the greatest increases in flood magnitude are simulated varies between catchments. In the Boyne, Blackwater and Suir, greatest increases in the magnitude of the 50-year return period are simulated by the 2020s. The most significant increases are suggested for the Blackwater, with the magnitude of flow associated with the 50-year return period increasing by 56%. On the other hand, only one significant change is simulated for the Suir where the 2-year flood shows a slight reduction of –1%. Large increases in the magnitude of floods are also likely for the Boyne, the Moy and the Suck. In the Boyne

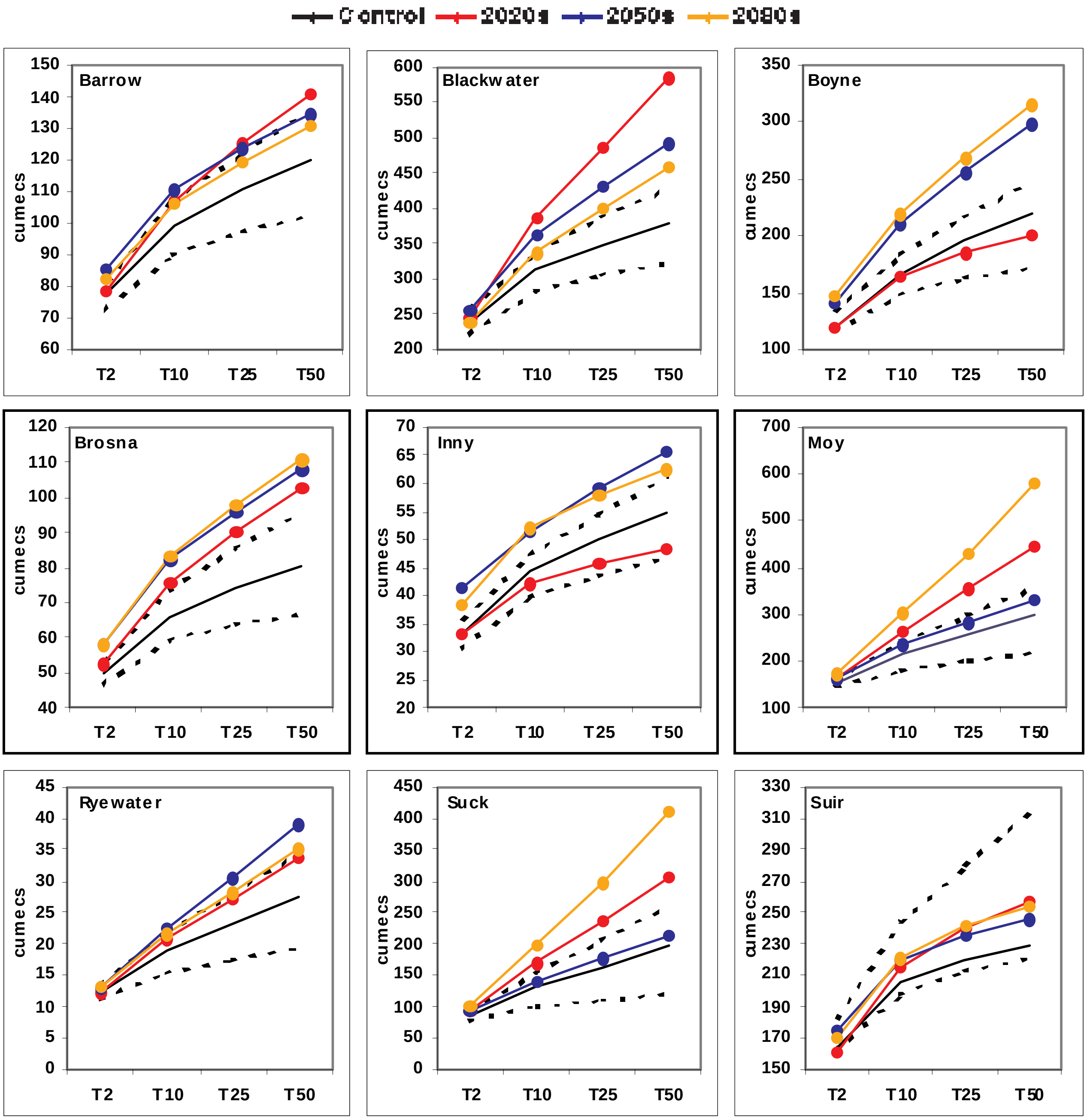

Figure 3.12. Changes in the magnitude of selected flood events for each future time period under the A2 emissions scenario.

catchment, significant increases in magnitude are likely for all return periods by the 2050s and 2080s. Greatest increases are likely for the larger return flows, with the 50-year return period showing a 47% increase by the end of the century. In the Moy, increases in flood magnitude are likely to be greatest during the 2020s and 2080s, while none of the increases suggested for the 2050s are significant at the 0.05 level. Again, greatest increases are associated with the 50-year return period, with an increase of 92% (almost double the magnitude under the control period) suggested by the end of the century. The Suck shows significant changes in flood magnitude for each return period during each time horizon. A similar trend to the Moy is evident, with the 2020s and 2080s showing the most significant increases in flood magnitude. By the end of the century the flow associated with the 25-year flood under the control period is suggested to increase by

