

Climate Change Research Programme (CCRP) 2007-2013 Report Series No. 16



Robust Adaptation to Climate Change in the Water Sector in Ireland

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Community and Local Government.

OUR RESPONSIBILITIES

LICENSING

We license the following to ensure that their emissions do not endanger human health or harm the environment:

- waste facilities (e.g., landfills, incinerators, waste transfer stations);
- large scale industrial activities (e.g., pharmaceutical manufacturing, cement manufacturing, power plants);
- intensive agriculture;
- the contained use and controlled release of Genetically Modified Organisms (GMOs);
- large petrol storage facilities;
- waste water discharges.

NATIONAL ENVIRONMENTAL ENFORCEMENT

- Conducting over 2,000 audits and inspections of EPA licensed facilities every year.
- Overseeing local authorities' environmental protection responsibilities in the areas of - air, noise, waste, waste-water and water quality.
- Working with local authorities and the Gardaí to stamp out illegal waste activity by co-ordinating a national enforcement network, targeting offenders, conducting investigations and overseeing remediation.
- Prosecuting those who flout environmental law and damage the environment as a result of their actions.

MONITORING, ANALYSING AND REPORTING ON THE ENVIRONMENT

- Monitoring air quality and the quality of rivers, lakes, tidal waters and ground waters; measuring water levels and river flows.
- Independent reporting to inform decision making by national and local government.

REGULATING IRELAND'S GREENHOUSE GAS EMISSIONS

- Quantifying Ireland's emissions of greenhouse gases in the context of our Kyoto commitments.
- Implementing the Emissions Trading Directive, involving over 100 companies who are major generators of carbon dioxide in Ireland.

ENVIRONMENTAL RESEARCH AND DEVELOPMENT

- Co-ordinating research on environmental issues (including air and water quality, climate change, biodiversity, environmental technologies).

STRATEGIC ENVIRONMENTAL ASSESSMENT

- Assessing the impact of plans and programmes on the Irish environment (such as waste management and development plans).

ENVIRONMENTAL PLANNING, EDUCATION AND GUIDANCE

- Providing guidance to the public and to industry on various environmental topics (including licence applications, waste prevention and environmental regulations).
- Generating greater environmental awareness (through environmental television programmes and primary and secondary schools' resource packs).

PROACTIVE WASTE MANAGEMENT

- Promoting waste prevention and minimisation projects through the co-ordination of the National Waste Prevention Programme, including input into the implementation of Producer Responsibility Initiatives.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

MANAGEMENT AND STRUCTURE OF THE EPA

The organisation is managed by a full time Board, consisting of a Director General and four Directors.

The work of the EPA is carried out across four offices:

- Office of Climate, Licensing and Resource Use
- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet several times a year to discuss issues of concern and offer advice to the Board.

EPA Climate Change Research Programme 2007–2013

Robust Adaptation to Climate Change in the Water Sector in Ireland

CCRP Report

Prepared for the Environmental Protection Agency

by

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

Authors:

Julia Hall, Conor Murphy and John Sweeney

ENVIRONMENTAL PROTECTION AGENCY

An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699

Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the Climate Change Research Programme 2007–2013. The programme is financed by the Irish Government under the National Development Plan 2007–2013. It is administered on behalf of the Department of the Environment, Community and Local Government by the Environmental Protection Agency which has the statutory function of co-ordinating and promoting environmental research.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the author(s) accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

The EPA Climate Change Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA CLIMATE CHANGE RESEARCH PROGRAMME 2007–2013

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-446-3

Price: Free

Online version

Details of Project Partners

Julia Hall

Irish Climate Analysis and Research Units
Department of Geography
National University of Ireland Maynooth
Maynooth
Ireland

Tel.:+353 1 70868362

Email: julia.hall@nuim.ie

Dr Conor Murphy

Irish Climate Analysis and Research Units
Department of Geography
National University of Ireland Maynooth
Maynooth
Ireland

Tel.:+353 1 7083494

Email: conor.murphy@nuim.ie

Prof. John Sweeney

Department of Geography
National University of Ireland Maynooth
Maynooth
Ireland

Tel.:+353 1 7086835

Email: john.sweeney@nuim.ie

Table of Contents

<u>Acknowledgements</u>	<u>ii</u>
<u>Disclaimer</u>	<u>ii</u>
<u>Details of Project Partners</u>	<u>iii</u>
<u>Executive Summary</u>	<u>vii</u>
<u>1 Introduction</u>	<u>1</u>
1.1 <u>Responding to Climate Change</u>	<u>1</u>
1.2 <u>The Nature of Adaptation</u>	<u>2</u>
1.3 <u>Adaptation and Irish Water Resources</u>	<u>2</u>
1.4 <u>The Challenge of Uncertainty for Adaptation</u>	<u>4</u>
1.5 <u>A Wait and See Approach is not an Option</u>	<u>4</u>
1.6 <u>A Way Forward: Robust Adaptation</u>	<u>5</u>
<u>2 The Development of a Decision Support Tool</u>	<u>7</u>
2.1 <u>Adaptation Framework</u>	<u>7</u>
2.2 <u>Decision Support Tool</u>	<u>8</u>
2.3 <u>Modelling Methodology</u>	<u>9</u>
2.4 <u>Overview of Climate Projections</u>	<u>10</u>
2.5 <u>Surface Water Abstractions</u>	<u>10</u>
2.6 <u>HYSIM</u>	<u>11</u>
2.7 <u>Model Conditioning</u>	<u>11</u>
2.8 <u>Future Hydrological Simulations</u>	<u>13</u>
2.9 <u>Water Evaluation and Planning Model Version 21</u>	<u>14</u>
2.10 <u>Water Resource Scenarios</u>	<u>14</u>
<u>3 Analysis of Model Outputs</u>	<u>16</u>
3.1 <u>Water Use-to-Resource Ratio</u>	<u>16</u>
3.2 <u>Statistical Measures of Performance</u>	<u>16</u>
3.3 <u>Vulnerability Analysis of Irish Water Schemes</u>	<u>18</u>
3.4 <u>Boyne Hydrometric Area</u>	<u>18</u>
3.5 <u>Boyne URR Analysis</u>	<u>18</u>
3.6 <u>RRV Analysis</u>	<u>22</u>

<u>4</u>	<u>Conclusions and Recommendations</u>	<u>28</u>
	<u>References</u>	<u>29</u>
	<u>Acronyms</u>	<u>33</u>
	<u>Appendix 1</u>	<u>35</u>
	<u>Appendix 2</u>	<u>37</u>

Executive Summary

Adaptation is necessary to position Ireland to better cope with the impacts of climate change. Impact studies to date have identified some strong climate signals, including an increase in river flows during winter and spring, along with reductions in late summer and autumn, with simulated changes becoming more pronounced by the middle and end of this century. For water supply management, the characteristics of the water supply system will have a strong bearing on vulnerability to climate change. Where there is adequate excess capacity, even a large change in climate may have limited effect. However, where a system is operating at, or close to, capacity even a small change in climate has the potential to tip the system past a critical threshold. Adaptation in the water sector is challenging where there is uncertainty in the magnitude of climate impacts, infrastructure is expensive and has a long lead time in terms of the planning and construction time required, has a long design life and is expected to function in present and future climate conditions. These challenges are coupled with tightened financial resources.

This report develops a framework for supporting adaptation to climate change and a tool for assessing adaptation options. The framework established is built on the identification of vulnerability for individual surface water abstraction points. Vulnerability is highlighted where climate change is likely to alter the availability of water to meet demands at that point. In such situations, an adaptation tool is developed to identify and appraise adaptation options that are robust to uncertainty in future climate. The tool developed is intended as an exploratory tool to identify where and when adaptation will be necessary and to identify if certain strategies are likely to be successful under the range of likely future conditions. It is flexible in that it can be applied to individual existing or new abstraction points or to entire catchments, can be readily updated when revised climate change information becomes available and allows the integration of different pressures.

A detailed case study application is provided for individual water abstraction points within the Boyne Catchment. Where vulnerability to climate change is identified, scenarios are developed to represent robust adaptation strategies. In particular, emphasis is given to soft strategies such as demand management and leakage reduction. It is evident from this and other studies that, in the water sector, adaptation measures need to be context specific. In the cases provided here, a combination of demand and leakage reduction was not sufficient to reduce the risk of high water stress entirely. Within this context, consideration will need to be given to what is an acceptable level of risk. Adaptation strategies should be evaluated according to the best available knowledge on climate change on a regular basis and be reconsidered if necessary. This adaptation approach ensures flexibility and the ability to respond to changes as revised climate scenarios emerge. This also reduces the risk of maladaptive action which would significantly constrain future possibilities. The application of a process-oriented 'vulnerability thinking' instead of an 'impacts thinking' approach in adaptation planning is therefore promoted here.

Based on the outcomes of this work the following recommendations are made:

- From the case studies conducted, uncertainties for the future are high. These uncertainties are related to climatic and non-climatic factors. Therefore, future adaptation planning in the water sector will need to account for this uncertainty.
- In the nearer term, many elements of adaptation planning can be identified that are robust to uncertainty, particularly non-climatic factors such as demand and leakage control. It is recommended that such robust, flexible strategies should form an important aspect of adaptation planning in the near term.
- The application of a process-oriented 'vulnerability thinking' instead of an 'impacts

thinking' approach in adaptation planning is promoted. A vulnerability thinking approach combines flexibility with planning over long time horizons and monitoring, as well as adaptive management, recognising the uncertainty in projected hydrological changes.

- In some cases, the implementation of adaptation options does not entirely reduce the occurrence of water stress. In such situations, consideration should be given to what are acceptable levels of risk.

- Where investment in new infrastructure is required, it is recommended that such infrastructure be subjected to a sensitivity analysis of performance under the full range of uncertainty associated with climate change.
- It is recommended that future work might investigate the application of more physically based models that can account for issues such as groundwater in greater physical detail.

1 Introduction

1.1 Responding to Climate Change

International efforts to combat the adverse impacts of projected global climate change have mainly concentrated on seeking agreements to reduce emissions of greenhouse gases (GHGs). Modest progress in achieving mitigation thus far has centred on the implementation of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, the provisions of which expire in 2012. The outlook for a successor to this, which will bind the major emitter countries to the targets necessary to avoid the 'dangerous climate change' level of two degrees of global warming above pre-industrial levels, is currently pessimistic. Responding to climate change thus requires a two-pronged strategy. Ambitious mitigation targets must be accompanied by strong adaptation efforts. These efforts will increasingly encompass both developing and developed countries, a necessary strategy if the targets are to be achieved.

Adaptation is necessary to position countries to better cope with the impacts they will experience. [Figure 1.1](#) shows that irrespective of what global emissions trajectory is followed over the current century it is only after the mid-century that the various emission

scenarios diverge significantly. Mitigation today will ultimately provide payback, principally in the second half of the century, but is vital to foster if major environmental and social damage is to be avoided. Clearly a medium-term commitment to an ongoing anthropogenic-led warming is likely over the next few decades. This may be enhanced or diminished somewhat by natural trends in climate; however, it is judicious to plan for an intensification of climate change impacts that are already being experienced both globally and in Ireland. Towards that end the Member States of the European Union have agreed both strict mitigation targets and also a strategic approach to adaptation. The latter is exemplified by the White Paper on Climate Change Adaptation designed to delimit the actions necessary to strengthen Member State resilience in coping with the problems likely to be experienced.

An objective of developing a national adaptation strategy for Ireland was expressed in the National Climate Change Strategy 2007–2012. This would provide a vehicle for integrating issues of climate change into national and local governance. This has as yet not been achieved and the present study

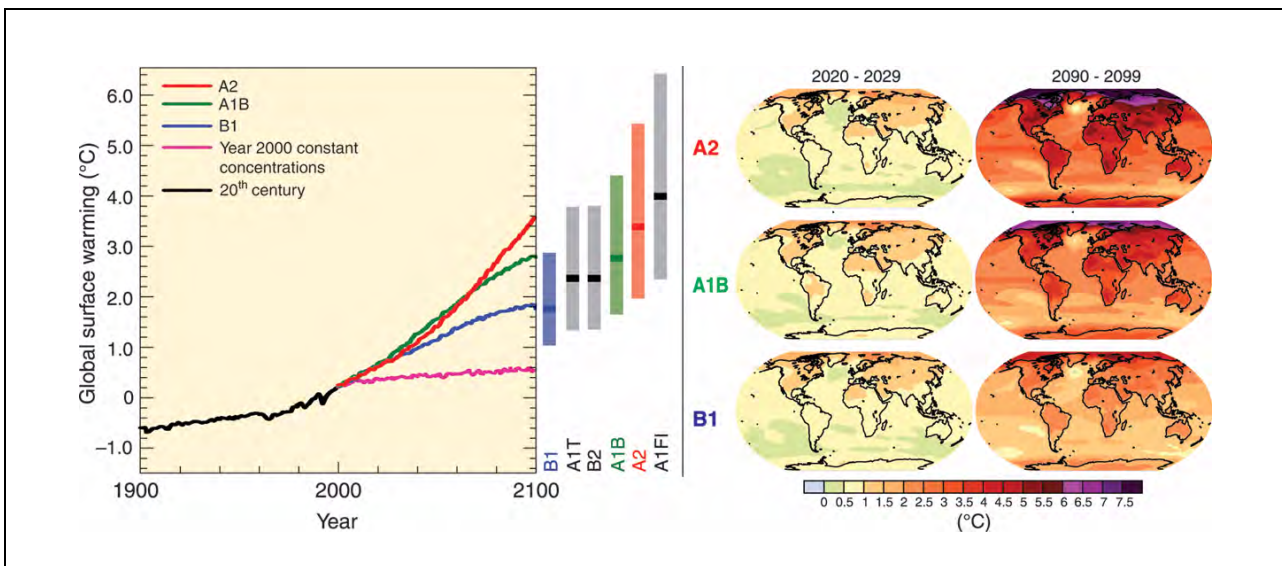


Figure 1.1. Projected global temperature rise under different emission scenarios (IPCC, 2007b).

constitutes a contribution to the development of such a strategy.

1.2 The Nature of Adaptation

There is no single uniform definition of adaptation. For example, the Intergovernmental Panel on Climate Change (IPCC) Working Group 2 defines adaptation as “*adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*” (IPCC, 2007b: p. 869). Working Group 3 characterises adaptation as “*initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects*” (IPCC, 2007b: p. 809). Vulnerability in this sense can be defined as the potential for loss. The EU Commission uses the following terminology: “*adaptation aims at reducing risk and damage from current and future harmful impacts, cost-effectively or by exploiting potential benefits*” (European Commission, 2007: p. 3). These definitions all imply adaptation as a process with the goal to moderate harm, exploit opportunities and benefits, and to reduce vulnerability as well as risk and damage of impacts. A variation on this theme is provided by the UK Climate Impact Programme (UKCIP) which terms adaptation as “*The process or outcome of a process that leads to a reduction in harm, or risk of harm, or realization of benefits associated with climate variability and climate change*” (Willows and Connell, 2003: p. 111). This definition adds the outcome as an additional dimension to the definition of adaptation.

To broaden the definition of adaptation, various types of adaptation are distinguished in the international literature regarding the timing of adaptation, its strategic approach or the actors involved. Depending on the timing, adaptation can be characterised as reactive or anticipatory. Reactive (also called responsive) adaptation takes place as a reaction to (climate change) impacts that have already occurred. A common example might be the building of flood defences or the installation of an early warning system following an extreme flood event. In contrast, in anticipatory adaptation measures are taken in advance of the occurrence of harm. An example of anticipatory adaptation in the water resource sector would be the

increase of storage capacity (e.g. the construction of a reservoir) to store excess winter rainfall to supply water during projected drier summer months or the addition of excess design capacity in water infrastructure. The goal of anticipatory adaptation is to minimise the expected impacts by reducing the vulnerability of water supply and water users to future climate change. Regarding the level of spontaneity, adaptation can be distinguished as autonomous or planned (Fankhauser et al., 1999; Bates et al., 2008). Autonomous adaptation is not purposely designed to deal with climate change, but rather comprises a non-coordinated response to change. On the other hand, planned adaptation directly takes climate variability and climate change into account to reduce the anticipated, or already felt, negative effects, or to seek to gain from the changed conditions. Depending on the actors involved in taking adaptation measures, adaptation can also be characterised as private or public. This report focuses on planned, anticipatory adaptation in the Irish public water resource sector.

