Marine Research Sub-Programme
(NDP 2007–'13) Series

SeaChange
Casadh na Taoide

RESCALE: Review and Simulate Climate and Catchment Responses at Burrishoole

Project-Based Award, Final Summary Report

Lead Partner: Department of Geography, National University of Ireland Maynooth

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ISSN: 2009-3195

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SeaChange Casadh na Taoide

Marine Research Sub-Programme 2007–2013

Project-based Award

RESCALE: Review and Simulate Climate and Catchment Responses at Burrishoole

Climate and Catchment Environment

(Project Reference: SS/CC/07/002(01))

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Project Duration:	01 May 2008 to 31 January 2010

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Acknowledgments

This project (Grant-Aid Agreement No. SS/CC/07/002(01)) was carried out under the Sea Change strategy with the support of the Marine Institute and the Marine Research Sub-Programme of the National Development Plan (NDP) 2007–2013.

The authors are grateful to the staff of the Marine Institute and in particular the Newport Facility for their help and assistance over the duration of the research. The authors would also like to thank Dr Phil McGinnity, University College Cork, Dr Glenn Nolan and Dr Michael O'Toole for their input and advice, Aengus Parsons and Veronica Cunningham (Marine Institute) for administrative support, Lee Hancox for data and statistical support and Winifred Power for editing the report. The authors also wish to acknowledge Met Éireann. We also wish to thank David Livingstone, Water Resources Department, Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (Eawag), Switzerland, and Pamela Naden, Centre for Ecology and Hydrology (CEH), United Kingdom, for their help and advice on river water temperature and dissolved organic carbon modelling, respectively, and the Centre for Water Research, University of Western Australia, for use of the DYRESM model.

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Executive Summary

Atmospheric concentrations of CO_2 and other greenhouse gases have increased significantly above pre-industrial levels

Atmospheric concentrations of CO_2 have risen, from pre-industrial levels of ~280 ppmv (parts per million volume), to 387 ppmv in 2009 (measured at Mauna Loa Observatory), an increase of 38%. Current concentration levels far exceed the natural range of CO_2 over the last 650,000 years (180 to 300 ppmv), as determined from ice cores (Intergovernmental Panel on Climate Change [IPCC], 2007). If the global warming potential (GWP) of all greenhouse gases (GHGs) (warming potential of a GHG converted to the effective warming of 1 tonne of CO_2) is considered, then CO_2-equivalent concentration levels of long-lived GHGs would be closer to 455 ppm CO_2-eq. When the effects of negative radiative forcings, such as aerosols, pollutants and land-use change, are included, the net effects range from 311 to 435 ppm CO_2-eq (IPCC, 2007a). If current rates of CO_2 emissions continue, a doubling of CO_2 above pre-industrial levels is likely to occur by the end of the present century. When CO_2-eq levels are considered, a doubling in the atmospheric concentrations of GHGs is likely to occur earlier, with consequent impacts on global temperatures.

Since instrumental records began, changes have been detected in global surface temperatures and other climate parameters

Since the beginning of instrumental records in the middle to late 1800s, global average surface temperatures have increased by approximately 0.8°C (1880–2009) (Goddard Institute for Space Studies [GISS], 2010). The decade from January 2000 to December 2009 replaced the 1990s as the warmest decade on record (GISS, 2010). Warming has been greatest in the northern hemisphere over land areas, rather than the oceans, due to the slower response times of large water bodies. According to the European Environment Agency (EEA), who employed data from the UK Met Office Hadley Centre and Climate Research Unit, University of East Anglia, average annual surface temperatures over the European land and ocean area have increased by 1.1°C over the period 1850–2009, relative to the 1850–1899 average (EEA, 2010). When ocean areas are excluded, the average annual surface temperature in Europe was found to have increased by 1.3°C (EEA, 2010).