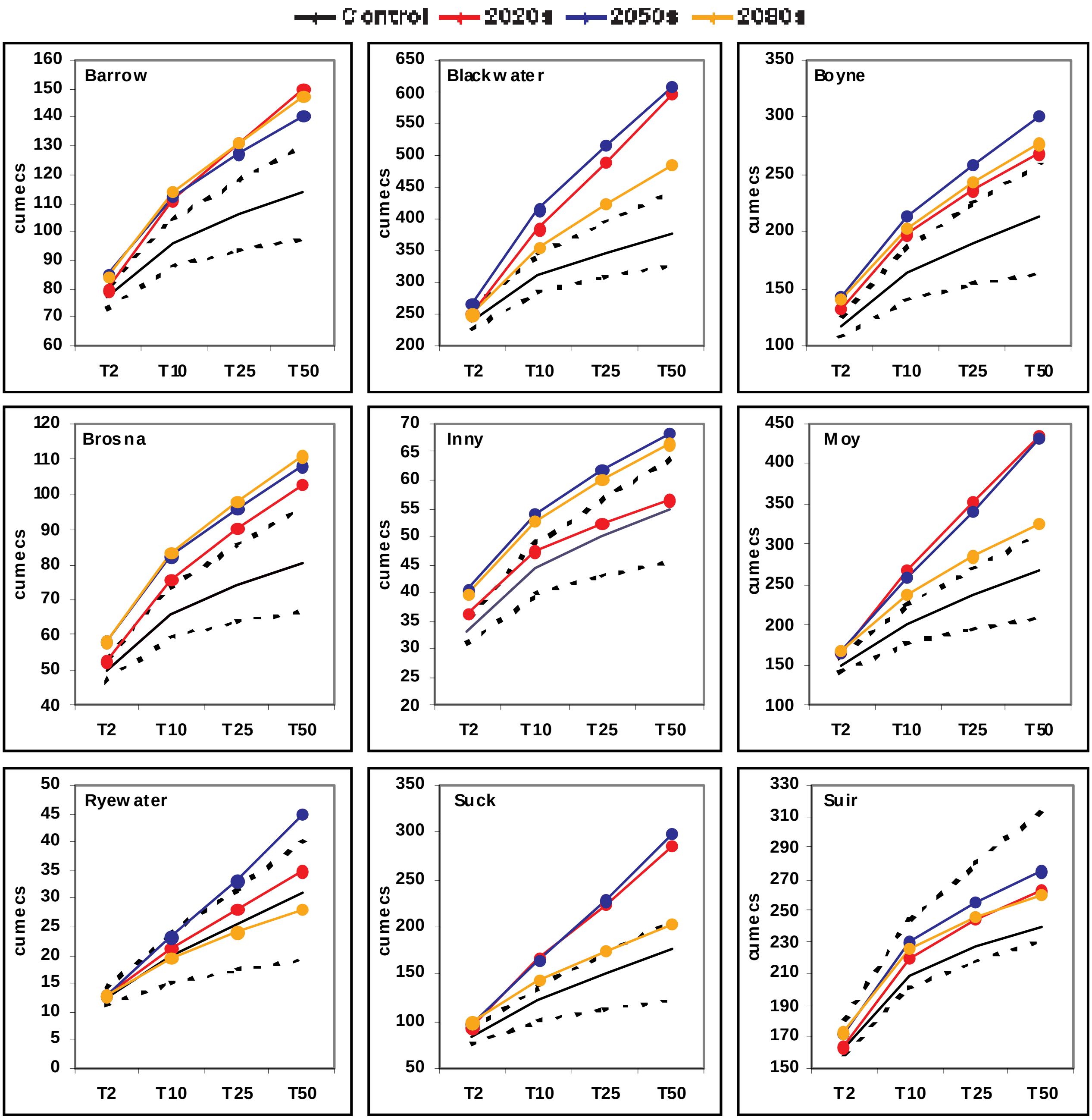

Figure 3.13. Changes in the magnitude of selected flood events for each future time period under the B2 emissions scenario.

64%, while the magnitude of the 50-year flood is likely to almost double, with an increase of 92%. Significant increases in flood magnitude are also simulated for the Ryewater and the Brosna, especially during the 2020s and 2050s; however, increases are not as large as those considered above.

Under the B2 (Fig. 3.13) scenario, greatest changes in the magnitude of flow associated with the return periods analysed are likely for the 2020s. As with the A2 simulations, the dominant signal is towards increased flood magnitude, with the greatest increases likely for flows associated with more infrequent return periods. Greatest increases in flood magnitude are suggested for the Blackwater, Moy and Suck. In the Blackwater, greatest increases are likely by the 2020s, with increases of +44% and +65% in the 25- and 50-year return periods. Increases in flood magnitude

Table 3.5. Percentage change in the magnitude of flow associated with floods of a given return period under the A2 and B2 emissions scenarios. Shaded cells show changes significant at the 0.05 level.

			Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
T2	**A2**	**2020s**	1	3	1	–3	1	6	1	6	–1
		2050s	11	7	18	12	18	7	8	7	7
		2080s	7	0	11	14	22	13	8	13	4
	B2	**2020s**	3	5	13	4	9	9	5	9	1
		2050s	10	10	22	15	21	11	3	11	6
		2080s	9	3	21	15	19	12	5	12	6
T10	**A2**	**2020s**	8	24	–3	–2	–5	24	12	24	5
		2050s	11	16	26	25	17	8	21	8	7
		2080s	7	9	26	16	17	39	15	39	8
	B2	**2020s**	15	24	21	15	6	29	9	29	5
		2050s	16	33	30	24	21	28	17	28	10
		2080s	18	13	25	25	18	17	0	17	8
T25	**A2**	**2020s**	13	40	–6	–2	–9	39	20	39	9
		2050s	12	23	32	34	19	9	34	9	7
		2080s	8	16	37	17	16	64	22	64	10
	B2	**2020s**	23	44	26	22	5	44	13	44	8
		2050s	20	49	36	30	23	46	33	46	13
		2080s	24	21	28	32	19	20	–3	20	9
T50	**A2**	**2020s**	18	56	–8	–1	–11	54	28	54	12
		2050s	12	30	36	42	21	11	46	11	7
		2080s	9	23	47	17	16	92	30	92	11
	B2	**2020s**	31	65	30	28	4	57	17	57	10
		2050s	23	63	40	34	25	65	49	65	15
		2080s	29	27	32	38	21	23	–6	23	9

become less pronounced through the 2050s and 2080s, although changes remain significant for all but the 2-year return period.

In the Moy catchment, increases in flood magnitude are not as pronounced as those simulated under the A2 scenario. Increases are suggested to be greatest for the 2020s and 2050s. All changes in flood magnitude are significant for each time period. In the Suck catchment, changes during the 2020s and 2050s are very similar, with increases greatest for the 25- and 50-year return periods by the 2050s. Although increases in magnitude are not as pronounced by the 2080s, changes remain outside the limits of sampling error and natural variability. For the remainder of the catchments, the most significant changes are likely for the Barrow, the Boyne, the Inny and the Brosna, with greatest increases suggested for the 2050s and 2080s.

Under the B2 scenario, the least significant changes are for the Ryewater and the Suir. In the latter, while increases are suggested for each return period during each future time horizon, none are significant at the 0.05 level. In the Ryewater, increases are suggested for the 2020s and 2050s, with only the magnitude of the 25- and 50-year return periods showing significant increases. Reductions in the majority of return periods are suggested by the 2080s; however, these remain within the error limits and are thus not significant.