1.3 Adaptation and Irish Water Resources

Climate change has the potential to impact significantly on Irish water resources. The IPCC states in its Technical Report *Climate Change and Water* (Bates et al., 2008) that changing climate over the past several decades can be associated with changes in a number of key components of the hydrological cycle. For instance, changes in precipitation (annual and seasonal pattern), precipitation intensity and extremes (high and low) have been observed around the world (Bates et al., 2008). These alterations can result in changes in annual and seasonal flow regimes, groundwater–surface water interactions and, therefore, affect raw water availability, which can also affect water quality and biodiversity.

The effects of climate change will be different at different locations on the earth. For example, climate models suggest a greater warming at high latitudes and less warming in the tropics (Hegerl et al., 2007), while precipitation changes will also not occur uniformly around the globe. Some locations will receive more rainfall, whereas other regions may suffer from extended drought periods. The impact of

climate change on water resources and supply systems will not only depend on the geography and magnitude of changes in the hydrological system but also on the water supply system itself. Depending on the main characteristics of water supply systems, the same change in climate can have different effects on water supply systems that differ from location to location. For example, a resilient water supply system can be thought of as one with large available headroom: the difference between water available for use and demand (Dessai and Hume, 2007). In such cases, the system has a high resistance and even a large change in inputs of raw water through rainfall change, or an increase in demand through warmer temperatures, will have little effect on the system. In contrast, in a system that is highly precarious and operating towards the limits of its capacity, with little available headroom, even a small change in climate or a relatively infrequent extreme event can push it past a critical threshold and result in failure of the supply system. Modelling results to date suggest that climate change will alter catchment hydrology over medium and long time scales and, in response to these anticipated changes, it is important that the resilience of water supply systems is analysed and that adaptation focuses on identifying adaptation options that are equitable both locally and on a catchment scale and that account for the many water users involved.

However, it is also important to remember that climate change is but one pressure on water resources and management. Factors that are independent of climatic change but that also need to be considered in future water resource management include population changes, changes in water demand, legislative changes (e.g. the Water Framework Directive or introduction of water charges), as well as water infrastructural changes driven by policy incentives (e.g. leakage reduction).

The traditional approach to water resource planning and management, in Ireland and elsewhere, is based on the assumption of the stationarity of the hydrological system. Stationarity assumes that the amount of raw water available for abstraction is constant over time, with some interannual or interdecadal variability. Frequency statistics are used

to assess the water resource, and future planning of the water supply system is undertaken accordingly. However, the assumption that the past will be the key to the future is no longer valid (Milly et al., 2008). The climate and therefore the entire hydrological system is changing, and relying on a traditional planning approach increases the risk of maladaptation. Maladaptation is defined as action taken to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups. Common forms of maladaptation include those actions that increase GHG emissions, disproportionately impact on the most vulnerable, present high opportunity costs, reduce the incentive for further adaptation, and instil a path dependency in dealing with a problem.

The future impacts of a changing climate on Irish catchment hydrology have been investigated in several studies. All of the assessment studies identify some strong climate signals, including an increase in river flows during winter and spring, along with reductions in summer and autumn, with simulated changes becoming more pronounced as the century progresses (Cunnane and Regan, 1994; Charlton and Moore, 2003; Murphy and Charlton, 2008; Steele-Dunne et al., 2008; Bastola et al., 2011a,b). While agreement is evident, there remain large uncertainties surrounding the actual magnitude of change (see in particular Bastola et al. (2011b) and Murphy et al. (2011)) and if we are to avoid expensive over- or under-adaptation we need to incorporate this uncertainty into future decision making.

This work builds on these previous studies and shifts the focus towards examining the implications of such changes in catchment hydrology and on how we might effectively adapt water resources management in an uncertain future.

The goals of this work are therefore:

- To identify vulnerability to climate change within the current Irish water supply systems. Here, vulnerability is defined for individual water abstraction points from surface waters where climate change is likely to alter the availability of water to meet demand for abstraction at that point;

- To develop a framework for the appraisal of adaptation options that are robust to climate change uncertainty; and
- To develop an adaptation tool to inform and aid decision and policy making for adapting to climate change in ensuring the provision of surface water resources at the scale of individual surface water abstraction points.

1.4 The Challenge of Uncertainty for Adaptation

Uncertainty in the timing and magnitude of future climate change impacts presents considerable challenges for adaptation, particularly where adaptation is based on optimal design. Such uncertainty is to be expected when analysing complex dynamic systems such as the global climate system and catchment hydrological system. At present we don't have a full appreciation and knowledge of these systems and, as such, simplifications are made in the models we use to understand how future climate and hydrology are likely to evolve. Similarly, uncertainty is associated with how the future concentrations of GHGs are likely to evolve over the coming century. Such scenarios make assumptions about the future, such as changes in political regimes, and social and economic changes that are difficult to attach likelihoods to. This uncertainty has been well recognised to date, with the largest uncertainties associated with local-scale impacts that are relevant for adaptation decision making.

Hall (2007) draws attention to the heavy criticisms proffered by policy makers to the large ranges of future changes presented in the IPCC's Fourth Assessment Report (AR4) for not providing sufficient information on which to base decisions about the future and the conception that uncertainty ranges are so large as to be useless. In essence, these criticisms have called for likelihoods or probabilities to be associated with future impacts. However, probabilistic approaches are subject to the same difficulties as the scenario approaches presented and can only represent a fraction of the uncertainty space. Additionally, probabilistic outputs are highly conditional on the assumptions made in their construction.

Therefore, uncertainties are unlikely to be significantly reduced within the timescale relevant for adaptation decision making. Dessai et al. (2009) draw attention to the fact that, after over 20 years of intense study, the uncertainty ranges for climate sensitivity (temperature response of the global climate to a doubling of carbon dioxide levels in the atmosphere) have not been significantly reduced. In fact, the outcome of further developments in understanding key processes and feedbacks is likely to result in the opposite case, where unveiling limits to our knowledge will result in further unknown processes, thereby increasing uncertainty. Recently, this is evidenced by the increased uncertainty associated with sea-level rise due to the discovery of previously unknown processes involved in the melting of large land-based ice sheets. At the same time, ignoring uncertainty, or waiting for uncertainty to be reduced, is a high-risk strategy, particularly when the provision of water supply is so crucial for the effective functioning of society.

1.5 A Wait and See Approach is not an Option

As a result of uncertainties, there is a risk of procrastinating on making commitments for adaptation until either uncertainty is reduced or until climate change signals become detectable from observational records. While it is agreed that early detection of climate change is essential for minimising adverse environmental and societal impacts (Ziegler et al., 2005), waiting for climate change signals to emerge from records is problematic as an approach to adaptation.

Detection of climate change at regional and local scales in Ireland and elsewhere is inherently difficult because of the relatively weak climate change signal compared with the large interannual variability of rainfall and river flows. The choice of index for assessment, strengths and assumptions of statistical tests, significance testing and confounding factors such as urbanisation and/or arterial drainage, all require careful consideration (Kundzewicz and Robson, 2004; Radziejewski and Kundzewicz, 2004; Svensson et al., 2005; Wilby et al., 2008; Fowler and Wilby, 2010). Therefore, despite the identification of change points due to natural climate variability in

hydrological records (Kiely, 1999), robust attribution of changes in hydrology at the basin scale is not currently feasible for Ireland. However, techniques have emerged for estimating the time horizons for the formal detection of climate change signals. Preliminary estimates using data for river basins in the US and UK suggest that statistically robust climate-driven trends in seasonal run-off are unlikely to be found until at least the second half of this century (Ziegler et al., 2005; Wilby, 2006). Wilby (2006) also used detection time relationships to estimate the strength of trend required for detection by specified time horizons. The analysis of UK winter and annual precipitation totals suggests that changes of ~25% would be needed for detection by the 2020s in the most sensitive basins, and significantly longer for basins with high levels of natural variation. In such situations, adaptation will have to take place in advance of change being statistically detected. Similarly, the prospect of significantly reducing uncertainty in the timescales required for adaptation are low, as discussed above.

1.6 A Way Forward: Robust Adaptation

With statistically robust climate change signals unlikely to emerge from observed records within the timescale required for adaptation, it is crucial that progress is made on adaptation under conditions of uncertainty. A 'wait and see' approach is not viable, as uncertainty cannot be avoided or eliminated (Langsdale, 2008). In addition, the uncertainties involved in modelling future climate pose questions as to the utility of top-down 'predict and provide'-based policy analysis for adapting to climate change where predictions are used to derive a few optimum solutions. Hallegatte (2009) goes so far as to state that uncertainties in future climate change are so large that it makes many traditional approaches to designing infrastructure and other long-lived investments inadequate. Therefore, novel approaches to anticipatory adaptation are required if we are to ensure successful adaptation to climate change.

In responding to this challenge, a number of authors have highlighted the potential for strategies that are robust to uncertainty (Lempert and Schlesinger, 2000; Hallegatte, 2009; Wilby and Dessai, 2010). Robust strategies have been qualified by Hallegatte (2009) and Wilby and Dessai (2010) as those that:

- Are **low-regret**, in that they are functional and provide societal benefit under a wide range of climate futures;
- Are **reversible**, in that they keep at a minimum the cost of being wrong;
- Provide **safety margins** that allow for climate change in the design of current infrastructure or easy retrofitting;
- Use **soft strategies** that avoid the need for expensive engineering and institutionalise a long-term perspective in planning;
- **Reduce the decision time horizons** of investments; and
- Are **flexible** and mindful of actions being taken by others to either mitigate or adapt to climate change.

However, the movement to such an approach for adaptation necessitates a paradigm shift in how we deal with climate change data, requiring a movement away from a predict and provide, top-down approach towards a bottom-up approach that allows climate scenarios to be used in exploratory modelling exercises that test the functionality of adaptation options to the uncertainties involved. Work in this respect is progressing and frameworks for robust adaptation and example applications in the water sector are beginning to emerge in the international literature (in the UK: Dessai and Hume, 2007; Lopez et al., 2009; in Ireland: Hall and Murphy, 2011). Key among these emerging examples is the usefulness of moving away from considering climate change impacts explicitly, but rather identifying where and when vulnerability to climate change may emerge and the application of frameworks for the identification and selection of robust adaptation options. In a study of the Wembley water resource zone in south-west England, Lopez et al. (2009) used the ensemble of the ClimatePrediction.net experiment to test the performance of different adaptation options under climate change. By analysing the frequency of failures to meet peak water demand, it was concluded that the previously identified option of increasing reservoir capacity was not enough to tackle successive dry

years and that demand reduction measures were also needed (Lopez et al., 2009).

It is evident from these studies that adaptation measures need to be context specific. Adaptation has to be planned and implemented on international (for trans-boundary river basins), national and regional (basin) levels. National planning and water management at the river basin scale can help in the understanding of current and future vulnerabilities and insufficiencies that need to be recognised and subsequently addressed (Stakhiv, 1998). Individual river basins are the level at which detailed adaptation plans have to be implemented. Adaptation strategies have to be evaluated according to the best available

knowledge on a regular basis and reconsidered if necessary. This adaptation approach ensures flexibility and the ability to respond to changes as revised climate change scenarios emerge. This also reduces the risk of maladaptive action, which would significantly constrain future possibilities. Matthews and Le Quesne (2009) therefore promote the application of a process-oriented 'vulnerability thinking' instead of an 'impacts thinking' approach in adaptation planning. A vulnerability thinking approach combines flexibility with planning over long time horizons and monitoring, as well as adaptive management, recognising the uncertainty in projected hydrological changes.

2 The Development of a Decision Support Tool

2.1 Adaptation Framework

To cope with the effects of climate change on Irish water resources, careful thought is required about how to plan and prioritise adaptation action. Scenario planning provides a range of possible outcomes on which to base decisions. Additionally, adaptation measures based on the results of vulnerability assessments help to further refine the possible impacts. However, it is important that the planned anticipatory adaptation measures are kept flexible to allow for further adaptation. Stakhiv (1998) advocates 'learning by doing' as an approach because adaptation to climate change is a relatively new concept and no past experience is available to guide decisions. Learning by doing is the basic idea of adaptive management or adaptive response, where policies and regulations are adjusted in response to new information and gained experiences.

Without any adaptation strategies, it will be difficult to face the future challenges in Irish water management. Adaptation plans with a co-ordinated adaptation

approach are needed. However, formulating a final adaptation strategy is complicated because of the number of actors involved as well as the range of measures available. To define the criteria for the success of an adaptation measure is always context specific and final decisions can always be argued (Dessai and Hume, 2007). Emphasis should be placed on building adaptive capacity by supporting research and expanding knowledge by the use of scenarios and models, as well as incorporating climate change into policy and water management plans.

The robust adaptation approach framing the assessments conducted in this study is a stepwise process to assist planning and decision-making under uncertainty. The framework consists of three circular processes (Fig. 2.1), recognising that adaptation is not a linear, unidirectional approach but an iterative feedback process (purple cycle on left), with repetitive cycles of problem definition, robust adaptation option identification, planning and implementing, monitoring and performance appraisal. The key components to the process that support decisions on anticipatory

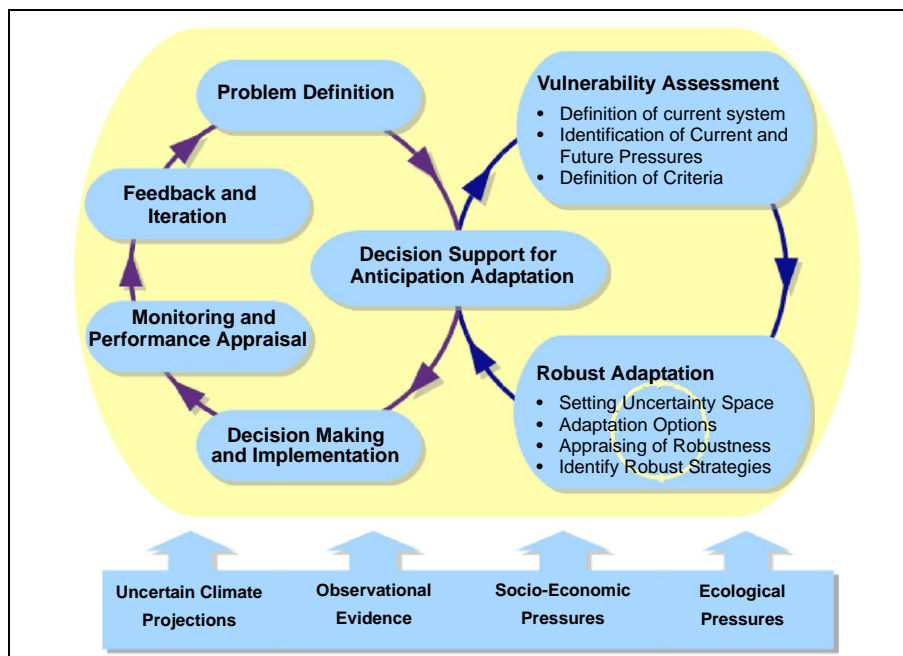


Figure 2.1. Adaptation framework for planned anticipatory adaptation.

adaptation are vulnerability assessment and robust adaptation option appraisal (blue circle on the right). Within this circle the step of robust adaptation encompasses a circular framework (yellow cycle) for scenario-neutral adaptation planning adapted from Wilby and Dessai (2010). All these iterative adaptation processes as a whole are influenced by observational evidence, socio-economic and ecological pressures, as well as by uncertain future climate projections (Fig. 2.1).