Changes have also been detected in 'natural' systems, consistent with the increases observed in surface temperatures

Changes are also evident in both marine and terrestrial ecosystems, resulting in phenological changes, changes in abundance, and distributional and elevational shifts in plant, animal and fish species, which have been linked to the observed increase in global and regional temperatures (IPCC, 2007b; Beaugrand et al., 2002). Migratory fish species, in particular salmonids and eel, are considered to be a sensitive indicator species of environmental change due to their life cycle having both a marine and freshwater component. Long term (>50 years) fish census data from the Burrishoole catchment indicate that returning Atlantic salmon (*Salmo salar*) numbers were high in the 1970s and subsequently fell in the 1980s, while returning sea trout (*Salmo trutta*) numbers collapsed in the late 1980s. Eel (*Anguilla anguilla*) recruitment into the catchment has also fallen dramatically since the early 1980s. These declines in recruitment have been linked to large-scale oceanic and atmospheric changes over this period in conjunction with anthropogenic pressures. Changes in the freshwater environment may also have contributed to the decline in marine survival rates.

Changes are occurring at the regional and local scale in Ireland, consistent with global trends

Analysis of mean annual and seasonal air temperatures at Furnace meteorological station, located in the Burrishoole catchment, indicates that significant warming, consistent with global and European temperature trends, has occurred over the period of record. Over the 50-year period from 1960 to 2009, mean annual air temperature anomalies (differences relative to the 1961–1990 average) were found to have increased by 1.48°C. The greatest increases in seasonal mean temperatures were found to have occurred in spring and winter, of 1.8°C and 1.7°C respectively. Seasonal mean summer and autumn temperatures also increased, by 1.5°C and 1.4°C respectively, over the 1960–2009 period. No significant trends were found to have occurred in the observed seasonal mean precipitation; however, the frequency and intensity of extreme precipitation events in winter and annually were found to have increased.

Reflecting these increases in air temperatures in the catchment, long-term lake water temperatures (LWTs) have also increased over the period of record. Increases in midnight LWTs were greatest in winter and spring, with an increase of 1.8°C. Annual midnight LWTs increased by 1.3°C (1960–2009). As water temperatures affect the rates of in-stream chemical and biological processes, such as water-quality parameters (e.g. dissolved oxygen), fish and insect phenology and growth rates, changes in water temperatures can impact on the functioning of the freshwater ecosystem. As Atlantic salmon have a higher thermal tolerance than trout, it is possible that they can adapt to gradual increases in stream temperatures; trout, however, because of their lower thermal tolerance range, are likely to be impacted negatively by increased temperatures. Eels in the catchment are currently at the lower end of their thermal range and evidence from the catchment, based on data from 1990 to the present, suggests that they are benefiting from increasing water temperatures.

The climate of the catchment is projected to change significantly over the present century

Projected changes in climate for the catchment indicate that the warming trend evident in the observational records is likely to continue over the present century. The rate of warming was found to be dependent on which GHG emissions scenario is more likely, with the greatest projected warming associated with the high or A2 emissions scenario, which estimates a doubling of equivalent CO_2 by the 2050s. Mean ensemble temperature projections, derived from three global circulation models (GCM) and two emissions scenarios (A2 and B2), suggest that the greatest warming will be experienced in the autumn (2.2°C) and spring (1.8°C) seasons, by the 2080s. The models also project an increasing tendency towards a more distinct seasonal precipitation regime, with increased precipitation during the winter months and reductions likely to be experienced during the summer months. Changes in the seasonal precipitation regime will affect stream flow within the catchment and on the frequency of extreme flow parameters, such as low and high events. Owing to the spatey nature, or short response times, of the sub-catchments in the Burrishoole, it is likely that more intense precipitation events will result in an increase in flood events in the catchment. Such changes are likely to be illustrative of impacts in similar characteristic catchments along the west coast of Ireland.