3.6.2 Changes in flood frequency

Because the relationships between return period and flood magnitude is unlikely to be linear, it is important to analyse how the frequency of fixed magnitude events may change in the future (Prudhomme *et al.*, 2003). With this in mind, the frequency of flows associated with each return period during the control was assessed for each future time period. Only the HadCM3 model runs are presented with changes in flood frequency simulated for both the A2 and B2 scenarios. Table 3.6 presents the results for each catchment.

By the 2020s, under the A2 scenario, seven of the catchments show an increase in the frequency of the 2-year flood, with the same flood expected every 1.5 to 1.9 years. The greatest increase in frequency is suggested for the Suck, with a return period of 1.5 years likely by this time. Only the Brosna and the Inny suggest a decrease in frequency, with new return periods of 2.1 and 2.5 years likely. By the 2050s, the

Table 3.6. Changes in the frequency of floods of a given magnitude for each future time period. Results are based on the Hadley Centre climate model (HadCM3) global climate model using both A2 and B2 emissions scenarios.

			Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
T2	**A2**	**2020s**	1.8	1.8	1.9	2.1	2.5	1.6	1.6	1.5	1.8
		2050s	1.6	1.5	1.4	1.5	1.4	1.5	1.4	1.4	1.7
		2080s	1.3	1.4	1.2	1.3	1.2	1.3	1.5	1.2	1.5
	B2	**2020s**	1.8	1.5	1.4	1.8	1.6	1.4	1.4	1.4	1.8
		2050s	1.6	1.5	1.4	1.4	1.3	1.4	1.7	1.4	1.8
		2080s	1.5	1.5	1.3	1.3	1.3	1.4	1.6	1.4	1.6
T10	**A2**	**2020s**	4.8	3.6	7.1	13.9	12.7	4.2	3.4	4.4	4.4
		2050s	4.8	4.2	3.4	3.4	4.5	4.4	3.3	4.5	6.9
		2080s	3.4	3.4	1.8	2	2	2.2	4.1	2.1	3.2
	B2	**2020s**	3.7	2.6	2.3	4	4.1	2.2	3.5	2.4	4.1
		2050s	4	2.6	3.5	3	3.5	4.6	5.5	5.5	4.1
		2080s	2.9	3.8	2.2	2.1	2.3	3.9	5.4	4.6	2.8
T25	**A2**	**2020s**	8.3	5.1	15.1	39.3	26.4	7.7	5.3	8.8	6.5
		2050s	10.1	7.3	5.6	4.9	7.5	8.5	5.5	9.7	16.9
		2080s	6.7	5.3	2.3	2.8	2.7	3.1	6.9	3	4.7
	B2	**2020s**	5.5	3.2	3	5.6	6.6	3	6.4	3.5	5.8
		2050s	7.7	3.4	6.9	4.5	6.1	10.3	11	14.2	5.8
		2080s	4.6	6.6	3.2	2.6	3.2	8.2	12.8	13.8	3.7
T50	**A2**	**2020s**	12.6	6.5	26.8	85.1	26.4	12.3	7.6	8.8	8.4
		2050s	18.3	11.1	8.2	6.4	10.6	13.9	8.1	17.8	34.4
		2080s	11.5	7.3	2.9	3.8	3.3	4	10.2	4	6.2
	B2	**2020s**	7.4	3.8	3.7	7.2	9.4	3.9	10.2	5.2	7.2
		2050s	13.2	4.1	12	6.1	9.1	19.6	18.5	29.7	7.2
		2080s	6.8	10.1	4.2	3.1	4.1	15	25.5	35.9	4.5

current 2-year flood is expected to occur more frequently in all catchments, with new return periods ranging from 1.4 years in the Boyne, Ryewater and Suck to 1.7 years in the Suir. The frequency of occurrence is further increased by the 2080s, where return periods range from 1.2 years in the Boyne and Inny to 1.5 years in the Ryewater and Suir catchments. Under the B2 scenario, the frequency of occurrence of the current 2-year flood is also likely to increase for all catchments, with a return period of around 1.3 years suggested for the Boyne, Inny and Moy by the 2080s.

Substantial changes in the frequency of the current 10-year return period are also likely. By the 2020s, under the A2 scenario the majority of catchments indicate an increase in the frequency of occurrence, with return periods ranging from 3.4 years in the Ryewater to 7.1 years in the Boyne. Again, both the Inny and Brosna show an increase in the return period, with the current 10-year flood expected once every 13.9 years by the 2020s in the Brosna. The signal becomes more consistent by the 2050s, with increased frequency of occurrence likely in all catchments, with return periods ranging from 3.3 years in the Ryewater to 6.9 years in the Suir. Further reductions in return period are likely by the 2080s, where the current 10-year flood is reduced to a 1.8-year flood in the Boyne. The smallest reductions in return period are likely for the Barrow and Blackwater, where a return period of 3.4 years is simulated. Under the B2 scenario, increases in frequency are not as pronounced. The greatest increases in frequency are indicated for the 2080s, where return periods range from 2.1 years in the Brosna to 5.4 years in the Ryewater.

A similar trend is suggested for the current 25-year flood under the A2 scenario, with an increasing frequency of occurrence likely for all but the Inny and Brosna catchments by the 2020s. For the remainder of the catchments, the return period associated with the same flow ranges from 5.1 years in the Blackwater to 15.1 years in the Boyne. By the 2050s, the return periods are further reduced, with all catchments showing an increase in frequency of occurrence. By the 2080s, the return periods range from 2.3 years in the Boyne to 6.9 years in the Ryewater. Under the B2 scenario, the 25-year flood is likely to increase in frequency for all catchments by each future time period. By the end of the century, return periods range from 3.2 years in the Boyne and Inny to 13.8 years in the Suck.

The final return period considered is the flood expected once every 50 years under current conditions. Unlike the results for the smaller return periods, the frequency of occurrence of the current 50-year return period is likely to increase in all but one catchment by the 2020s under the A2 scenario. Only the Brosna indicates a decrease in frequency, with a return period of 85.1 years suggested. For the remainder, the return periods simulated range from 6.5 years in the Blackwater to 26 years in the Boyne and Inny. By the 2050s, further reductions in return period are indicated, ranging from 6.4 years in the Brosna to 34.4 years in the Suir. By the 2080s, the return period of the current 50-year flood is reduced to less than 10 years in seven of the catchments. Greatest reductions are suggested for the Boyne, Brosna and Inny, with return periods ranging from 2.9 years to 3.8 years. Both the Barrow and Ryewater show reductions of 11.5 and 10.2 years, respectively. The frequency of the 50-year flood is also suggested to increase significantly under the B2 scenario, with all catchments again showing reductions in the return period for each future time horizon. By the end of the century, the return period is reduced to less than 10 years in five catchments, with return periods ranging from 3.1 years in the Brosna to 35.9 years in the Suck.