The decision support tool for the Irish water resource sector presented next is located within this context and is represented by the blue circle of vulnerability assessment and robust adaptation option identification to support decisions for planned anticipatory robust adaptation.

2.2 Decision Support Tool

The tool developed in this study to assess vulnerability and robust adaptation options in the Irish water resource sector is shown in Fig. 2.2. The tool is versatile, powerful and can add significant value in numerous areas, including:

- **Awareness raising**
The tool can effectively incorporate hydrological simulations of future climate change impacts to

raise awareness of potential impacts of climate change for water supply systems.

- **Recognition of vulnerability**
By incorporating likely impacts of climate change and current extraction capabilities, the tool can help identify where vulnerability or susceptibility to climate change lies within the supply system.
- **Timescale of vulnerability**
By allowing the incorporation of population growth, etc., the tool can be used to identify when vulnerability is likely to emerge at specific water extraction points.
- **Identification and appraisal of useful adaptation strategies**
This allows examination of how climate change compares with other pressures, identifies priorities for adaptation, allows integration of new operational rules and exploration of different adaptation options and their functionality under wide ranges of uncertainty.
- **Flexibility**
As soon as revised climate scenarios or water resource scenarios are developed, they can be readily incorporated. Additionally, the critical thresholds used to identify vulnerability can be readily changed to meet user needs.

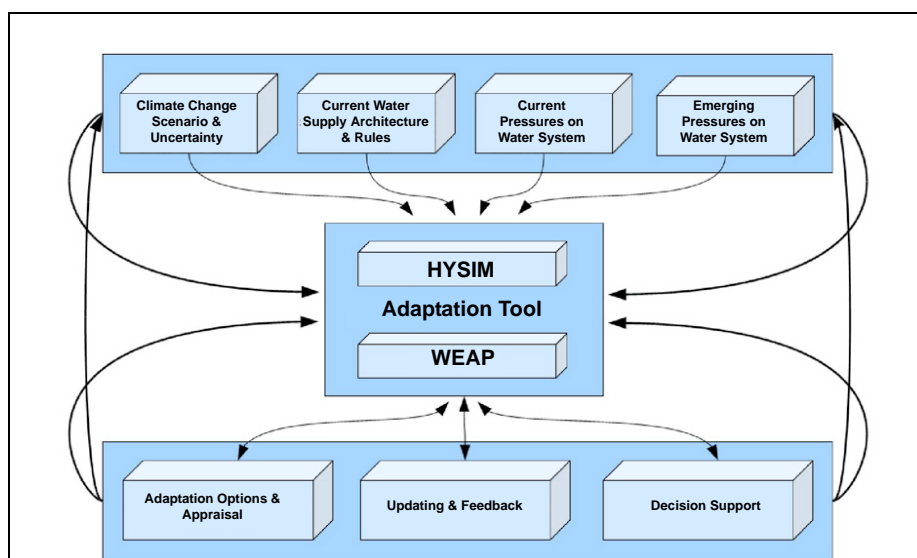


Figure 2.2. Schematic of the adaptation tool design showing the inputs and possible feedback mechanisms. HYSIM, HYdrological Simulation Model; WEAP, Water Evaluation And Planning.

- **Integration of pressures**

The tool allows current and future pressures on water supply to be integrated, along with specific flow requirements when testing adaptation options.

The decision support tool (Fig. 2.2) couples a hydrological rainfall run-off model (HYSIM¹) with a water-accounting model that accounts for the water supply system architecture and operating rules (Water Evaluation And Planning, WEAP). Uncertainty in future climate change impacts derived from future emissions of GHGs, uncertainty in Global Climate Models (GCMs), downscaling techniques, and rainfall run-off model uncertainties can be readily incorporated. The WEAP model allows current water supply architecture and operating rules to be incorporated, along with current and emerging pressures on the water supply system. The flexibility of the tool means that as updated climate scenarios emerge from the next generation of GCMs and emissions scenarios they can be incorporated. Most importantly, when used effectively, the tool can provide important information and appraisal of robust adaptation pathways to support crucial decisions. The following sections provide further information on the modelling approach, climate change scenarios and water-use scenarios on which the tool is based.

1. HYSIM, HYdrological Simulation Model.

2.3 Modelling Methodology

The modelling approach developed to assess vulnerability and to identify robust adaptation options is comprised of five steps (Fig. 2.3). Each step is dealt with in further detail in subsequent sections.

In Step 1 downscaled climate change projections that represent uncertainties in GCMs and future GHG emission scenarios are used to incorporate these uncertainties into the assessment. The climate change projections are used to drive a hydrological model. In modelling hydrological response, conceptual rainfall run-off models are widely used. These models, due to simplification of hydrological processes, are also associated with uncertainties, particularly related to model structure and parameters. To further expand the uncertainty space, every effort was made to incorporate rainfall run-off model uncertainty in capturing future hydrological response. Both model structure and parameter uncertainty are incorporated using the Generalised Likelihood Uncertainty Estimation (GLUE) technique of Beven and Binley (1992) and Beven and Freer (2001). The vulnerability of the water resource system is assessed by extrapolating the features of the current water resource system into the future (Business as Usual scenario). The performance of the system is assessed under a range of future hydrological conditions. Where future vulnerability exists, Steps 4 and 5 of the modelling approach are conducted. In Step 4, possible future strategies (water-use scenarios) are assessed with regard to their effectiveness and robustness to

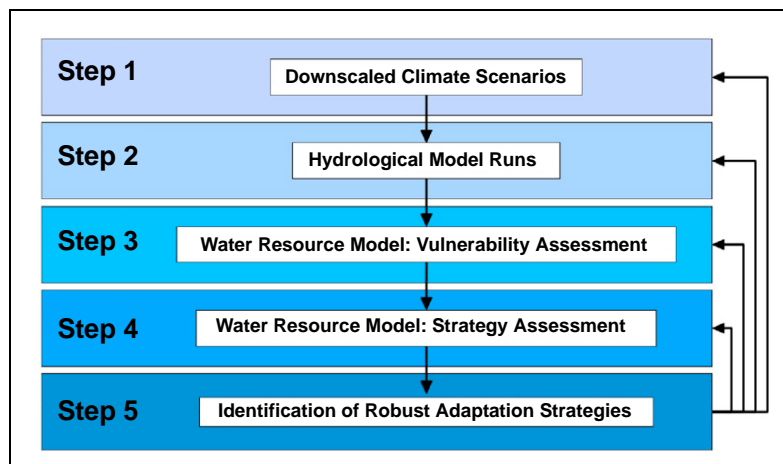


Figure 2.3. Stepwise modelling approach, with feedback/review loops.

uncertainty over the range of climate scenarios. The final step in this modelling approach involves the identification of robust adaptation strategies that function well across the range of scenarios. If new information becomes available, the assessment can be readily updated.

2.4 Overview of Climate Projections

The climate projections employed here consist of statistically downscaled data from three different GCMs (Hadley Centre (HadCM3), the Canadian Centre for Climate Modelling and Analysis (CCCma) (CGCM2) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Mark 2)) forced with two emissions scenarios (Fealy and Sweeney, 2007, 2008; Sweeney et al., 2008). The future GHG emissions were taken from the IPCC Special Report on Emission Scenarios (SRES). Both emission scenarios, A2 (medium-high) and B2 (medium-low), project a more regionally imbalanced future development trajectory with either a more market economic (A2) or environmental (B2) focus (IPCC, 2000). The data from the coarse grid resolution of the six different GCMs were empirically statistically downscaled for the synoptic stations located across Ireland (Fealy and Sweeney, 2008; Sweeney et al., 2008). The methodology employed by Fealy and Sweeney (2008) was primarily focused on generating climate projections that are able to model the mean

climate state. Therefore, it is likely that extremes (high and low) in temperature and precipitation are underestimated (Figs 2.4 and 2.5). However, the significant trends shown for precipitation and temperature are consistent with expected changes as suggested by the GCMs (Sweeney et al., 2008). However, climate is only one of many factors that will affect the future water resources and water supply. Non-climatic variables will also influence the future of the water resource systems.

2.5 Surface Water Abstractions

In Ireland, the bulk of municipal drinking water (83.7%) originates from surface water (abstractions from rivers and lakes) (EPA, 2009). This study focuses on river abstractions of water schemes within each of the investigated hydrometric areas, as surface water abstractions are directly influenced by changes in catchment hydrology induced by a changing climate.

The locations of the individual water abstraction points were obtained from the National Abstractions Further Characterisation Project for the Water Framework Directive conducted by CDM (2009). The amount of water abstracted is based on the individual water scheme's population and abstraction volume obtained from *The Provision and Quality of Drinking Water in Ireland* report (EPA, 2009). For some locations, the data obtained from CDM and the EPA² differed considerably in the abstraction and population and

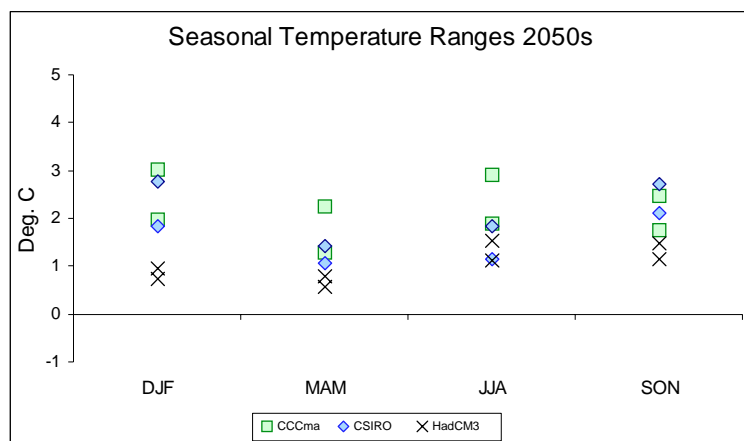


Figure 2.4. Seasonal temperature ranges (2050s) for stations showing the smallest and largest changes for the A2 emissions scenario (Sweeney et al., 2008). CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Climate Model 3.

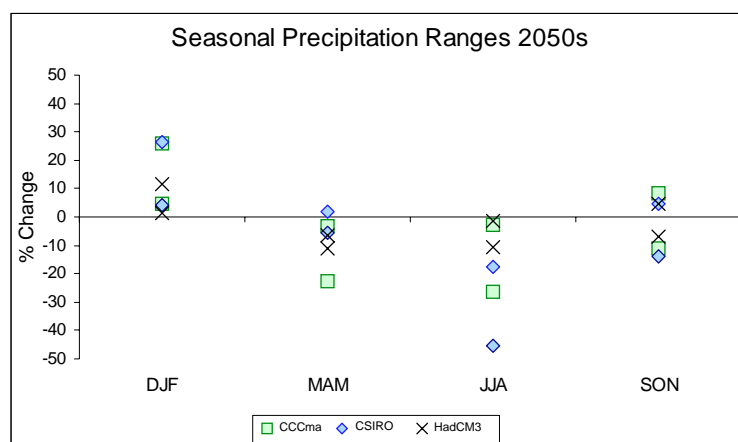


Figure 2.5. Seasonal temperature ranges (2050s) for stations showing the smallest and largest changes for the A2 emissions scenario (Sweeney et al., 2008). CCCma, Canadian Centre for Climate Modelling and Analysis; CSIRO, Commonwealth Scientific and Industrial Research Organisation; HadCM3, Hadley Centre Climate Model 3.

source definition. While priority was given to the EPA data set in these circumstances, for some abstraction sites interpolation between the two data sets was necessary to facilitate the modelling process.

2.6 HYSIM

The HYSIM model (Manley, 2006) used in this study is a physically based lumped conceptual rainfall run-off model (see [Appendix 2](#) for consideration of model selection). The model is forced with daily precipitation and potential evapotranspiration data input to return a river flow series. The hydrological routing within the HYSIM model consists of seven internal stores that represent the catchment hydrology. The parameters within the model can be divided into two groups: physically based and 'free' parameters. The former are observable from field measurement or spatial data sets, while the latter are inferred parameters, values for which are derived during the calibration process. The majority of parameters within the HYSIM model are physically based and can be measured from field observations or spatial data sets. This makes the HYSIM model particularly suitable for the application to ungauged catchments, such as in this study where no measured river flow record exists at the examined water abstraction points. The minority of model parameters are classified as 'free' parameters, which

are not directly measurable and require fitting during model calibration as described in [Section 2.7](#).

The HYSIM model has previously been used in several catchment hydrology and water resources studies in Ireland and the UK (Pilling and Jones, 1999, 2002; Mountain and Jones, 2001, 2006; Charlton and Moore, 2003; Fowler et al., 2003; Charlton et al., 2006; Murphy et al., 2006). Therefore, the HYSIM model is suitable for Irish hydrological conditions, and in comparison with the performance of other lumped models, such as the Nedbør-Afstrømnings Model (NAM), shows similar performance.

In many instances, the investigated surface water abstraction points have no measured streamflow record. Therefore, the HYSIM model was used to model the river flows for each abstraction point individually. The physical model parameters were obtained according to the catchment's physical characteristics, the process parameters in such instances were conditioned in a calibration procedure using a split-sample, proxy-basin procedure after Klemeš (1986) which is described in [Section 2.7](#).

2.7 Model Conditioning

The physical characteristics of each catchment were obtained using a Geographical Information System (GIS). The relevant hydrological properties were derived from the *General Soil Map of Ireland* (Gardiner

2. CDM, Camp Dresser & McKee; EPA, Environmental Protection Agency.

and Radford, 1980) and CORINE (Co-ORdination of INformation on the Environment) Land Cover (CLC) data (EPA, 2007). The main soil texture within each catchment was used to obtain the soil parameters, the dominant land cover type defined the vegetation characteristics and land-use parameters. Aquifer characteristics of each catchment were derived from the Geological Survey of Ireland's (GSI) *National Bedrock Aquifer Map* (GSI, 2007) or calculated from measured streamflow records (EPA, 2010; OPW, 2010). Future applications of the model can incorporate the next generation of spatial data sets such as the Irish Soils Information System (2013) and CORINE (2013) as they become available.

The process parameters in the HYSIM model were obtained using two methods: a split-sample test and a proxy-basin test which tests the transferability of model parameters (Klemeš, 1986). In the split-sample test, the measured streamflow record is split into two segments, with 70% of the record used for model calibration and 30% for model verification. The hydrological model process parameters are calibrated against observed historical streamflow in two sub-catchments with similar soil, land cover and aquifer characteristics within or close by the catchment. These sub-catchments have to be comparable in their characteristics to the ungauged abstraction catchments and have to be located

upstream to ensure low influence of major settlements and their water abstractions (Hall and Murphy, 2011).

When testing the transferability of the free HYSIM process parameters within the catchments, a proxy-basin split sample test is applied (Fig. 2.6). Two gauges representing catchments with similar soil and CLC characteristics are cross-checked during calibration and validation. The model is calibrated for one catchment (70% of streamflow record) and then run with the derived behavioural parameter sets in the other catchment for validation (30% of record) and vice versa. The behavioural parameter sets obtained in both validation periods are combined and then applied together with the physically based model parameters for future hydrological simulations at the ungauged abstraction point (with similar catchment characteristics).