Climate change is likely to have both positive and negative impacts on the catchment

The impacts of climate change on the survival rates of salmonid fish and eel are multifactorial and complex, partly because a portion of their life stage is spent in the marine environment but also because of the different climate-related impacts associated with particular life stages. Climate change represents an additional stressor to the catchment, and projected impacts are unlikely to occur in isolation. Whether climate change will have a positive or negative impact will depend on fish species and life stage. Where a particular species is at the limits of its distributional or thermal tolerance range, climate change is likely to have a negative impact on that species (e.g. trout). For eel, which currently inhabit sub-optimal thermal conditions in the catchment, climate change is likely to have a positive impact during the freshwater phase of their life cycle.

However, changes in land use, pollution, commercial exploitation, water quality or additional stressors, may increase a species' susceptibility, or decrease their ability to adapt, to climate change. For example, McGinnity et al. (2009) have previously shown that while Atlantic salmon may be able to adapt to gradual increases in temperature, supplementation of native salmon stocks with ranched or hatchery fish may result in catastrophic population collapse within a few generations. Similarly, for wild sea trout, the development of salmon farming in the late 1980s, in combination with increased winter and spring temperatures and increased levels of sea lice, corresponded with a reduction in their marine survival rates. Following this collapse in numbers, stock levels of wild sea trout returning to the catchment have yet to return to their pre-1980s' levels.

Decision making in the face of uncertainty

The research findings outlined in this report provide climate change information at the catchment scale to assist catchment stakeholders in integrating climate change considerations into their decision-making processes. While the study was focused on the Burrishoole catchment, the results are illustrative of many similar type, ecologically important, catchments along the west coast of Ireland. Critically, the report highlights the need for refined assessments at the catchment, and even stream scale to further our understanding of the complex interactions between climate and migratory fish species in the freshwater environment.

Significant uncertainties exist with regards to future climate projections. Therefore, this report is not intended to be prescriptive; rather, the findings will find greater value in stress testing existing and future management plans for the catchment. This approach to developing adaptation strategies is essential as it seeks to minimise the risk of mal-adaptation, while maximising the ability of catchment managers and stakeholders to reduce vulnerability to climate change, through the development of robust adaptation strategies that are largely insensitive to climate change uncertainties.

1. Introduction

1.1. Background

The current scientific consensus attributes most of the increase in global temperature experienced since the middle of the 20th century, to anthropogenic activities (Intergovernmental Panel on Climate Change [IPCC], 2001). In confirming this in their recent report, the IPCC attribute a confidence level of 90% to the contention (IPCC, 2007a). This warming is associated with increasing atmospheric concentrations of greenhouse gases (GHGs), primarily CO_2, which has increased from pre-Industrial Revolution levels of 280 ppmv (parts per million volume) to current levels of 387 ppmv – a level that has not been exceeded during the past 650,000 years and most likely not during the past 20 million years (IPCC, 2001; 2007a). In the absence of strict emissions controls, a doubling of atmospheric concentrations of CO_2 is likely by the end of the present century. As a consequence, global temperatures are projected to increase by between 1.8 and 4°C over the same period depending on climate sensitivity to increased levels of greenhouse gases (GHGs). The future temperature rise for mid-to-high latitude land areas, such as Europe, is projected to be greater than the increase expected for the planet as a whole. At present, Europe is warming faster than the global average. The temperature in Europe has risen by an average of 0.95°C in the last 100 years and is projected to increase by a further 2.0–6.3°C this century (compared to 0.74°C and 1.8–4.0°C globally respectively) (European Environment Agency [EEA], 2010).

An increase of this magnitude is likely to have a significant impact on climate-related processes operating at various scales – from global and hemispherical to the regional and local. Substantial new evidence is emerging that observed changes in marine and freshwater biological systems are associated with rising water temperatures, as well as related changes in salinity, dissolved oxygen (DO) and circulation changes (IPCC, 2007b).

The changes identified include:

- shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans
- increases in algal and zooplankton abundance in high-latitude and high-altitude lake ranges
- earlier migrations of fish in rivers.