3.7 Key Future Impacts and Vulnerabilities

3.7.1 Catchment storage

The impact of climate change on subsurface hydrology presents results that vary greatly between catchments and that 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 dependent 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. This finding is best illustrated through the comparison of results for the Boyne and the Suir. In the Suir catchment, soils are characterised as well drained, with a highly permeable sand and gravel subsoil. Given the poor ability to retain water, large reductions in soil moisture occur during the summer and are extended well into the autumn months. On the other hand, over 35% of the soils in the Boyne catchment are poorly drained and underlain by a less permeable limestone and shale till subsoil. Reductions in soil moisture are not as pronounced and recover much earlier than in the Suir. 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. Such projected changes in soil moisture storage may affect key soil processes such as respiration and thus key ecosystem functions such as carbon storage. Furthermore, the increased duration of soil moisture deficits will reduce the proportion of the year that soils act as a carbon sink.

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). For each of the catchments, elevated water levels persist into the early summer months. However, from late summer to the end of the year, water levels are generally lower than at present. Given the magnitude of changes for many of the catchments analysed, the possibility exists for low-lying streams to become perched above the water table during times of low groundwater storage and thus lose water to groundwater. Under current conditions, the late autumn and winter recharge period is critical to sustaining groundwater levels throughout the year. For each of the time periods considered, all catchments show longer, sustained periods of low groundwater levels. 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 (e.g. the Suir, Blackwater and Barrow).

Changes in the characteristics of winter precipitation may also have significant implications for groundwater recharge. Prolonged rainfall is more effective at recharging groundwater levels; however, climate change is likely to result in shorter, more intense, periods of intense precipitation becoming more frequent, thus decreasing the amount of water that is infiltrated to storage (Arnell and Reynard, 1996). Furthermore, changes in storage within catchments are likely to be highly variable and there is a need to assess impacts for individual regionally important aquifers.

3.7.2 Changes in streamflow

From the results outlined above it can be concluded that 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 run-off. 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 a lesser extent, the Shannon sub-catchments. In catchments where surface run-off is more dominant (the Boyne, the Ryewater and the Moy), changes 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 the modelled 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. For example, average reductions in November range from –26% in the Brosna to –76% in the Ryewater. Largest increases in streamflow are suggested for the winter and spring months. The month of February shows the most significant increases of between +10% and +25%. 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 percentage changes suggested for streamflow due to the non-linear nature of catchment response.

Changes in the variability of streamflow are also influenced by the role of groundwater in individual catchments. Smallest changes in variability are simulated for the Blackwater, Barrow and Suir. In terms of changes in flow percentiles, there is a large amount of uncertainty depending on the GCM and scenario employed. In general, Q5 is likely to increase under the majority of model runs by the end of the century. However, while the direction of change is largely consistent, there are large differences in the magnitude of change between catchments. Such increases in Q5 are likely to result in increased flooding. Reductions in Q95 are likely to result in more extreme low flows. While considerable uncertainty is evident, greatest reductions in Q95 are suggested for the Ryewater, the Boyne and the Moy. Furthermore, changes in the number of low flow days are likely to have considerable implications for water resources management. In groundwater-dominated catchments, increased contributions to streamflow from groundwater in the summer are likely to decrease the number of annual low flow days. However, where reductions in summer and autumn streamflow are greatest, a significant increase in the number of low flow days is simulated. Such impacts are likely to be problematic for water quality, with less water available to dilute pollution, and for water supply.

3.7.3 Changes in flood characteristics

One of the most high-profile impacts of climate change is on flood frequency and risk, with major areas of concern relating to the integrity of flood defences, planning and development control, urban storm drainage and the implications for the insurance industry (Arnell, 1998). Recent flood events in Ireland have been highly publicised due to the severe economic losses and personal hardships experienced during events such as the November 2000 floods in the east and south-east. From the above analysis, an increase in both the magnitude and frequency of flood events is suggested over the coming years.

Although the results presented above are representative of output from the HadCM3 model or a weighted average response from each of the GCMs, there is a consistent indication that the magnitude of future flood events will significantly increase in the majority of catchments under all model runs and scenarios. Generally, there is little regional variation present in the results, with changes being 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 changes in the magnitude and frequency of flood events are suggested under the B2 scenario, especially during the 2020s and 2050s. However, by the 2080s there is less difference between scenarios and, indeed, in many cases the most significant increases in flood magnitude and frequency are suggested under the A2 scenario. Greatest change in flood magnitude is associated with the largest floods, with the greatest percentage increase in magnitude suggested for the 50-year flood in the majority of catchments, while the smallest changes are associated with the more frequent 2-year flood.

There are substantial variations between catchments in terms of the time period representative of most significant changes in flooding. Under the A2 scenario, the 2020s represent the most significant increases in flood magnitude in the Barrow and Blackwater, while in the Inny and the Ryewater the 2050s show the most significant increases. In the remainder of the catchments (the Boyne, Brosna, Suck, Moy and Suir), the most substantial increases in flood magnitude under the A2 scenario are suggested for the 2080s. Under the B2 scenario, the time period showing the greatest increase in flood magnitude remains the same for the Brosna, Inny and Ryewater. Under the B2 scenario, the majority of catchments (Blackwater, Boyne, Inny, Ryewater, Suck and Suir) are likely to experience the greatest increases during the 2050s.

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 led 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 is suggested, it is likely that areas that are not currently prone to flooding may become at risk in the future, especially areas that are located close to the confluence of major rivers. Furthermore, flood defences are built to design standards based on the probability of occurrence of floods under the current climate. The significant increases in flood magnitude and the increased frequency of occurrence of larger flood events may cause flood defences to fail, resulting in increased flood risk in many areas.