In the model calibration process, feasible ranges for the free parameters were defined by the lowest possible parameter value and twice the manual calibrated optimum parameter (Wilby, 2005). From these ranges, 20,000 random parameter sets were sampled from a uniform distribution using Monte Carlo Random Sampling. The sampling procedure used to derive the free parameter sets to input for the calibration and verification is based on the principle of equifinality which holds that there are multiple equally feasible model parameter sets resulting in equally well

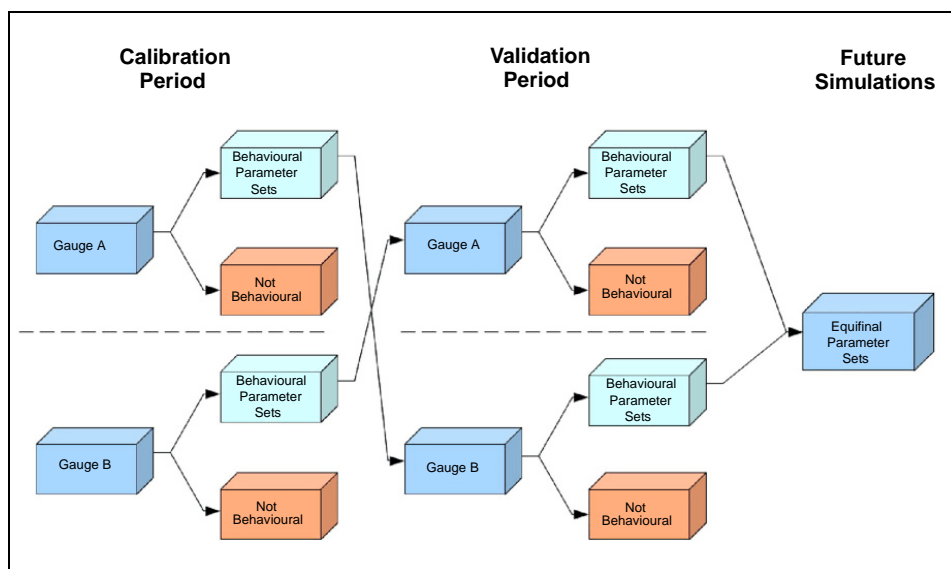


Figure 2.6. Schematic of split-sample test and a proxy-basin test to obtain parameter sets.

performing models and not one single optimum model (Beven, 2006).

In order to determine the behavioural or acceptable parameter sets, a number of different criteria, based on absolute and relative error measures, were employed:

- (i) Water balance equals zero within the HYSIM model;
- (ii) Mean absolute error (MAE) less than half the standard deviation of the observed flow ($STDEV_{obs}$) (Singh et al., 2004; Moriasi et al., 2007); and
- (iii) Model evaluation performance ratings (Table 2.1) for the Nash–Sutcliffe Efficiency Coefficient (EC) (Nash and Sutcliffe, 1970), the Percent Bias (PBIAS) (Gupta et al., 1999) and the Root Mean Square Error (RMSE)-Observations Standard Deviation Ratio (RSR) (Singh et al., 2004) recommended by Moriasi et al., (2007).

The MAE is an absolute error measure, whereas the EC is a relative error measure (goodness of fit) that indicates how well the plot of observed streamflow against simulated flow data fits the 1:1 line (Nash and Sutcliffe, 1970). The PBIAS measures the average tendency of the simulated flow to be smaller or larger than the observed flow at the same time step. The RSR is the standardised version of the RMSE error measure by the observed flow’s standard deviation.

Behavioural parameter sets were selected when they fulfilled Criterion (i) (zero water balance) and Criterion (ii) (MAE less than half the observed standard deviation), and additionally had a ‘Very Good’ performance rating in Criterion (iii) (EC, PBIAS and RSR) (Table 2.1). If no parameter set had a ‘Very

Good’ performance, a ‘Good’ performance was used as the criterion for selecting the parameter set. The selected behavioural parameter sets were then used in the proxy catchment for the model validation period and again assessed according to the same criteria to obtain the combined parameter sets used in future simulations. The maximum number of parameter sets representing the solution space of the free parameters was limited to 500 in order to constrain the computational time required to produce future simulations.

2.8 Future Hydrological Simulations

After the hydrological model is conditioned, the behavioural parameter sets are used in the HYSIM model to simulate future streamflow supplying the water abstraction points driven by future climate data input. The physical and the free model parameters are assumed to remain unchanged under future conditions for all future model runs. This is a commonly held assumption in rainfall run-off modelling for environmental change impact assessment and therefore implies that possible future feedback mechanisms are not considered in a modelling approach (Bronstert, 2004) (see work of Vaze et al. (2010) in Australia and similar findings are emerging from similar work in Ireland by Bastola et al. (2011a)).

The future flow regime model in the HYSIM model is driven by an unweighted ensemble of the six future climate projections (previously described) along with the 500 behavioural parameter sets derived above. The resulting 3,000 monthly streamflow series for each water abstraction point for each of the behavioural parameter sets and combination of climate projections is then used as input to drive the future water resource model WEAP21 as described in Section 2.9.

Table 2.1. Details of the three criteria used to determine behavioural parameter sets. General performance ratings for a monthly time step (adapted from Moriasi et al., 2007).

Performance Rating	EC	PBIAS	RSR
Very Good	$0.75 < EC \leq 1.00$	$PBIAS < \pm 10$	$0.00 \leq RSR \leq 0.50$
Good	$0.65 < EC \leq 0.75$	$\pm 10 \leq PBIAS < \pm 15$	$0.50 < RSR \leq 0.60$
Satisfactory	$0.50 < EC \leq 0.65$	$\pm 15 \leq PBIAS < \pm 25$	$0.60 < RSR \leq 0.70$
Unsatisfactory	$EC \leq 0.50$	$PBIAS \geq \pm 25$	$RSR > 0.70$

EC, Efficiency Coefficient; PBIAS, Percent Bias; RSR, Root Mean Square Error (RMSE)-Observations Standard Deviation Ratio.

Therefore, the simulations derived from the HYSIM model attempt to incorporate uncertainties from future emissions scenarios, global climate models and hydrological model structure/parameters. However, it must be made clear that not all sources of uncertainty are captured or fully sampled. In a robust adaptation framework, future work should focus on sampling an increased representation of the uncertainty space through, for example, the incorporation of more GHG and GCM scenarios, consideration of the uncertainties associated with the downscaling procedure, as well as the use of multiple hydrological models and the incorporation of possible future land-use changes.

2.9 Water Evaluation and Planning Model Version 21

The model used to analyse the water resource system is the Water Evaluation And Planning Model Version 21 (WEAP21). WEAP is a forecasting tool for integrated catchment hydrology and water supply modelling, assessment and planning based on the water accounting principle (Yates et al., 2005a,b). The water mass balances are calculated on node structures, which are linked to water supply (in this study streamflow) and demand sites (abstraction points). WEAP is used to model alternative sets of assumptions within the water resource system and to analyse and compare the resulting behaviour within the river basin. Details on the water accounting procedures of the WEAP model can be found in Yates et al. (2005a,b).

The WEAP model has been applied to numerous catchments and water resource assessment studies internationally. Several studies have also successfully used WEAP in the context of water resources and climate change (e.g. Groves et al., 2008; Purkey et al., 2008; Joyce et al., 2009; Ingol-Blanco and McKinney, 2010). For example, Groves et al. (2008) used climate change projections to assess the performance of current regional water management plans in southern California. Purkey et al. (2008) used WEAP in analysis of future climate change impacts on water for agriculture and other sectors in the Sacramento Valley in California.

2.10 Water Resource Scenarios

Future water resource scenarios are constructed to allow for the evolution of water management policy into the future. This scenario-based method allows investigating a range of possible futures. Scenario thinking is used as a planning tool to test and assess the future impact of different strategies used for decision making in the water resource sector. The aim is to learn about the future by understanding the impact of the different drivers and their effect on the water supply system. Therefore, WEAP21 is not used as an optimisation tool or as a planning tool for designing future water resource systems, but rather to indicate where and to what extent adaptation may become necessary, by exploring possible future states of the water resource system.

Here, for each water-use scenario, water abstractions are based on the individual water scheme's population and abstraction volume obtained from *The Provision and Quality of Drinking Water in Ireland – A Report for the Years 2007–2008* (EPA, 2009) and from the *National Abstractions Further Characterisation Project for the Water Framework Directive* conducted by CDM (2009). Future scenarios for the surface abstraction points are based on the population growth rate from the Irish Central Statistics Office's (CSO) report on *Population and Labour Force Projections* (CSO, 2008), the estimates of unaccounted for water (leakages) are derived from the *Assessment of Water and Waste Water Services for Enterprise* (Forfás, 2008) and the reduction of unaccounted for water are based on the Department of the Environment, Heritage and Local Government (DEHLG) water conservation programme estimates (CDM, 2004). Unaccounted for water is modelled in the per capita abstracted water volume, as is the case for demand measurement under current conditions.

Four future 'what-if scenarios', comprising a 'no-measure', a 'demand side', a 'supply side' and an 'integrated' measure shown in the Scenario Matrix (Fig. 2.7) are modelled. The aim is to assess the vulnerability of the abstraction point, investigate the interaction between different measures and to appraise their robustness to uncertainty as well as to

		Per Capita Water Demand	
		Constant Water Demand At 2008 Value	Reduced Water Demand 5% Reduction of 2008 Value by 2020
Leakage Level	Leakage Constant National Average of 43%	Scenario A Business as Usual	Scenario B Reduced Water Demand
	Leakage Reduction Stepwise up to 25% by 2015	Scenario C Reduced Leakages	Scenario D Reduced Water Demand & Leakages

Figure 2.7. Scenario Matrix showing the four investigated scenarios.

compare the impacts of climate change with other non-climatic pressures.

The following is a brief description of the scenarios and assumptions made:

1. Scenario A – ‘Business as Usual’. The population of 2008 is extrapolated into the future using the annual average change of the CSO projections. Per capita water abstractions and supply infrastructure remain constant. The level of unaccounted for water is the national average of 43%.
2. Scenario B – ‘Reduced Water Demand’. Increasing awareness in water conservation results in a stepwise annual per capita water demand reduction of up to 5% by 2020. The level of unaccounted for water remains unchanged at 43%.
3. Scenario C – ‘Reduced Leakages’. Improved water supply infrastructure results in an annual stepwise-reduced leakage level from 43% to 25% by 2015. Daily per capita water demand remains unchanged at its 2008 level.

4. Scenario D – ‘Reduced Demand and Reduced Leakages’. Combination of Scenario B and Scenario C. Reduction of the per capita water demand and leakage reduction, as above.

Scenario A corresponds to Step 3 in the modelling framework, which is an assessment of the vulnerability of each individual water abstraction point, when current characteristics of the water supply system are extrapolated into the future. Details on how the vulnerable areas were identified can be found in [Chapter 3](#). The abstraction points that did not indicate any need for future measures are excluded from further analysis. For the surface water abstraction points indicating vulnerability, Step 4 of the modelling framework is applied, which means that the future demand side, supply side and integrated strategies (Scenarios B, C and D, respectively) are modelled. The three alternative strategies/scenarios selected can be characterised as ‘low or no regrets’ strategies, which are able to cope with climate uncertainty and provide benefits, even in the absence of climate change (Hallegatte, 2009). Therefore, in uncertain conditions their application is to be favoured over high-cost, potentially high-regret strategies.

3 Analysis of Model Outputs

3.1 Water Use-to-Resource Ratio

Over the past 20 years many indices have been developed to quantitatively evaluate water resource availability. Characterising water stress is difficult given that there are many equally important facets to water use, supply and scarcity (Brown and Matlock, 2011). Common indices in use are built around human water requirements (e.g. the Falkenmark Indicator), water resource vulnerability, indices incorporating environmental water requirements and others built on life-cycle assessments and water footprinting. Given the context of this study, a water resource vulnerability index was employed; however, the incorporation of any other index is readily achievable within the modelling framework.

In this study, the water Use-to-Resource Ratio (URR), or Water Resources Vulnerability Index, was used to analyse model simulations in identifying vulnerability and testing the success of robust adaptation strategies. This index is a vulnerability measure used to derive a quantitative indication of the water resources pressure imposed on the examined abstraction points. This physical index of vulnerability is the water used (withdrawals) divided by the available water supply, on average, (Raskin, 1997; Arnell, 1999) and provides a local index of water stress (Vörösmarty et al., 2000). The index is divided into four categories as shown in [Table 3.1](#).

Table 3.1. Water Use-to-Resource Ratio (URR) (adapted from Raskin, 1997).

Withdrawal (Q)	Classification
<10%	No Stress
10–20%	Low Stress
20–40%	Stress
>40%	High Stress

3.2 Statistical Measures of Performance

The modelling results are also evaluated using the Reliability, Resilience, and Vulnerability (RRV) indices first introduced by Hashimoto et al. (1982). RRV indices are statistical evaluation measures for water resource system performance, which have been widely used in the water resources sector. Kundzewicz and Kindler (1995) used RRV indices in a framework for multiple criteria evaluation for water resource systems in Poland under historical flow conditions. Loucks (1997) used RRV to quantify trends in water supply system sustainability for future regional development alternatives. Kay and Mitchell (1998) evaluated the performance of Israel's water system under a new master plan with the help of RRV performance. Lettenmaier et al. (1999) used RRV indices to assess the water resource implications of global warming from a US regional perspective. Kay (2000) measured the sustainability in Israel's water system, by applying the RRV indices. Fowler et al. (2003) modelled the impacts of climatic change and variability on the reliability, resilience, and vulnerability on the Yorkshire Water Resource System in the UK.

All of the above studies used different threshold criteria to assess the performance of different water supply systems. This is the advantage of the use of the RRV indices, which are flexible, but are also based on the judgement of what is satisfactory or unsatisfactory with respect to the goals of system performance. Generally, as a statistical performance measure, RRV summarises the time-series performance of a system with reference to a predefined criterion C or so-called threshold value. This threshold value divides the simulated time series in unsatisfactory U or satisfactory S system performance values (Hashimoto et al., 1982) ([Fig. 3.1](#)). Depending on the selected criterion C the threshold can be an upper limit UC , a lower limit LC , or both.

To derive a mathematical expression for the RRV values, the time series value is X_t and the future evaluation time period is T (Hashimoto et al., 1982;

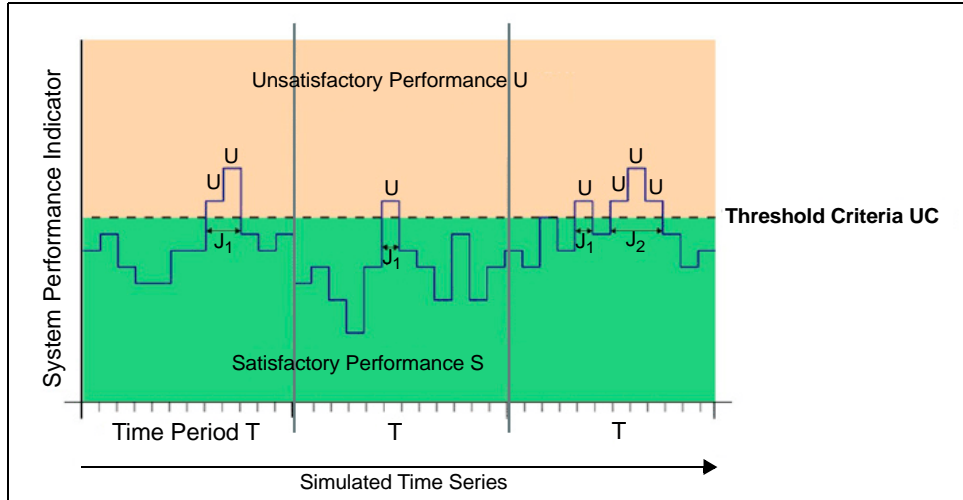


Figure 3.1. Derivation of system performance indicators from a simulated time series.

Fowler et al., 2003). In this work, the system performance indicator used is the water URR (Water Stress), which is an upper limit threshold criterion (UC). Therefore, the individual time steps in the time period T are evaluated as follows:

If $X_t \leq UC$ then $X_t \in S$ and $Z_t \in 1$
 else $X_t \in U$ and $Z_t \in 0$

Additionally, W_t indicates the transition from an unsatisfactory to a satisfactory event (Hashimoto et al., 1982; Fowler et al., 2003)

$W_t = \begin{cases} 1, & \text{if } X_t \in U \text{ and } X_{t+1} \in S \\ 0, & \text{otherwise} \end{cases}$

The continuous periods of unsatisfactory events are defined as J_1, J_2, \dots, J_N (including single unsatisfactory time steps) (Hashimoto et al., 1982; Loucks, 1997) with each $J_{1...N}$ within each time period T .