Freshwater fish, including salmonids, are highly sensitive to climate variability, in particular to changes in water temperature (Finstad et al., 2004; Solomon and Sambrook, 2004; McGinnity et al., 2009) and stream flow (e.g. Walsh and Kilsby, 2007). High water temperatures in late winter and early spring can have negative impacts on survival during egg and parr stages of salmon (Finstad et al., 2004; McGinnity et al., 2009) while extreme high temperatures during summer have been associated with increases in fish mortality (Solomon and Sambrook, 2004). Additional factors critical for salmonid productivity, such as DO concentrations (Alabaster and Gough, 1986; Solomon and Sambrook, 2004) and stream-water pH levels (Lacroix, 1985; Bowman and Bracken, 1993; Donaghy and Verspoor, 1997) are themselves sensitive to climate variability. Although stream pH is primarily a function of catchment geology (Bowman, 1991) and soil processes (e.g. Clark et al., 2005), acid deposition, associated with increases in industrial emissions during the latter half of the twentieth century, has been linked with decreases in stream pH and associated fish mortality (e.g. Bowman and Bracken, 1993).

The impacts of acid deposition are greatest in naturally occurring acid-sensitive waters, which, in Ireland, are chiefly located in areas with acid bedrock and include the Burrishoole catchment area (Bowman, 1991). Stream DO concentration is a function of water temperature, together with rates of in-stream primary productivity and decomposition of organic carbon. The production of dissolved organic carbon (DOC) compounds is influenced by temperature and soil moisture levels (Naden and McDonald, 1989; Davidson and Janssens, 2006; Worrel and Burt, 2007). The decomposition of DOC can result in low oxygen levels in lake surface waters, providing a refuge for prey species less sensitive to oxygen availability than fish (Wissel et al., 2003). High water colour can also reduce light intensity in lakes and rivers and therefore lower the reactive distance of fish and their ability for size-selective predation (Wissel et al., 2003).

1.2. The Burrishoole Catchment

The Burrishoole research facility, located in the Burrishoole catchment, an important habitat for salmon (*Salmo salar*), trout (*Salmo trutta*) and eel (*Anguilla anguilla*) (Whelan et al., 1998), has been a sentinel site of fisheries research since the mid-1950s. Today the Burrishoole site, under the Marine Institute, has a well-established environmental monitoring programme with developed platforms in place to continuously monitor essential climate and aquatic variables. Field monitoring is conducted on lakes, rivers and streams. The meteorological variables measured include air temperature, surface water temperature, river discharge, precipitation, air pressure, surface radiation, wind speed, wind direction and solar irradiance.. The expansion of the monitoring platforms at the Marine Institute research station over various projects has amplified the site importance and suitability for climate change research, particularly in relation to climate, land use and water interactions. The environmental monitoring programme was progressively established with colleagues from TCD (Trinity College Dublin) and CEH (Centre for Ecology and Hydrology, UK) under various projects including EU LIFE, REFLECT, LIFE II, and CLIME and national funds including Salmon Research Agency, Marine Institute, Environmental Protection Agency (EPA) and National Development Plan (NDP) funding (RESCALE, INSIGHT, ILLUMINATE) (Table 1).

Table 1: Summary of projects and installation of equipment in the Burrishoole catchment. AWQMS = automatic water quality monitoring station (lake); ARMS = automatic river monitoring station.

Funding		EU Funding						National Funding	
	1960	1996	1998	2000	2002	2004	2006	2008	2010
Projects		Life	Reflect	Life II		CLIME	INSIGHT	RESCALE	
								ILLUMINATE	
Equipment		AWQMS Feeagh		ARMS	Climate Change impact on lakes			AWQMS Furnace	

The overall principle scientific aim of the EU projects was to illustrate the value of a high-resolution monitoring instrument as a tool with which to improve understanding of the physical, chemical and biological responses of the catchment ecology. As the programme was operated over an increasing time-period, the data became increasingly more useful, allowing annual, seasonal, daily and sub-daily analyses to be undertaken, and therefore facilitating a much wider range of objectives and projects than the original aim. The INSIGHT and ILLUMINATE projects used palaeolimnology to set the current ecological conditions in Irish catchments (including the Burrishoole catchment) in a temporal and historical context (Box 1).