Increases in the magnitude and frequency of flood events as a result of climate change also have the potential to degrade water quality. Increased flood magnitude is likely to result in greater levels of erosion, especially following prolonged dry spells. Consequently, increased sedimentation and greater suspended loads may alter the quality of river water and prove problematic for aquatic life. Furthermore, sedimentation may reduce the capacity of impoundment reservoirs through decreasing the amount of water that can be stored for water supply. Flooding also provides problems for foul sewer systems and the effective functioning of water treatment plants. During times of flood such infrastructure can become overburdened and result in the release of pollutants into watercourses. As well as extreme flow events, precipitation extremes may also impact on water quality through increased soil and fluvial erosion, increasing the amount of suspended solids and altering the nutrient loads of rivers.

3.7.4 Water resources management

In Ireland, both surface water and groundwater are important resources for drinking water supply. On a national level groundwater provides between 20% and 25% of drinking water supplies. However, many counties rely substantially more on groundwater resources, with 90%, 86% and 60% of drinking water in counties Cork, Roscommon and Offaly, respectively, derived from groundwater (DOELG, 1999). Furthermore, in many rural areas not served by public or group water schemes, groundwater is the only source of supply, with many thousands of wells and springs in operation throughout the country (DOELG, 1999). Reductions in groundwater of the magnitude simulated may have significant implications for groundwater supplies. Unfortunately, it is the areas where reliance on groundwater supplies is greatest that the most significant reductions in groundwater storage are suggested. The Blackwater, draining large parts of north Co. Cork, the Suck draining large areas of Roscommon and the Brosna draining large areas of Co. Offaly are all likely to experience substantial reductions in groundwater storage by the middle of the current century, with greatest reductions occurring when groundwater storage is at a minimum.

In terms of surface water, simulations indicate that all catchments will experience decreases in streamflow, with greatest decreases in the majority of catchments likely to occur in the late summer and autumn months, when water provision is already problematic in many areas. However, the degree to which water supply will be impacted will be determined by adaptation measures taken locally. The most notable reductions in surface water are simulated for the Ryewater and Boyne. Unfortunately, these catchments are the most heavily populated in the analysis and comprise a substantial proportion of the Greater Dublin Area. Significant reductions in the Boyne are suggested by the 2020s in early summer and autumn, with reductions becoming more pronounced for each time period considered. By the 2080s, reductions begin in May and persist until October, with greatest decreases of up to –70% in August streamflow by the 2080s. In the Ryewater, reductions are more extreme and persist for longer, with significant implications for water supply by the 2020s, where reductions of approximately –20% are simulated for summer months, while October streamflow is more than halved. By the end of the current century, reductions of –30% are likely in summer, with autumn reductions ranging from –30% to –80%. Such reductions are likely to pose serious problems for efficient and sustainable water supply within the region.

Non-climatic drivers such as changes in population, consumption, economy, technology and lifestyle predominantly govern water use. Over the past decade or so, the Greater Dublin Area has been successful in catering for unprecedented demand growth. However, due to the extent of population growth, water provision within this area is coming under increasing pressure. Taking account of projected population growth, with the population of the region projected to double by 2031, existing primary sources of water supply from the Liffey at Ballymore Eustace and the Ryewater at Leixlip will be unable to cope with projected demands over the coming years. Work is currently under way to supplement sources of water supply in the medium term through the extraction of water from Lough Ree to increase resources in the Greater Dublin Area. Added to this is the fact that non-climatic drivers of water demand in the past will be supplemented by climate change. Herrington (1996) in studying the impact of climate change on water consumption in the UK suggests that a rise in temperature of about 1.1°C would lead to an increase in average domestic *per capita* demands of approximately 5%, with increased demand greatest for personal washing and gardening. Peak demands are likely to increase by a greater magnitude, while the frequency of occurrence of current peak demand is also likely to increase (Zhou *et al*., 2001). From the simulations conducted, it is during times of the year that demand is greatest (summer and autumn) when the greatest reductions in surface water resources are likely. Furthermore, increases in evaporation are likely to result in increased losses from storage reservoirs. It is also important to note that it is not just the domestic sector from which pressures are likely to increase, with agricultural demand being particularly sensitive to climate change. Reductions in soil storage of the extent suggested in many catchments may require the implementation of irrigation practices for particular crops. Furthermore, industrial demands are likely to increase, especially where water is used for cooling purposes. Therefore, increased competition between sectors for declining resources is likely. Obvious then is the fact that water provision is likely to become an increasingly complex task, where even under current conditions demand is projected to be at the limit of projected supply capacity in the Greater Dublin Area by 2015. Serious long-term plans need to be initiated for the sustainable development of water supply within all regions.

Closely linked with issues of water resources management are the likely impacts of climate change on water quality, with the contamination of aquifers, rivers and lakes posing problems for water supply and the sustainability of freshwater ecosystems. The IPCC Third Assessment Report asserts that water quality is threatened from both direct and indirect effects of climate change (IPCC, 2001). Direct effects include issues such as increasing water temperatures and the associated reduction in the dissolved oxygen concentrations of surface waters and the contamination of coastal aquifers from saline intrusion as a result of changes in the water table. Indirect effects are linked to the increased pressure exerted on the hydrological system from anthropogenic factors, such as increased abstractions and discharges from watercourses. In the Irish context, the greatest effects on water quality are associated with drying during the summer and autumn months. Reductions in groundwater storage of the scale simulated in many catchments increases the vulnerability of aquifers to contamination from saline intrusion in coastal areas as well as from the application of domestic, industrial and agricultural effluents to the ground. Shallow, unconfined aquifers are most susceptible to contamination. However, where increased soil moisture deficits result in decreased percolation to the water table, contamination may be prevented (Cunnane and Regan, 1994). Furthermore, the introduction of irrigation practices in many areas is likely to increase the nutrient load and salinity of groundwater.

In terms of surface waters, the reduction in low flows in many catchments will decrease the amount of water available to dilute pollution from both point and non-point sources, while there is a strong relationship between increased water temperatures and the occurrence of coliforms (Peirson *et al*., 2001; Chigbu *et al*., 2004). It is therefore essential that effluents to watercourses be closely monitored, especially during the months in which reductions in streamflow are suggested. Indeed reductions in Q95 values in many catchments may require the adjustment of flows used in Integrated Pollution Prevention Control (IPPC) discharge licensing. The increased duration of low flow events will serve to exacerbate the problems mentioned above and may have significant implications for wetland habitats and ecosystems.