The RRV indices are defined as follows:

- **Reliability** measures the probability of a system being in a satisfactory state. *Temporal Reliability* is the ratio of the number of satisfactory time steps divided by the total number of values per time period considered (Hashimoto et al., 1982; Kundzewicz and Kindler, 1995).

$$C_{Rel} = \frac{\sum_{t=1}^T Z_t}{T}$$

- **Resilience** is a measure of the ability of the system to recover after being in an unsatisfactory state, which gives an indication of the speed of system recovery. Resilience is computed as the number of times an unsatisfactory outcome is followed by a satisfactory outcome, divided by the number of unsatisfactory values within a specified time interval. Resilience measures the ability of a system to recover from an unsatisfactory event (Hashimoto et al., 1982).

$$C_{Res} = \frac{\sum_{t=1}^T W_t}{T - \sum_{t=1}^T Z_t}$$

- **Vulnerability** can be calculated either by the extent or by the duration of unsatisfactory conditions. In this study, the *Expected Duration Vulnerability* is used, which is a measure of the average duration of the water resource system being in an unsatisfactory state. It is calculated by the total number of unsatisfactory time steps divided by the number of occurrences of continuous unsatisfactory events (including single unsatisfactory time steps) (Loucks, 1997).

$$C_{DV} = \frac{T - \sum_{t=1}^T Z_t}{\sum_{i=1}^N J_i}$$

The RRV indices are a means of combining the output of the multiple future simulations and can allow for a cross-comparison of different scenarios modelled. The system performs best with high Reliability and high Resilience values (near the maximum value of 1) and low Duration Vulnerability values. As the RRV indices primarily depend on the criterion used to define satisfactory or unsatisfactory performance, this approach is highly flexible and can be used to evaluate different performance criteria for each water scheme. However, the outcomes of an analysis will always be dependent on the criterion used to evaluate the water scheme. The threshold criteria used in this study are derived from the URR Index and are applied to surface water abstractions.

3.3 Vulnerability Analysis of Irish Water Schemes

The original water URR developed by Raskin (1997) is based on annual values, and an assessment of the water scheme's vulnerability based on annual values could result in misleading outcomes in regions with pronounced seasonality of water availability and no water storage facilities. Therefore, the index is refined to take seasonality and lack of storage into account by using monthly totals (Hall and Murphy, 2011).

Results based on model projections are analysed using monthly totals of water withdrawals and available streamflow (Q) to derive the water URR for each investigated water scheme. Additionally, the URR is used to define the criterion C (threshold value) for the RRV analysis of the water schemes. To illustrate the modelling approach, four Irish catchments and their surface water abstractions were investigated: the Barrow, the Boyne, the Erriff and the Moy catchments (Fig. 3.2). For ease of presentation, only results for the Boyne Catchment are shown and discussed below; results for other catchments will be available in subsequent reports. It should be noted that this assessment framework can be applied to any surface water supply system. The future simulations are not intended to be predictions or forecasts of future events,

but rather to give an approximate indication of what might happen for the modelled scenarios.

3.4 Boyne Hydrometric Area

The Boyne River catchment is located in the Eastern River Basin District (Fig. 3.3) and extends over an area of ~2,692 km². The catchment has an average elevation of 89 m and ranges from 0 to ~338 m in the northern part of the catchment. The slopes in the catchment range from 0% to 38% and on average they are gentle with a mean slope of 1.6%. Flats and undulating lowlands are the prevailing physiographic feature, with Grey Brown Podzolics being the principal soil class (30.6%), followed by Gleys (24.5%) and Minimal Grey Brown Podzolics (20.5%). The parent material of the dominating soils is Limestone Glacial Till (24%), Limestone Shale Glacial Till (21.6%) and Alluvium (12%), resulting in locally important aquifers underlying ~68.6% of the catchment. The main land-use types within the catchment are pastures (~79.4%) and arable land (~8%), as well as peat bogs (~4.2%) mainly located in the southern parts of the catchment.

Table 3.2 describes the abstraction points analysed in applying the tool to the Boyne case study area (Fig. 3.3). The proxy-basin catchments for the rainfall run-off model calibration and validation, along with their performance measures, are listed in Tables 3.3 and 3.4. For each water resource scenario, the full range of simulations, consisting of 3,000 model runs made up of 2 GHG emission scenarios × 3 GCMs × 500 hydrological parameter sets, is employed. Figure 3.4 shows indicative results for Kells with the aid of violin plots. Violin plots are useful for displaying the range of results and show the kernel density of the data at different values (similar to a histogram), and a marker for the median of the simulations at each time step.

3.5 Boyne URR Analysis

Athboy, Kilcarn and Trim water supplies do not indicate any water stress in the Business as Usual scenario and are therefore not analysed further here. Drogheda water supply indicates URR values ranging to medium water stress in summer and autumn, whereas in winter and spring no water stress is indicated. For presentation purposes, only the water abstractions of

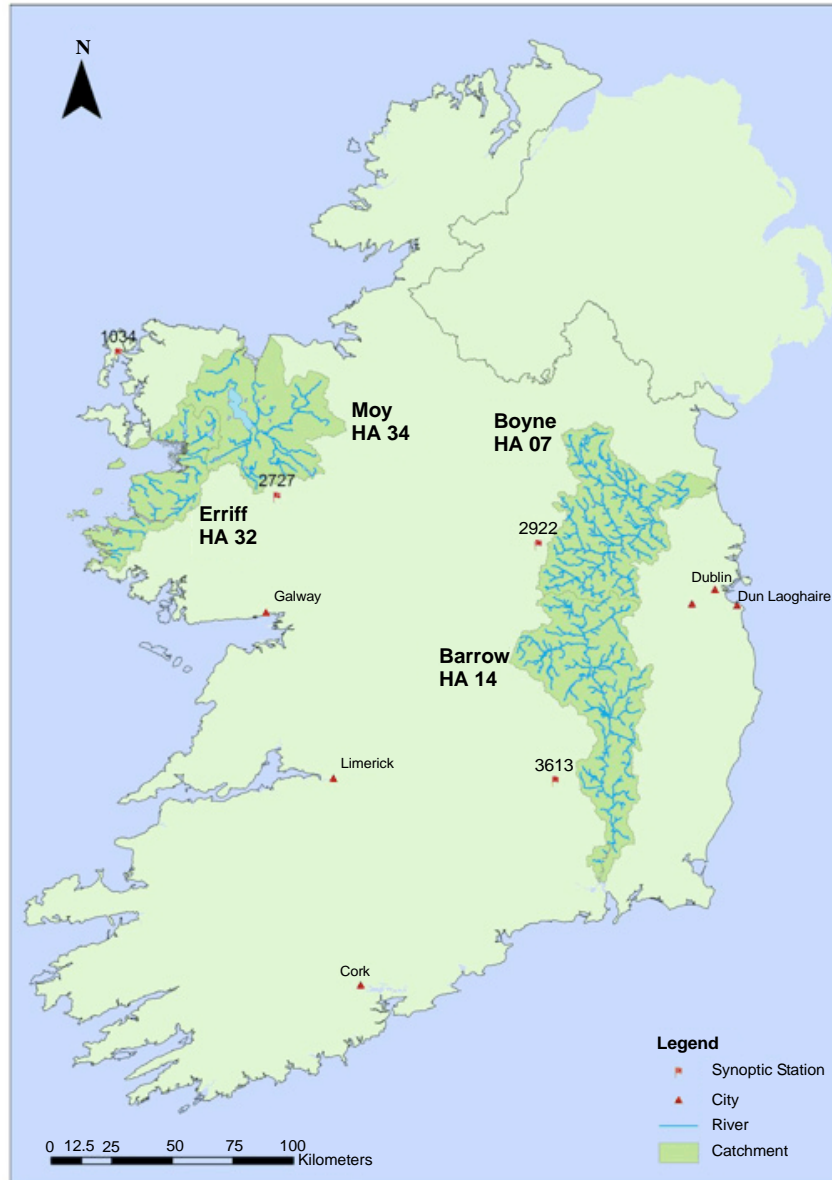


Figure 3.2. Case study areas and synoptic stations.

Kells and Liscarthan water supplies are analysed for their annual URR.

For both water abstraction points, all future scenarios in winter and spring remain below the low water stress threshold, except one year (2055), where some simulations indicate low water stress in spring (not shown). In summer and autumn, all ranges of water stress can be found within the different scenarios modelled. Generally, throughout the simulated time period, the number of simulations falling into the water stress categories increases over time for all water scenarios (also indicated by the orange median trend lines).

[Figure 3.4](#) for Kells shows that as the simulation length increases so does the spread of the simulation outcomes. This increasing spread of data represents the increasing uncertainty ranges. However, when looking at individual water resource scenarios, there is a significant reduction of the spread of simulation outcomes with the implementation of demand, supply and integrated measures. The Business as Usual scenario has the highest uncertainty ranges and the highest occurrence of simulations in the water stress categories. The number of simulations falling into water stress categories is subsequently reduced in Scenarios B and C, resulting in a significant reduction

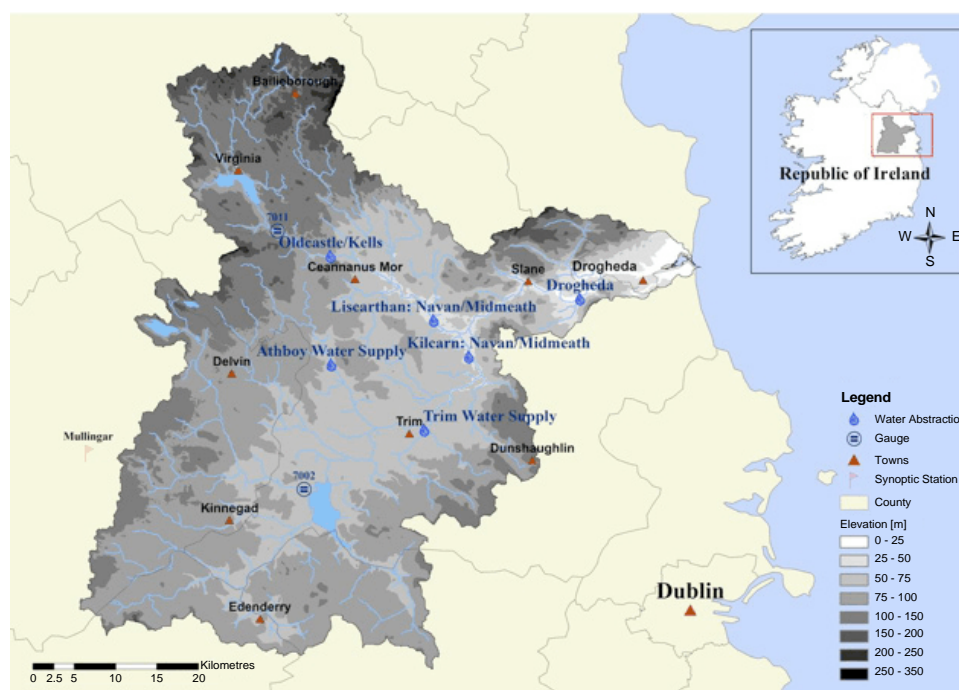


Figure 3.3. The Boyne Catchment, including catchment elevation, water abstractions, gauges, synoptic stations and towns.

Table 3.2. Boyne abstractions studied (CDM, 2009; EPA, 2009).

Scheme name	Scheme code	Population served	Volume (m ³ /day)
Athboy water supply	2300PUB1001	3,000	2,200
Drogheda	2100PUB1019	23,077	27,692
Kilcarn: Navan/Midmeath	2300PUB1016	5,600	2,800
Lisearthan: Navan/Midmeath	2300PUB1016	22,400	11,200
Oldcastle/Kells	2300PUB1011	2,024	1,447
Trim water supply	2300PUB1009	8,000	3,200

Table 3.3. Boyne – hydrometric station, calibration and validation.

Hydrometric station	Number	Calibration	Behavioural parameter sets	Validation	Behavioural parameter sets
Killyon	07002	1984–1993	3,418	1994–1997	637
O'Daly's Bridge	07011	1984–1993	4,314	1994–1997	981

Table 3.4. Boyne – station and performance criteria used in calibration and validation.

Hydrometric station	Calibration				Validation			
	MAE	EC	PBIAS	RSR	MAE	EC	PBIAS	RSR
Killyon	<1.361	>0.75	<±10	≤0.50	<1.654	>0.75	<±25	≤0.50
O'Daly's Bridge	<2.579	>0.75	<±10	≤0.50	<3.197	>0.75	<±25	≤0.50

MAE, mean absolute error; EC, Efficiency Coefficient; PBIAS, Percent Bias; RSR, Root Mean Square Error (RMSE)-Observations Standard Deviation Ratio.

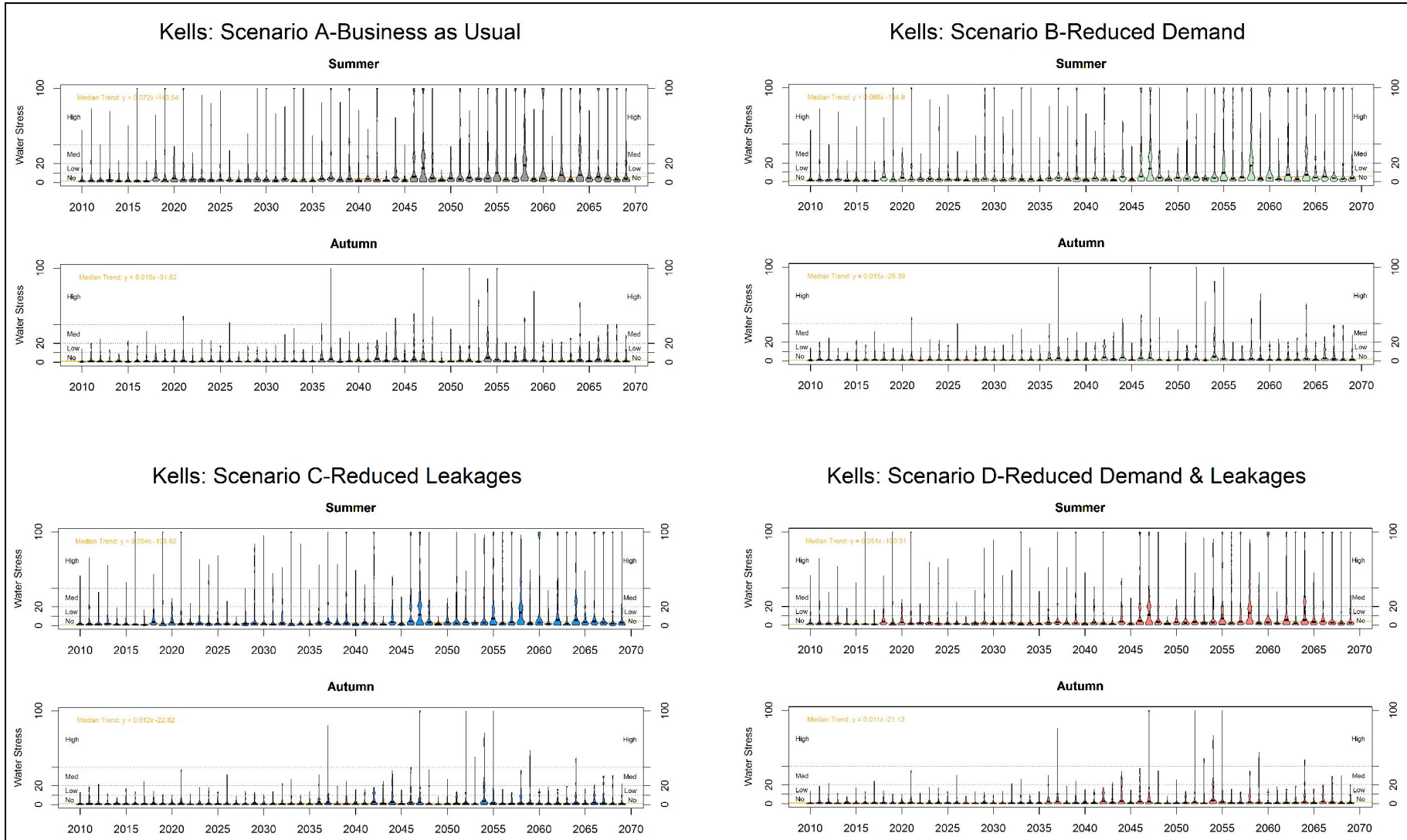


Figure 3.4. Kells – Use-to-Resource Ratio (URR) analysis for the four scenarios (median trend line indicated in orange).

in Scenario D. Therefore, these adaptation options can be classified as robust since the adaptation measures have a positive impact on water stress, as represented by a decrease in the number of simulations associated with these categories after implementation. The median of all simulations is also influenced by the adaptation measures. For example, in summer under the Business as Usual scenario, the median values show a statistically significantly increasing trend (orange line) of the water URR. With the reductions in water demand and leakage, the exhibited increasing trend is mitigated. The same applies to the median values in autumn.