3.8 Conclusions

The impacts of climate change on hydrology and water resources are diverse and complex, while each catchment's individual characteristics play a pivotal role in determining the hydrological response to climate change. Although the results for individual catchments should be referred to, a number of general conclusions can be made:

- For each catchment, reductions in soil moisture storage throughout the summer and autumn months are likely. However, the extent of decreases are largely dependent on the soil characteristics of individual catchments: the lower the capacity of soils to hold moisture, the greater the sensitivity to climate change.

- Reductions in soil moisture of the scale simulated may have serious implications for agricultural practices, while more frequent wetting and drying may alter the nutrient status of many soils.

- From the results obtained, it can be inferred that soil moisture deficits will begin earlier and extend later in the year than currently experienced. Increases in the magnitude and duration of soil moisture deficits may affect key soil processes such as respiration and thus key ecosystem functions such as carbon storage.

- Reductions in groundwater recharge and lower groundwater levels during critical times of the year are likely to alter the nature of groundwater–surface water dynamics for entire rivers.

- By mid to late century, significant 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. However, large differences exist in the magnitude of change simulated between catchments. The greatest reductions are suggested for the Boyne and the Ryewater in the east, while greatest increases are likely for the two most westerly catchments, the Suck and the Moy.

- The seasonality of streamflow is also likely to increase in all catchments, with higher flows in winter and spring, while extended dry periods are suggested for summer and autumn in the majority of catchments.

- In all catchments, Q5 is likely to increase while Q95 is likely to decrease. Changes in the number of low flow days are likely to have considerable implications for water resources management.

- The magnitude and frequency of flood events are shown to increase, with the greatest increases associated with floods of a higher return period. Such changes may have important implications for property and flood plain development, the reliability of flood defences, water quality and insurance costs. There are substantial variations between catchments in terms of the time period representative of the most significant changes in flooding.

- Water quality is likely to be threatened from both direct and indirect impacts of climate change. Direct effects include increased water temperatures and the contamination of coastal aquifers from saline intrusion, while indirect effects relate to increasing demands placed on limited resources from human pressures, especially during times of low flow.

3.9 Adaptation

Water is central to sustainable development. Changes in the quantity and quality of water resources, as well as changes in the frequency, magnitude and duration of extreme events may have considerable implications for society, ecology and the economy, with sectors such as forestry, agriculture, industry, construction, energy, tourism and insurance being highly dependent on a reliable water supply and effective defence from extreme events. Thus, climate change presents both significant challenges and potential opportunities for water management in Ireland. From the impacts and vulnerabilities highlighted above, it is likely that the hydrological response to climate change will be appreciably determined by the capacity of individual catchment characteristics to buffer the suggested changes in precipitation and evaporation. Therefore, in order to successfully adapt to projected changes, strategies must be capable of accounting for the complex processes and interactions that occur at the catchment scale.

Modern approaches to water management have been founded on the ability to react and adapt to changing pressures and demands, with adaptation historically based on reactive measures that are triggered by past or current events, or anticipatory measures where decisions are based on some future assessment of future conditions. While such decision-making practices are unlikely to change in the future, increasing importance must be placed on the anticipation of impacts. Traditionally, such anticipatory measures have been built on the premise that the past is the key to the future. Changing trends in many important hydrological time series, such as rainfall intensity and maximum flood peaks, have introduced non-stationarity, with the result that past events can no longer be relied upon in driving future decision making. Therefore, 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 the 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 on altering the exposure of the system, through preparedness, to the effects of climate change (Adger *et al.*, 2005)

3.9.1 The role of technology

In the past, the role of technology has been essential in water resources management and is likely to remain so into the future. The emphasis placed on technology in adaptation is largely dependent on economic conditions, policy initiatives and future scientific breakthroughs, with perhaps the greatest potential in water supply management. At present, options such as improved water treatment and reuse, deep well pumping, the transfer of resources between catchments and desalinisation are becoming ever more accessible. Indeed, in anticipation of future resource needs in the Greater Dublin Area, the transfer of water from the Shannon to the east is already under way and provides a novel option to supplement water resources in the medium to long term. At present, the economic cost of desalinisation is too high for it to be feasible on a large scale in Ireland; however, this is likely to change in the future. It is of prime importance that the employment of technology in adapting to climate change be environmentally sustainable, with equity fairly distributed between all resource stakeholders.

3.9.2 Integrated assessment and decision making

Historically, water management has been largely concentrated on the physical control of water and economic cost–benefit analysis, where the allocation of economic worth to many natural resources has been underestimated. On the whole, environmental and social effects have at best been given token consideration, as has the involvement of local communities in the decision-making process (Jakeman and Letcher, 2003). Internationally, the recent shift towards the integrated assessment of natural resources and environmental modelling has resulted in a less narrowly focused and disjointed approach to environmental management. Integrated resource management offers considerable potential to decision making in adapting to climate change. Characteristic of such an approach is the consideration of multiple issues and multiple stakeholders, the ability to further understand the interaction between nature and society, as well as the ability to model the impact of critical decisions over a range of scales. Given the increased availability of spatial data sets, integrated management offers the potential to manage water in a way that meets a broad range of demands and expectations. Furthermore, integrated analysis allows for the quantification and reduction of uncertainty in determining system response. Natural systems, even without human intervention, present considerable difficulties for modellers due to the complexity of natural systems, spatial heterogeneity and the inability to comprehensively measure internal system variables (Jakeman and Letcher, 2003). Integrated assessment allows the perturbation of the system, its inputs and parameters, using likely scenarios of change, so that the impact of decisions can be anticipated and assessed, therefore offering a robust methodology to aid decision making, describe policy impacts and prioritise research needs in adapting to climate change.

3.9.3 Decision making in the face of uncertainty

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. Burton *et al.* (2002) highlight a number of reasons for this, with the central issues being the wide range of potential impacts derived from uncertainty in modelling climate change. Such uncertainty exists at every scale and is visible in areas such as likely future development pathways and future emissions of greenhouse gases, uncertainty in modelling complex environmental systems from the global climate system to individual catchment processes, as well as a mismatch in scales between global change and local impacts. In an effort to deal with such uncertainty, impact assessment has evolved to deal with scenarios of change so that a number of possible realisations can be accounted for. Where different scenarios lead to divergent results, decision making in adapting to climate change becomes challenging, with traditional decision-making tools proving inadequate. The focus of international research has thus turned to bridging the gap between impacts and the information required by decision makers. Central to this task is the role of probability through the determination of likelihoods and the construction of confidence intervals for simulated impacts. The ability to attribute probabilities to impacts offers huge potential to decision-making approaches, with risks defined as the probability of hazard times the vulnerability. The use of probabilities in this way offers the potential for decision makers to account not only for the most likely impacts, but also for low probability, high impact surprise events while accounting for the vulnerability of individual stakeholders. The application of probability is especially useful in the water resources sector where managers and engineers already use probabilities in everyday decisions.

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Appendix 3.1

Table A3.1a. Percentage change (%) in monthly streamflow simulated for each catchment in the 2020s using the mean ensemble. Upper (+) and lower (–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2020	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**
Jan	0.7	0.5	0.4	4.5	0.1	0.1	0.6	0.8	0.7	–1.4	0.3	0.5	1.0	4.0	1.9	–1.4	1.0	1.2	2.6	0.9	0.5	2.5	0.9	1.1	4.6	0.2	0.2
Feb	–0.3	0.7	0.7	0.9	0.1	0.1	–0.6	1.0	1.0	0.2	0.7	0.8	0.9	1.1	1.1	0.6	0.6	0.5	0.8	0.1	0.1	1.6	0.3	0.3	1.2	0.3	0.3
Mar	8.9	1.0	1.4	3.6	0.0	0.0	7.1	0.7	1.2	9.4	1.4	1.8	7.0	1.6	1.7	11.0	1.9	1.4	4.4	1.5	0.5	5.5	1.0	0.6	4.3	0.2	0.2
Apr	5.2	0.8	1.0	1.7	0.0	0.0	3.0	0.7	0.5	4.9	1.2	1.3	3.1	0.7	0.8	6.9	0.9	1.0	2.9	0.1	0.1	2.1	0.3	0.7	2.5	0.1	0.1
May	1.8	0.5	0.6	0.8	0.2	0.2	–2.3	1.0	1.0	0.9	0.6	0.6	–0.9	1.7	2.0	–4.4	1.5	2.7	1.5	0.4	1.0	–2.0	1.2	2.5	3.1	0.2	0.2
Jun	–0.6	0.8	1.0	–2.5	0.2	0.2	–6.4	2.1	1.0	0.4	1.0	1.2	–5.1	2.4	3.4	–22.3	4.7	8.2	–1.1	0.9	3.3	–6.2	1.6	2.0	1.3	0.5	0.4
Jul	–1.2	1.0	0.8	–4.0	0.5	0.5	–4.6	1.6	1.3	0.4	0.6	0.5	–10.0	7.2	11.7	–17.6	2.5	5.1	–2.4	0.7	2.5	–5.0	1.1	2.3	0.9	0.4	0.4
Aug	–0.7	0.6	0.8	–10.9	0.2	0.3	–3.8	1.0	0.6	0.7	0.5	0.5	–16.1	9.6	16.4	–15.8	2.7	5.0	–4.7	0.6	2.5	–5.9	0.9	2.1	–0.9	0.7	0.5
Sep	–4.4	2.0	2.3	–11.0	0.4	0.4	–8.1	3.7	4.1	–0.6	0.9	0.8	–19.1	7.3	10.3	–24.9	6.3	8.4	–8.0	1.5	4.8	–18.1	3.2	4.9	–11.1	3.7	2.5
Oct	–21.3	3.6	3.4	–6.0	0.0	0.0	–23.0	4.5	4.5	–20.3	5.0	5.2	–15.4	3.2	6.2	–56.8	2.3	3.8	–15.7	4.1	4.8	–12.8	8.1	7.1	–22.4	3.5	3.3
Nov	–12.7	5.9	6.9	–1.9	0.1	0.1	–19.0	8.9	14.1	–10.0	5.2	8.0	0.6	5.2	11.3	–19.2	10.0	11.0	–14.1	2.9	4.5	–5.6	4.8	2.0	–0.6	0.6	0.8
Dec	1.0	0.7	0.7	2.8	0.0	0.0	–1.9	1.2	1.2	2.5	0.6	1.1	–5.5	4.1	4.2	–5.3	3.2	2.5	–2.4	2.3	1.1	0.8	1.5	1.9	2.5	0.3	0.4

Table A3.1b. Percentage change (%) in monthly streamflow simulated for each catchment in the 2050s using the mean ensemble. Upper(+) and lower (–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2050	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**	**%**	**+**	**–**
Jan	10.2	0.5	0.4	10.2	0.1	0.2	8.8	0.7	0.6	2.1	0.3	0.5	5.4	6.1	3.3	5.0	1.9	2.0	10.5	2.7	1.0	11.0	1.2	1.2	9.7	0.4	0.6
Feb	17.9	1.0	0.9	10.0	0.1	0.1	15.2	1.4	1.4	10.7	1.0	1.0	15.5	4.5	3.7	13.6	1.3	0.9	14.4	2.3	0.7	14.2	0.6	0.3	10.2	0.1	0.4
Mar	15.8	0.8	0.7	7.4	0.2	0.2	10.7	1.0	0.8	12.5	1.0	1.5	11.4	4.2	4.4	12.6	1.1	1.2	12.9	0.7	0.6	8.4	1.0	2.5	7.5	0.4	0.3
Apr	3.9	1.6	1.7	–1.8	0.1	0.1	–3.1	2.4	1.7	2.3	1.2	1.2	–5.5	2.4	3.7	–4.8	1.7	2.9	4.2	1.5	4.5	–3.1	2.4	3.2	0.0	1.7	1.0
May	3.4	2.5	2.0	–5.2	0.3	0.3	–5.5	3.1	1.5	1.4	1.9	1.6	–12.5	3.7	6.2	–17.9	3.6	5.5	–0.3	1.4	4.7	–8.1	3.4	4.9	–0.1	1.3	0.7
Jun	3.8	1.4	1.4	–10.1	0.1	0.1	–4.9	3.0	2.1	2.5	1.2	1.6	–15.7	7.5	9.0	–34.9	5.8	10.0	–3.7	1.7	5.9	–10.9	3.1	4.7	–1.0	1.3	0.8
Jul	4.5	1.4	1.5	–13.4	0.4	0.4	–2.9	2.4	1.3	2.7	0.8	0.9	–25.3	13.7	20.9	–30.3	4.4	8.2	–7.2	1.4	5.1	–10.9	2.3	5.0	–1.7	1.0	0.7
Aug	5.7	0.7	0.9	–18.6	0.2	0.3	–1.0	1.6	1.3	3.1	0.7	0.8	–36.2	15.6	23.4	–26.8	4.2	7.5	–11.0	1.2	3.7	–13.8	2.4	4.8	–3.9	1.3	0.9
Sep	0.8	2.3	2.7	–27.3	0.6	0.4	–5.2	4.3	4.0	1.3	1.0	0.9	–32.2	9.2	12.7	–31.6	6.1	8.9	–13.6	1.7	4.9	–33.4	7.0	12.5	–16.3	4.7	3.1
Oct	–20.6	4.7	4.4	–15.0	0.2	0.2	–27.0	7.3	6.7	–20.1	5.5	5.7	–16.3	8.2	7.5	–65.1	4.1	3.4	–26.4	3.0	7.1	–31.7	12.5	13.8	–39.4	4.9	5.1
Nov	–11.8	6.3	6.9	–0.3	0.1	0.1	–22.0	10.9	18.2	–9.6	5.2	8.4	7.4	7.6	16.8	–27.0	12.2	13.5	–18.4	5.8	8.6	–6.6	11.4	6.9	–3.5	0.7	1.4
Dec	8.6	0.7	0.9	5.6	0.1	0.1	1.5	1.6	3.3	5.7	0.8	1.0	–1.5	8.5	11.0	–4.6	4.0	3.5	–0.6	5.1	1.6	7.5	1.9	1.8	5.0	0.6	1.3