Figures 3.5 and 3.6 present the increase in the percentage of all summer simulations located in the high water stress category for the Kells and Liscarthan water supply systems. It is clear that the occurrence of high water stress increases in frequency with time. Additionally, the effectiveness of the adaptation measures represented by the water scenarios in reducing the number of simulations showing high water stress is shown. While each measure is successful in reducing the frequency of occurrence of

high water stress it is evident from the results that such soft strategies alone will not be sufficient to avoid the occurrence of high water stress. For instance, for the water abstractions at Kells, in the time period 2049–2069, 25% of the years have more than 15% of all their simulations reaching the high water stress category (Fig. 3.5). For the period 2059–2069, on average more than 10% of the simulations are in the high water stress category, indicating that the simulated adaptation measures might not be enough to adequately deal with climate change. More water demand and leakage reduction or additional measures might be necessary to increase the robustness of water supply to climate change.

3.6 RRV Analysis

For Kells and Liscarthan, two upper limit threshold criteria, *UC*, were investigated with regard to the URR of the water abstractions. The first *UC* threshold criterion investigated is related to the URR of 10%, which means that the system performance of the water abstraction point is considered unsatisfactory if low water stress is occurring. The second *UC* criterion investigated is the URR higher than 20%, indicating

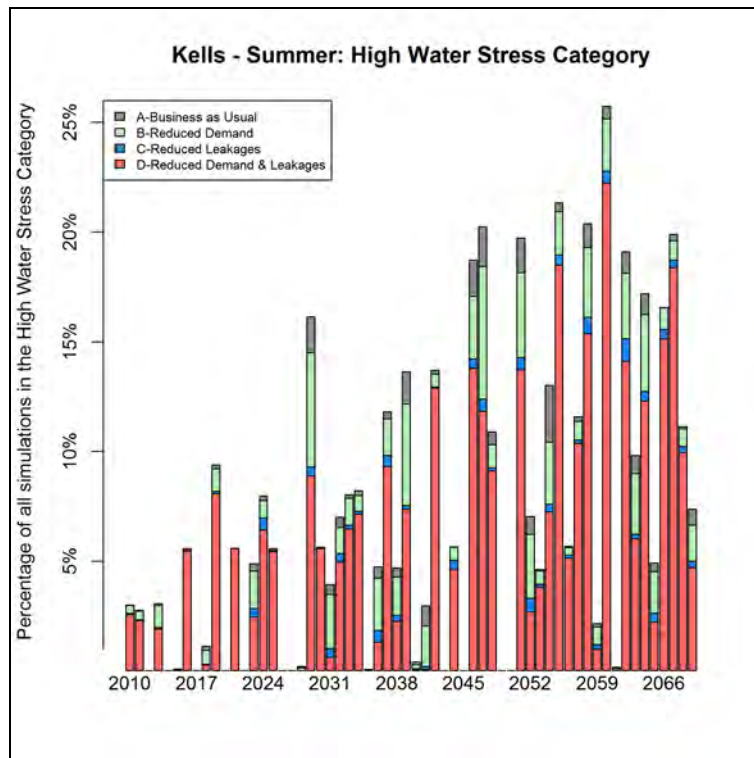


Figure 3.5. Kells – summer: percentage of all simulations in the high water stress category.

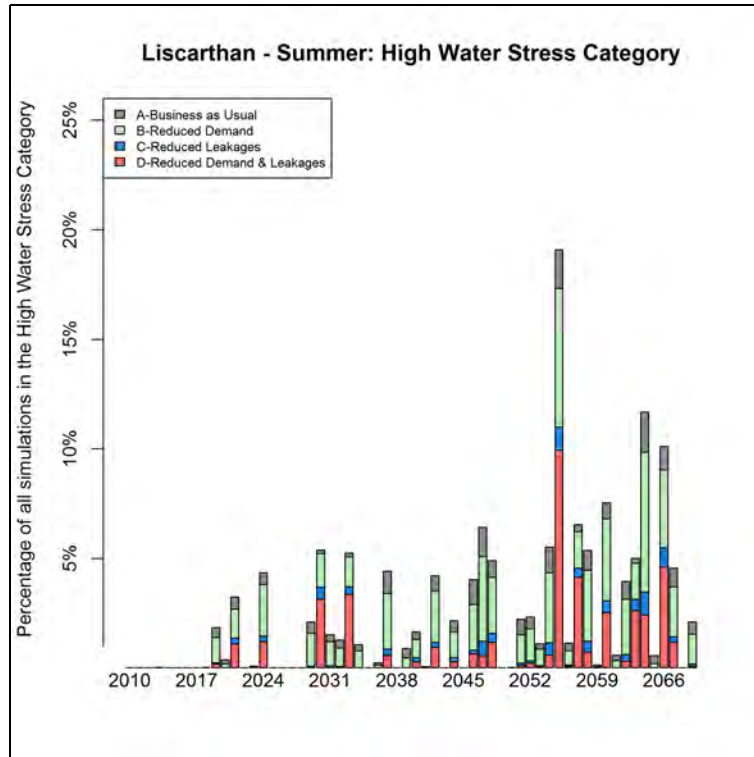


Figure 3.6. Liscarthan – summer: percentage of all simulations in the high water stress category.

the occurrence of water stress shown in [Figs 3.7](#) and [3.8](#). For simplification, only the differences between Scenario A (Business as Usual) and integrated measures in Scenario D (Reduced Water Demand and Reduced Leakage) are discussed below in detail.

3.6.1 Water URR >10%

For the first threshold criterion, the water abstractions at Kells and Liscarthan show a decreasing trend in the Reliability (probability of the system being in a satisfactory state, i.e. no water stress). The same applies to the Resilience (probability of the system to recover from an unsatisfactory event), whereas the Duration Vulnerability (average duration of the water resource system being in an unsatisfactory state) increases. When looking at the median trend line start and end values ([Table 3.5](#)) it becomes apparent that Reliability has a stronger decrease in Liscarthan than in Kells across all scenarios. In Liscarthan, the Resilience values are generally lower than in Kells. For example in Scenario A, an immediate recovery from a low water stress event occurs in 50% of the simulations (Resilience value of 0.5) at the start of the simulation time; however, by the end of the simulation period only 32% of the simulations recover immediately. Due to

adaptation measures in Scenario D, Resilience increases to 39% at the end of the simulation period. The magnitude of decrease in Resilience, however, is higher in Kells, with a start value of 0.76 to only 37% immediate recovery in Scenario A. The reduction measure in Scenario D minimises the decrease from 0.8 to a 47% recovery from low water stress. The average Duration Vulnerability in Scenario A increases from 1.43 months at Kells and 2.15 months in Liscarthan to 2.8 and 3.18 months, respectively, for both water abstraction points at the end of the simulation period.

3.6.2 Water URR >20%

Generally, the RRV analysis for the URR-20% threshold criterion will produce less severe results compared with the URR-10% threshold criterion as a higher threshold criterion is used. Water URR values above 10% were considered to be unsatisfactory for the URR-10% threshold criterion; however, URR values up to and including 20% are now considered to be satisfactory. Due to the higher threshold for the system performance to be considered as unsatisfactory, the system performs better, resulting in a more reliable and resilient water supply system with

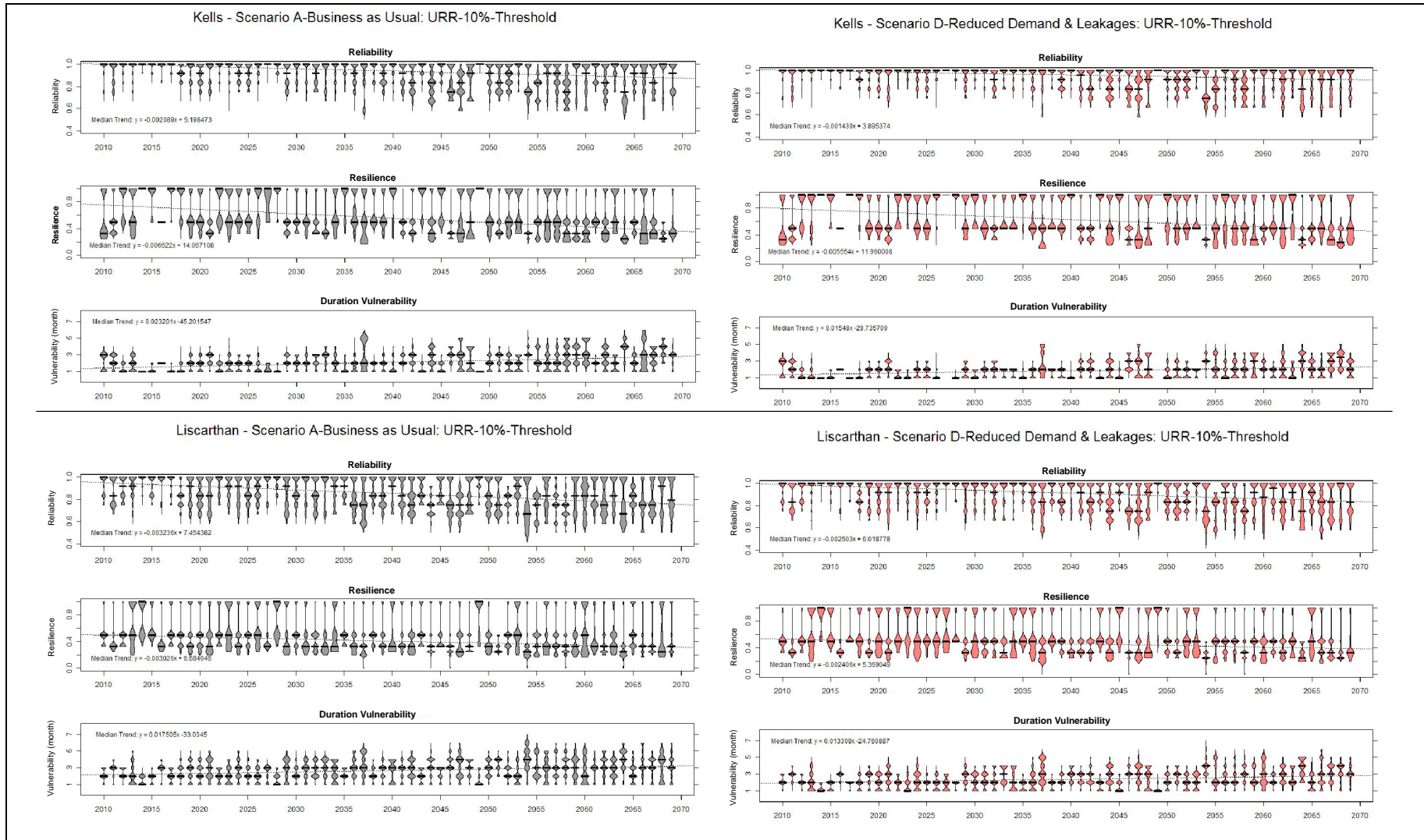


Figure 3.7. Kells and Liscarthan – Reliability, Resilience and Duration Vulnerability (RRV) indices (threshold criterion: 10% water Use-to-Resource Ratio (URR)).

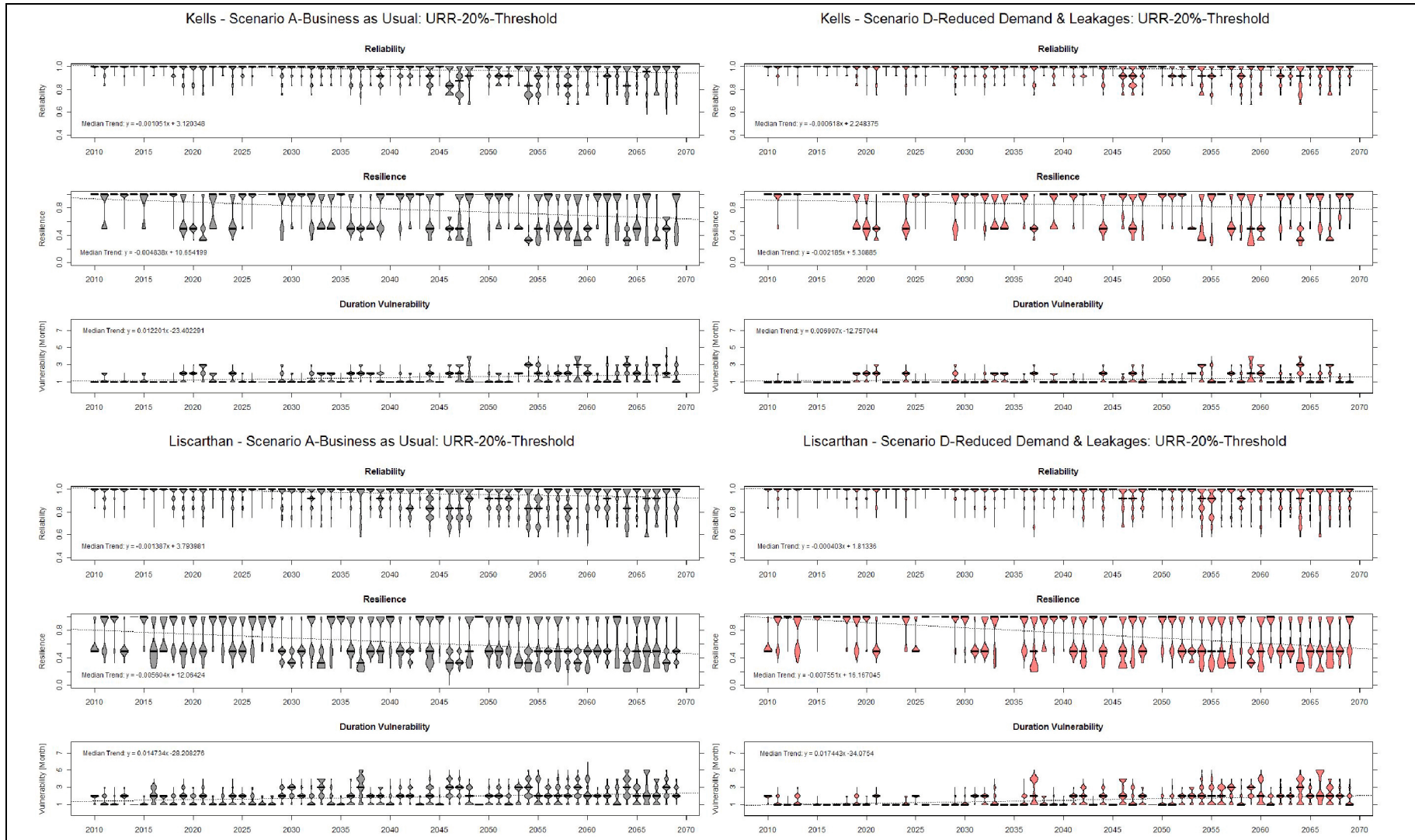


Figure 3.8. Kells and Liscarthan – Reliability, Resilience and Duration Vulnerability (RRV) indices (threshold criterion: 20% water Use-to-Resource Ratio (URR)).

Table 3.5. Reliability, Resilience, and Duration Vulnerability (RRV) – trend line values for the start and end of the period of the upper limit threshold criterion (UC) of the 10% water Use-to-Resource Ratio (URR).

	Scenario	Reliability		Resilience		Duration Vulnerability	
		Start	End	Start	End	Start	End
Kells	A	1.00	0.88	0.76	0.37	1.43	2.8
	B	1.00	0.89	0.76	0.38	1.43	2.74
	C	1.00	0.92	0.79	0.47	1.43	2.28
	D	1.00	0.92	0.80	0.47	1.38	2.29
Liscarthan	A	0.95	0.76	0.5	0.32	2.15	3.18
	B	0.96	0.77	0.49	0.33	2.12	3.11
	C	0.98	0.83	0.53	0.37	2.01	2.86
	D	0.99	0.84	0.53	0.39	1.99	2.78

shorter duration vulnerability. Overall, for the URR-20% threshold criterion, the same trends towards a reduction in Reliability and Resilience of the water abstractions are evident. However, when the Reliability and the Resilience of the system to recover from water stress are compared with the low water stress, the Reliability and Resilience values are higher, and the duration of a water stress event (Vulnerability) is reduced.

[Table 3.6](#) shows the values located on the median trend line for the URR-20% threshold. Generally, if this threshold criterion is applied to investigate the water abstractions of the Kells and the Liscarthan systems, the Reliability is high at the end of the simulation

period, with 95% and 92% (Kells and Liscarthan: Business as Usual), and improves through the integrated measures in Scenario D to a Reliability of 97% and 98%, respectively. The Resilience for both water supply systems is reduced considerably until the end of the evaluation time. Demand and leakage reduction improve the Resilience. Nevertheless, only in 79% (Kells) and 54% (Liscarthan) of the simulation time steps is immediate recovery from a water stress event projected. This is particularly important when combining this result with the average expected duration Vulnerability, which indicates a duration of 1.5 and 2 months, respectively, even with integrated reduction measures modelled.

Table 3.6. Reliability, Resilience and Duration Vulnerability (RRV) – trend line values for the start and end of period of the upper limit threshold criterion (UC) of the 20% water Use-to-Resource Ratio (URR).

	Scenario	Reliability		Resilience		Duration Vulnerability	
		Start	End	Start	End	Start	End
Kells	A	1	0.95	0.93	0.64	1.12	1.84
	B	1	0.95	0.93	0.67	1.13	1.80
	C	1	0.97	0.92	0.77	1.13	1.60
	D	1	0.97	0.92	0.79	1.13	1.53
Liscarthan	A	1	0.92	0.80	0.47	1.41	2.28
	B	1	0.93	0.85	0.47	1.28	2.29
	C	1	0.98	0.99	0.49	1.01	2.13
	D	1	0.98	0.99	0.54	0.99	2.01

These differences in the results between the two criteria investigated highlight the importance of the selection of the threshold criterion for the analysis of the sustainability of the water resource system and the selection of robust adaptation options. Nevertheless, through the flexibility in the selection of the threshold criteria, a wide range of additional criteria could be investigated in future work.

It is interesting to note that although Liscarthan had a much lower percentage of simulations than Kells, indicating high water stress in the URR assessment ([Figs 3.7](#) and [3.8](#)), the RRV indices indicate a worse performance of the Liscarthan water supply system. This highlights the importance of the use of multiple criteria in the evaluation of water supply systems.

4 Conclusions and Recommendations

The modelling tool developed in this research allows the identification of vulnerability within water supply systems and the assessment of robust adaptation options through an exploratory scenario-based modelling approach. Ranges of possible future outcomes are explored by the incorporation of uncertainties stemming from climate and hydrological models. This enables an assessment of robustness to possible futures and departs from the traditional 'predict, provide and optimise' approach to a single outcome approach. The tool derived is flexible and can be used with different threshold criteria and updates as new information and projections become available. For the case studies employed, climate change is likely to result in a reduction in the reliability and resilience and an increase in the vulnerability of water supply. In many cases, the reduction of leakage and demand is successful in reducing the occurrence of water stress. However, for some abstractions, such soft strategies alone will not be sufficient to avoid the occurrence of high water stress and alternative supply sources may be required. Within this context, consideration will need to be given to what is an acceptable level of residual risk once demand management options have been exhausted.

Based on the outcomes of this work the following recommendations are made:

- From the case studies conducted, uncertainties for the future are high. These uncertainties are related to climatic and non-climatic factors. Therefore, future adaptation planning in the water sector will need to account for this uncertainty.
- In the nearer term, many elements of adaptation planning can be identified that are robust to uncertainty, particularly non-climatic factors such as demand and leakage control. It is recommended that such robust, flexible strategies should form an important aspect of adaptation planning in the near term.
- The application of a process-oriented 'vulnerability thinking' instead of an 'impacts thinking' approach is promoted in adaptation planning. A vulnerability thinking approach combines flexibility with planning over long time horizons and monitoring, as well as adaptive management, recognising the uncertainty in projected hydrological changes.
- In some cases, the implementation of adaptation options does not entirely reduce the occurrence of water stress. In such situations, consideration should be given to what are acceptable levels of risk.
- Where investment in new infrastructure is required, it is recommended that such infrastructure be subjected to a sensitivity analysis of performance under the full range of uncertainty associated with climate change.
- The work conducted here is based on the application of simple, conceptual hydrological models due to the priority given to accounting for uncertainties. It is recommended that future work might investigate the application of more physically based models that can account for issues such as groundwater in more physical detail.

References

- Arnell, N., 1999. Climate change and global water resources. *Global Environmental Change* **9**: S31–S49.
- Bastola, S., Murphy, C. and Sweeney, J., 2011a. Evaluation of the transferability of hydrological model parameters for simulations under changed climatic conditions. *Hydrology and Earth System Sciences* **8**: 5891–5915.
<http://www.hydrol-earth-syst-scidiscuss.net/8/5891/2011/doi:10.5194/hessd-8-5891-2011>
- Bastola, S., Murphy C. and Sweeney J., 2011b. The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. *Advances in Water Resources*
doi:10.1016/j.advwatres.2011.01.008.
- Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P., 2008. *Climate Change and Water*. IPCC Secretariat, Geneva, Switzerland, Technical Paper of the Intergovernmental Panel on Climate Change, 210 pp.
- Beven, K.J., 2006. A manifesto for the equifinality thesis. *Journal of Hydrology* **320**: 18–36.
- Beven, K. and Binley A., 1992. The future of distributed models: Model calibration and uncertainty prediction, *Hydrological Processes* **6**: 279–298.
- Beven, K. and Freer, J., 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology* **249**: 11–29.
- Boyle, D., 2001. *Multicriteria Calibration of Hydrological Models*. PhD dissertation. Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, USA.
- Bronstert, A., 2004. Rainfall-runoff modelling for assessing impacts of climate and land-use change. *Hydrological Processes* **18**: 567–570.
- Brown, A. and Matlock, M.D., 2011. *A Review of Water Scarcity Indices and Methodologies*. University of Arkansas, Arkansas, USA. The Sustainability Consortium. White Paper #106, April 2011.
- CDM, 2004. *Economic Analysis of Water Use in Ireland – Final Report*. Camp Dresser & McKee, Ireland, Ltd.
- CDM, 2009. *National Abstractions Further Characterisation Project for the Water Framework Directive*. Camp Dresser & McKee, Ireland, Ltd.
- CSO, 2008. *Population and Labour Force Projections*. Central Statistics Office, Dublin, Ireland.
- Charlton, R. and Moore, S., 2003. The impact of climate change on water resources in Ireland. In: Sweeney, J. (Ed.), *Climate Change: Scenarios and Impacts for Ireland – Final Report*. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. pp. 81–102.
- Charlton, R., Fealy, R., Moore, S., Sweeney, J. and Murphy, C., 2006. Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. *Climatic Change* **74**: 475–491.
- Cunnane, C. and Regan, S., 1994. Hydrology and freshwater resource. In: McWilliams B.E. (Ed.) *Climate Change: Studies of the Implications for Ireland*. Department of the Environment, Stationery Office, Dublin, Ireland. pp. 89–108.
- Dessai, S., Hulme, M., Lempert, R. and Pielke, Jr., R., 2009. Climate prediction: a limit to adaptation? In: Adger, W.N., Lorenzoni, I. and O'Brien, K. (Eds) *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press, Cambridge, UK. p. 530.
- Dessai, S. and Hume, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change* **17**: 59–72.
- EPA, 2007. *The Provision and Quality of Drinking Water in Ireland – A Report for the Years 2006–2007*. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. Available at: <http://www.epa.ie/downloads/pubs/water/drinking/DW%20Report%2020062.pdf> (accessed on 20 August 2008).
- EPA, 2009. *The Provision and Quality of Drinking Water in Ireland – A Report for the Years 2007–2008*. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.
- EPA, 2010. EPA HydroNet – Access to Hydrometric Data. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. Available at: <http://hydronet.epa.ie/hydronet.html> (accessed in January 2010).
- European Commission, 2007. *Adapting to Climate Change in Europe – Options for EU Action*. Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions (COM 2007 354), Commission of the European Communities.

- Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0354:FIN:EN:PDF> (accessed in February 2010).
- Fankhauser, S., Smith, J.B. and Tol, R.S.J., 1999. Weathering climate change: Some simple rules to guide adaptation decisions. *Ecological Economics* **30**: 67–78.
- Fealy, R. and Sweeney, J., 2007. Statistical downscaling of precipitation for a selection of sites in Ireland employing a generalised linear modelling approach. *International Journal of Climatology* **27**: 2089–2094.
- Fealy, R. and Sweeney, J., 2008. Statistical downscaling of temperature, radiation and potential evapotranspiration to produce a multiple GCM ensemble mean for a selection of sites in Ireland. *Irish Geography* **41**: 1–27.
- Forfás, 2008. *Assessment of Water and Waste Water Services for Enterprise*. Forfás, The National Policy and Advisory Board, Dublin, Ireland.
- Fowler, H.J. and Wilby, R.L., 2010. Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk. *Water Resources Research* **46**: W03525.
- Fowler, H.J., Kilsby, C.G. and O'Connell, P.E., 2003. Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resources Research* **39**: SWC10-1–SWC10-11.
- GSI, 2007. *National Draft Bedrock Aquifer Map*. Geological Survey of Ireland, Dublin, Ireland.
- Gardiner, M.J. and Radford, T., 1980. *General Soil Map*. Soil Survey Bulletin 36. An Foras Talúntais, Dublin, Ireland.
- Groves, D.G., Yates, D. and Tebaldi, C., 2008. Developing and applying uncertain global climate change projections for regional water management planning. *Water Resources Research* **44**: W12413.
- Gupta, H.V., Sorooshian, S. and Yapo, P.O., 1999. Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *Journal of Hydrologic Engineering* **4**: 135–143.
- Hall, J., 2007. Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes* **21**: 1127–1129.
- Hall, J. and Murphy, C., 2011. Robust Adaptation Assessment – climate change and water supply. *International Journal of Climate Change Strategies and Management*. **3(3)**: 302–319.
- Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change* **19**: 240–247.
- Hashimoto, T., Stedinger, J.R. and Loucks, D.P., 1982. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research* **18**: 14–20.
- Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E. and Stott, P.A., 2007. Understanding and attributing climate change. In: Solomon, S., Qin, D., Mannin, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds) *Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, and New York, USA, p. 685.
- IPCC, 2000. *Special Report on Emission Scenarios – Summary for Policymakers*. Nakicenovic, N. and Swart, R.A. (Eds). Special Report of IPCC Working Group III. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
- IPCC, 2007a. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (Eds). Cambridge University Press, Cambridge, UK, and New York, NY, USA.
- IPCC, 2007b. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Handson, C.E. (Eds). Cambridge University Press, Cambridge, UK.
- Ingol-Blanco, E. and McKinney, D., 2010. *Transboundary Climate Change Effects on the Hydrologic Regime in the Rio Conchos Basin*. American Society of Civil Engineers, Conference Proceedings World Environmental and Water Resources Congress. doi:[http://dx.doi.org/10.1061/41114\(371\)8](http://dx.doi.org/10.1061/41114(371)8)
- Joyce, B., Mehta, V., Purkey, D., Dale, L. and Hanemann, M., 2009. *Climate Change Impacts on Water Supply And Agricultural Water Management in California's Western San Joaquin Valley, And Potential Adaptation Strategies*. White paper for the California Climate Change Center, Report No. CEC-500-2009-051-F.
- Kay, P.A., 2000. Measuring sustainability in Israel's water system. *Water International* **25**: 617–623.
- Kay, P.A. and Mitchell, B., 1998. Performance of Israel's water system under a new master plan: post-audit and implications for the future. *Water Resources Development* **14**: 107–119.
- Kiely, G., 1999. Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources* **23**: 141–151.