Table A3.1c. Percentage change (%) in monthly streamflow simulated for each catchment in the 2080s using the mean ensemble. Upper (+) and lower(–) uncertainty bounds are also provided.

	Barrow			Moy			Suir			Blackwater			Boyne			Ryewater			Inny			Brosna			Suck		
2080	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–	%	+	–
Jan	13.8	0.8	1.2	13.6	0.2	0.2	12.3	0.6	1.0	3.0	0.6	1.2	6.7	7.3	3.8	12.9	2.9	2.8	12.4	4.3	1.3	16.0	2.0	1.6	13.0	0.7	1.3
Feb	25.0	1.4	1.4	16.3	0.1	0.2	21.7	2.0	2.4	12.5	1.3	1.5	23.7	6.0	4.8	24.0	1.9	1.4	21.0	4.4	1.4	25.7	1.6	0.9	16.6	0.5	1.2
Mar	16.9	1.1	0.9	10.8	0.2	0.2	10.7	1.5	1.2	9.3	0.9	1.5	14.6	5.8	6.1	17.3	1.2	1.3	17.2	0.9	0.9	11.6	1.5	3.7	10.1	0.6	0.4
Apr	8.4	1.0	0.8	2.1	0.0	0.0	0.6	1.0	0.6	2.4	0.7	0.7	–0.8	2.6	3.7	4.1	1.4	2.1	8.8	1.5	4.3	2.2	2.0	2.5	4.6	1.3	1.0
May	6.3	1.9	1.5	–3.4	0.4	0.4	–4.9	2.9	1.7	0.1	1.7	1.5	–9.5	4.0	6.9	–11.5	3.5	5.7	3.9	1.5	4.8	–4.4	3.5	5.4	4.2	1.2	0.5
Jun	4.4	1.6	1.5	–11.3	0.2	0.2	–6.8	3.3	2.2	–0.5	1.5	1.6	–16.3	9.1	11.2	–31.8	6.4	11.0	–0.7	2.1	7.0	–8.3	3.1	4.2	1.7	1.6	1.0
Jul	3.7	1.8	1.9	–17.9	0.6	0.6	–5.7	2.9	1.4	–0.6	1.3	1.3	–29.9	17.6	25.8	–31.1	5.6	10.6	–5.6	1.9	6.6	–9.3	2.5	5.2	0.0	1.5	1.1
Aug	5.5	1.1	1.1	–29.5	0.3	0.3	–3.2	2.0	1.6	0.1	1.0	1.0	–43.3	19.1	27.4	–27.5	5.4	10.1	–10.3	1.6	4.3	–11.7	2.5	4.2	–2.0	1.7	1.4
Sep	0.9	2.7	2.9	–35.8	0.8	0.6	–6.8	4.5	4.1	–0.9	1.2	1.0	–32.9	9.4	12.9	–32.4	6.4	10.2	–11.9	2.0	5.2	–25.5	4.9	9.0	–16.7	5.6	3.6
Oct	–29.8	6.5	6.2	–20.0	0.2	0.2	–36.0	9.9	9.4	–30.9	7.7	8.3	–14.3	12.0	9.3	–76.0	6.6	4.6	–28.8	2.8	9.0	–26.8	8.8	8.8	–50.9	6.2	6.5
Nov	–27.5	9.4	9.9	–7.4	0.1	0.1	–33.4	12.6	20.4	–23.1	8.4	11.8	3.7	8.9	20.8	–38.0	14.5	16.1	–27.9	8.0	12.1	–13.4	15.1	8.7	–13.6	0.8	1.4
Dec	2.8	1.8	2.4	6.6	0.1	0.2	–6.7	2.6	5.6	–0.2	1.0	1.4	–4.7	12.5	17.1	–9.9	4.6	4.0	–3.6	7.3	2.8	8.8	3.5	3.5	6.9	1.1	2.3

Appendix 3.2

Table A3.2. Student *t*-test results for monthly streamflow simulated using the mean ensemble. The asterisk highlights months for which changes in streamflow are significant at the 0.05 level.

	Barrow			Blackwater			Boyne			Brosna			Inny			Moy			Ryewater			Suck			Suir		
2020	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
Jan		*	*			*		*	*		*	*	*	*	*	*	*	*		*	*	*	*	*		*	*
Feb		*	*		*	*		*	*		*	*		*	*		*	*		*	*		*	*		*	*
Mar	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Apr	*	*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	
May		*	*		*			*	*		*	*			*		*	*	*	*	*	*		*	*	*	*
Jun		*	*		*		*	*	*	*	*	*		*		*	*	*	*	*	*			*	*	*	*
Jul		*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*		*	*	*
Aug		*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*		*
Sep	*						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Oct	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Nov	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*		*	*	*	*		*	*	*	*	*
Dec		*			*		*		*		*	*			*	*	*	*	*	*	*	*	*	*			*