- Klemeš, V., 1986. Operational testing of hydrological simulation models. *Hydrological Sciences Journal* **31**: 13–24.
- Kundzewicz, Z.W. and Kindler, J., 1995. Multiple criteria for evaluation of reliability aspects of water resources systems. *Modelling and Management of Sustainable Basin-scale Water Resource Systems (Proceedings of a Boulder Symposium)*. IAHS Publication **231**: 217–224.
- Kundzewicz, Z.W. and Robson, A.J., 2004. Change detection in hydrological records – A review of the methodology. *Hydrological Science Journal* **49**: 7–19.
- Langsdale, S., 2008. Communication of climate change uncertainty to stakeholders using the scenario approach. *Journal of Contemporary Water Research and Education* **140**: 24–29.
- Lempert, R.J. and Schlesinger, M.E., 2000. Robust strategies for abating climate change. *Climatic Change* **45**: 387–401.
- Lettenmaier, D.P., Wood, A.W., Palmer, R.N., Wood, E.F. and Stakhiv, E.Z., 1999. Water resources implications of global warming: a U.S. regional perspective. *Climatic Change* **43**: 537–579.
- Lopez, A., Fung, F., New, M., Watts, G., Watson, A. and Wilby, R.L., 2009. From climate model ensembles to climate change impacts and adaptation: A case study of water resource management in the southwest of England. *Water Resources Research* **45**: W08419.
- Loucks, D.P., 1997. Quantifying trends in system sustainability. *Hydrological Sciences journal* **42**: 513–530.
- Manley, R.E., 2006. *A Guide to Using HYSIM*. R.E. Manley and Water Resource Associates, Ltd., Henley-on-Thames, UK.
- Matthews, J.H. and Le Quesne, T., 2009. *Adapting Water Management: A Primer on Coping with Climate Change*. WWF-UK, Surrey, UK.
- Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P. and Stouffer, R.J., 2008. Stationarity is dead: Whither water management? *Science* **319(5863)**: 573–574.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Binger, R.L., Harmel, R.D. and Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**: 885–900.
- Mountain, N.C. and Jones, J.A.A., 2001. Estimating low flow frequencies in the mid to late 21st century for two basins in central Wales. *Cuadernos de Investigación Geográfica* **27**: 107–123.
- Mountain, N.C. and Jones, J.A.A., 2006. Reconstructing extreme flows using an airflow index-based stochastic weather generator and a hydrological simulation model. *Catena* **66**: 120–134.
- Murphy, C. and Charlton, R., 2008. The impact of climate change on water resources. In: Sweeney J. (Ed.) *Climate Change: Refining the Impacts – Final Report*. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. pp. 39–81.
- Murphy, C., Fealy, R., Charlton, R. and Sweeney, J., 2006. The reliability of an ‘off-the-shelf’ conceptual rainfall runoff model for use in climate impact assessment: uncertainty quantification using Latin hypercube sampling. *Area* **38**: 65–78.
- Murphy, C., Bastola, S., Hall, J., Harrigan, S., Murphy, N. and Holman, C., 2011. Against a ‘wait and see’ approach in adapting to climate change. *Irish Geography* **44(1)**: 81–95.
- Nash, J.E. and Sutcliffe, I.V., 1970. River flow forecasting through conceptual models. Part I – A discussion of principles. *Journal of Hydrology* **10**: 282–290.
- OPW, 2010. Hydro-Data Web-Site, Office of Public Works. Available at: <http://www.opw.ie/hydro/index.asp> (accessed in January 2010).
- Pilling, C.G. and Jones, J.A.A., 1999. High resolution climate change scenarios: implications for British runoff. *Hydrological Processes* **13**: 2877–2895.
- Pilling, C.G. and Jones, J.A.A., 2002. The impact of future climate change on seasonal discharge, hydrological processes and the extreme flows in the Upper Wye experimental catchment, mid-Wales. *Hydrological Processes* **16**: 1201–1213.
- Purkey, D.R., Joyce, B., Vicuna, S., Hanemann, M.W., Dale, L.L., Yates, D.N. and Dracup, J.A., 2008. Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. *Climatic Change* **87**: S109–S122.
- Radziejewski, M. and Kundzewicz, Z.W., 2004. Detectability of changes in hydrological records. *Hydrological Science Journal* **49**: 39–51.
- Raskin, P., 1997. *Water Futures: Assessment of Long-Range Patterns and Problems*. Background Document to the Comprehensive Assessment of the Freshwater Resources of the World Report. Stockholm Environment Institute, Stockholm, Sweden.
- Singh, J., Knapp, H.V. and Demissie, M., 2004. *Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT*. ISWS CR 2004–08, Illinois State Water Survey. Available at: <http://www.sws.uiuc.edu/pubdoc/CR/ISWSCR2004-08.pdf> (accessed in September 2009).
- Stakhiv, E., 1998. Policy implications of climate change on water resource management. *Water Policy* **1**: 159–175.

- Steele-Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hanafin, J. and Nolan, P., 2008. The impacts of climate change on hydrology in Ireland. *Journal of Hydrology* **356**: 28–45.
- Svensson, C., Kundzewicz, Z.W. and Maurer, T., 2005. Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrological Science Journal* **50**: 811–824.
- Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M., et al., 2008. *Climate Change – Refining the Impacts for Ireland*. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.
- Vaze, J., Post, D.A., Chiew, F.H.S., Perraud, J.-M., Viney, N.R. and Teng, J., 2010. Climate non-stationarity – validity of calibrated rainfall-runoff models for use in climate change studies. *Journal of Hydrology* **394**: 447–457.
- Vörösmarty, C.J., Green, P., Solisbury, J. and Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284–288.
- Wilby, R.L., 2005. Uncertainty in water resource model parameters used for climate change impact assessment. *Hydrological Processes* **19**: 3201–3219.
- Wilby, R.L., 2006. When and where might climate change be detectable in UK river flows? *Geophysical Research Letters* **33**: L19407.
- Wilby, R.L., Beven, K.J. and Reynard, N.S., 2008. Climate change and fluvial flood risk in the UK: More of the same? *Hydrological Processes* **22**: 2511–2523.
- Wilby, R.L. and Dessai S., 2010. Robust adaptation to climate change. *Weather* **65**: 180–185.
- Willows, R. and Connell, R., 2003. *Climate Adaptation: Risk, Uncertainty and Decision-Making*. UK Climate Impacts Programme Technical Report, UKCIP, Oxford, UK.
- Yates, D., Sieber, J. and Purkey, D. and Huber-Lee, A., 2005a. WEAP21-A demand-, priority- and preference-driven water planning model. Part 2: Aiding freshwater ecosystem service evaluation. *Water International* **30**: 501–521.
- Yates, D., Sieber, J., Purkey, D. and Huber-Lee, A., 2005b. WEAP21-A demand-, priority- and preference-driven water planning model. Part 1: Model characteristics. *Water International* **30**: 487–500.
- Ziegler, A.D., Maurer, E.P., Sheffield, J., Nijssen, B., Wood, E.F. and Lettenmaier, D.P., 2005. Detection time for plausible changes in annual precipitation, evapotranspiration, and streamflow in three Mississippi River sub-basins. *Climatic Change* **72**: 17–36.

Acronyms

AR4	Fourth Assessment Report
CCCma	Canadian Centre for Climate Modelling and Analysis
CDM	Camp Dresser & McKee
CLC	CORINE Land Cover
CORINE	Co-ORdination of INformation on the Environment
CRR	Conceptual Rainfall Run-off
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSO	Central Statistics Office
DEHLG	Department of the Environment, Heritage and Local Government
EC	Efficiency Coefficient
EPA	Environmental Protection Agency
EU	European Union
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographical Information System
GLUE	Generalised Likelihood Uncertainty Estimation
GSI	Geological Survey of Ireland
HadCM3	Hadley Centre Climate Model 3
HYMOD	HYdrologic MODel
HYSIM	HYdrological Simulation Model
IPCC	Intergovernmental Panel on Climate Change
LC	Lower limit threshold criterion
MAE	Mean absolute error
NAM	Nedbør-Afstrømnings Model
NS	Nash–Sutcliffe
PBIAS	Percent Bias
RMSE	Root Mean Square Error
RRV	Reliability, Resilience, and Vulnerability

RSR	RMSE-Observations Standard Deviation Ratio
SRES	Special Report on Emission Scenarios
STDEV_{obs}	standard deviation of the observed flow
UC	Upper limit threshold criterion
UKCIP	UK Climate Impact Programme
URR	Use-to-Resource Ratio
WEAP	Water Evaluation And Planning

Appendix 1 Key Definitions

- **Adaptation**

According to the International Panel on Climate Change (IPCC) (IPCC, 2007a: p. 878), adaptation is defined as the adjustment in natural or *human systems* in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation:

Anticipatory adaptation – Adaptation that takes place before impacts of *climate change* are observed. Also referred to as proactive adaptation.

Autonomous adaptation – Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or *welfare* changes in *human systems*. Also referred to as spontaneous adaptation.

Planned adaptation – Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

- **Adaptive Capacity**

Defined by IPCC Working Group 2 as “*the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*” (IPCC, 2007a: p. 869).

- **Mitigation**

Defined by IPCC Working Group 2 as “*an anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks*” (IPCC, 2007a: p. 878).

- **Resilience**

Defined by IPCC Working Group 2 as “*the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change*” (IPCC, 2007a: p. 880).

As defined by the European Commission, resilience is “*the capacity of a natural or human system, community or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable structure and level of functioning. For human systems this is determined by the degree to which the system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures*” (European Commission, 2007: p. 24).

- **Vulnerability**

Defined by IPCC Working Group 2 as “*the degree to which a system [physical, human, societal] is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*” (IPCC, 2007a: p. 883).

- **Maladaptation**

An action or process that increases vulnerability to climate-change-related hazards. Maladaptive actions and processes often include planned development policies and measures that deliver short-term gains or economic benefits but lead to exacerbated vulnerability in the medium to long term.

- **Climate Projection**

The calculated response of the *climate system* to *emissions* or *concentration scenarios* of *greenhouse gases* (GHGs) and *aerosols*, or

radiative forcing scenarios, often based on simulations by *climate models*. Climate projections are distinguished from *climate predictions* in that the former critically depend on the emissions/concentration/*radiative forcing* scenario used, and therefore on highly uncertain assumptions of future socio-economic and technological development.

- **Climate (Change) Scenario**

A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships and assumptions of *radiative forcing*, typically constructed for explicit use as input to climate change impact models. A 'climate change scenario' is the difference between a climate *scenario* and the current climate.

- **Emissions Scenario**

A plausible representation of the future

development of emissions of substances that are potentially radiatively active (e.g. GHGs, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships.

- **Special Report on Emissions Scenarios**

The storylines and associated population, *Gross Domestic Product* (GDP) and *emissions scenarios* associated with the Special Report on Emissions Scenarios (SRES) (IPCC, 2000), and the resulting *climate change* and *sea-level rise scenarios*. Four families of *socio-economic scenarios* (A1, A2, B1 and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns.

Appendix 2 Comparison of Conceptual Rainfall Run-Off Models

Conceptual Rainfall Run-Off (CRR) models use relatively simple mathematical equations to conceptualise and aggregate the complex, spatially distributed, and highly interrelated water, energy, and vegetation processes in a watershed. Here, four models are compared in simulating the monthly flows for the Boyne at Slane Castle (st7012). Each of the models varies in the way it conceptualises the key hydrological processes and in complexity, primarily related to the number of parameters requiring calibration. All four models have been applied in numerous applications and their potential for application to simulate flow under changed climate has been discussed previously. The models employed are independently developed by different researchers and organisations.

Groundwater plays a significant role in the hydrological cycle. The outflow from the groundwater reservoir represents the discharge from the groundwater storage in the absence of further replenishment. Various hydrological models have used a range of conceptual representations to model various complexities associated with subsurface flow – by far the most common is the use of simple linear reservoirs using exponential recession implying that storage is proportional to outflow. Most conceptual hydrological models use this approach to model outflow from groundwater storage.

The short study presented here compares the performance of the HYdrological SIMulation Model (HYSIM) with other common conceptual rainfall run-off models. The following paragraphs provide a brief overview of the models followed by a comparison of performance. The HYSIM model is described within the text and not repeated here. The models used also differ in the way they represent the spatial variability of response within the basin. The HYdrologic MODel (HYMOD) uses a statistical distribution function to model spatial variability in soil infiltration capacity, whereas the HYSIM model, Tank model and Nedbør-

Afstrømnings Model (NAM) do not take spatial variability within the basin into account. The simulation time step of interest is monthly river flows, the comparison of performance is conducted for daily flows.

The NAM model describes, in a simplified quantitative form, the behaviour of the different phases of the hydrological cycle, accounting for the water content in different mutually interrelated storages, namely surface zone storage, the root zone storage, and the groundwater storage. The surface and interflow component of total run-off is routed through two linear reservoirs and the base flow is routed using a single reservoir. Each linear reservoir is characterised by a specific time constant. In the present application, the nine most important parameters of the NAM model were determined by calibration.

The HYMOD is also a conceptual and lumped model, originally proposed by Boyle (2001) in order to address the need for the development of models with complexity levels suitable for capturing typical and commonly measured hydrologic fluxes. The objective of the HYMOD is to provide a research tool for scientific evaluation purposes.

The Tank model is a conceptual model comprised of four vertical tanks with primary and secondary storage. For each basin, processes of infiltration, unsaturated and saturated flow, and throughflow, are represented using a simple 'non-linear tank model' approach.

From [Figs A2.1](#) and [A2.2](#) presented overleaf, while all models perform well in their task of reproducing river flows, poorest performance is derived for the Tank model. Further work on identifying the parameters of the NAM model from field observation would likely increase its performance. The key point is that performance of the HYSIM model compares favourably to the other models used and gives support to using it in this study.

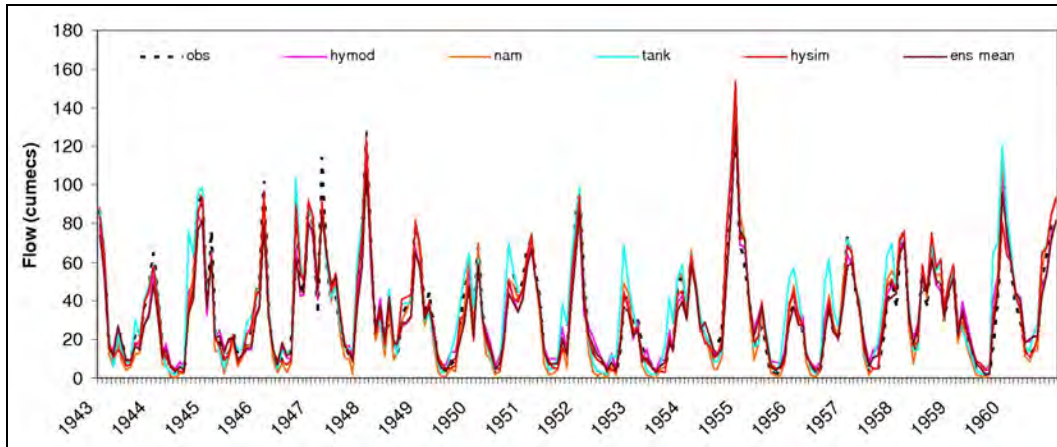


Figure A2.1. Comparison of monthly flows from each model with observations for the period analysed.

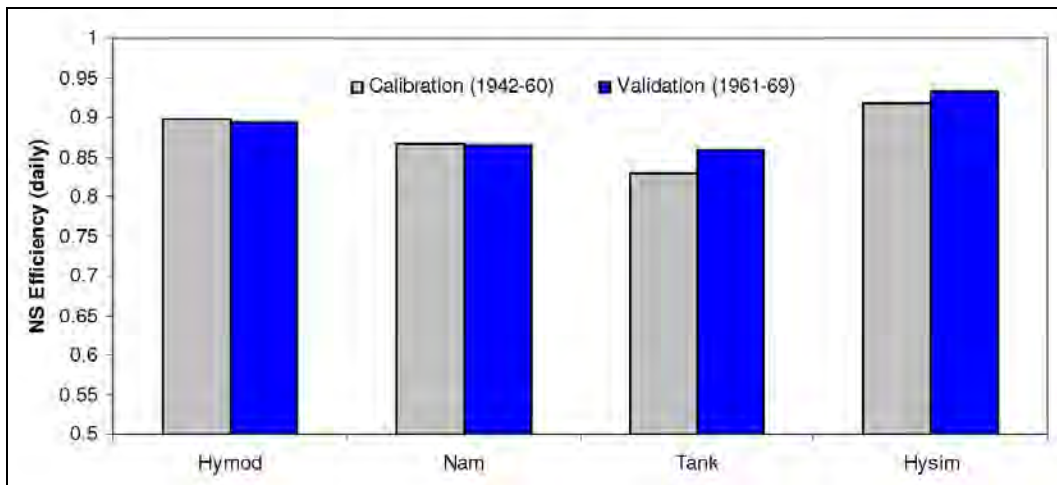


Figure A2.2. Comparison of Nash–Sutcliffe (NS) values for each model for the calibration and validation periods used. A perfect model has an NS value of 1; values are calculated from the comparison of daily simulated and observed flows.

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaoil do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomhnithe a bhfuilimid gníomhach leo ná comhshaoil na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaoil i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistriúcháin dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreal; agus
- scardadh dramhuisce.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí chomhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaoil mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOIL

- Monatóireacht ar chaighdeán aer agus caighdeán aibhneacha, locha, uisce taoide agus uisce talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntiú a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Caimníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdeán aer agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaoil na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaoil a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózón.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaoil na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstíúrthóir agus ceithre Stíúrthóir.

Tá obair na Ghníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.



Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments. The programme is structured according to four linked thematic areas with a strong cross cutting emphasis.

Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see
www.epa.ie/whatwedo/climate/climatechangeresearch



ENVIRONMENTAL PROTECTION AGENCY
PO Box 3000, Johnstown Castle Estate, Co. Wexford, Ireland
t 053 916 0600 f 053 916 0699
LoCall 1890 33 55 99
e info@epa.ie w <http://www.epa.ie>



Comhshaoil, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government