Table 2: Summary of outputs from both the national and internationally funded research projects undertaken on the Burrishoole catchment. A list of selected outputs is given in Appendix I.

EU LIFE and LIFE II	EU REFLECT	EU CLIME	EPA INSIGHT	EPA ILLUMINATE
	Jennings et al. (2000)			
	George et al. (2005)			
Allot et al. (2005)		Jennings et al. (2006; 2009)	Leira et al. (2006)	
May et al. (2005)		Blencker et al. (2007)		
		McGinnity et al. (2009)		
May & Place (2005)		Arvola et al. (2010)		Dalton et al. (2010)
Rouen et al. (2005)		George et al. (2010)		
		Jennings et al. (2010)		
		Naden et al. (2010)		

In 2007, the Burrishoole catchment became a member of the Global Lake Ecological Observatory Network (GLEON), an association of limnologists, information technology experts and engineers whose goal is to establish a persistent network of lake ecology observatories (http://www.gleon.org). Data from these observatories (of which Lough Feeagh and Lough Furnace, both located in the Burrishoole, are included) will allow a better understanding of key processes, such as the effects of climate and land use on lake function, episodic events and carbon cycling within lakes. The research involvement in GLEON is a continuation of the work carried out under various national and internationally funded projects (Table 2).

Box 1: Summary of the results from the ILLUMINATE project (2006–2009) for the Burrishoole catchment (Dalton et al. 2010).

The EPA-funded ILLUMINATE project (2006–2009) used a combination of palaeolimnology and modelling techniques to explore past variations in ecological pressures and responses in several Irish lakes (Dalton et al., 2010). Palaeolimnology uses fossilised remains and chemical data from sediment cores to reconstruct the history of a lake (Dalton et al., 2009). Lough Feeagh and Lough Bunaveela were amongst the lakes included in the project. The potential impacts of climate change on nutrient export from the Black sub-catchment of Lough Feeagh were also assessed.

Sediment cores were taken from both lakes. Radioactive isotopes (210Pb and 137Cs) present in lake sediments were used to establish the rate of sediment accumulation, providing a reasonably accurate idea of the period of time covered by each core (Dalton et al., 2010). The base of the cores from Lough Feeagh and Lough Bunaveela were dated to *c.* 1895 and *c.* 1890 respectively. Analysis of fossil diatom remains in the sediment, together with sediment chemical data, indicated that both lakes had relatively low nutrient levels until the mid-1950s (Feeagh) and the mid-1980s (Bunaveela) respectively. The diatom species indicated nutrient enrichment in Feeagh dating from *c.* 1955. Enrichment commencing *c.* 1980 was also indicated for Bunaveela. Sediment-based remains of plants also confirmed a shift in catchment vegetation, and in particular an increase in conifers (presumably part of afforestation in the catchment) around Feeagh from *c.* 1955 and Bunaveela from the early 1980s. Assessment of historical trends in the drivers of nutrient loading for Lough Feeagh was also carried out using the Generalized Watershed Loading Functions model (GWLF) (Dalton et al., 2010). This supported the conclusions drawn from analysis of the sediment archive, indicating that catchment disturbance associated with afforestation and overgrazing was the main factor responsible for nutrient enrichment. A significant change point in the modelled total phosphorus (TP) loading was identified at *c.* 1960, shortly after initial afforestation in the catchment and just prior to an increase in sheep numbers that occurred from the 1970s to the 1990s. Total phosphorus includes both dissolved and particulate forms. Overgrazing in the catchment had been linked to substantial erosion of upland peats during that period (Weir, 1996). Trends in modelled annual TP loading and measured sediment phosphorus levels were in close agreement for Feeagh and for other lakes assessed in the project.

The ILLUMINATE project results indicated that neither Lough Feeagh nor Bunaveela are currently in what would be classed as a ‘reference’ state as defined in the Water Framework Directive (Directive 2000/60/EC). Reference conditions are the biological and chemical characteristics of the water body that existed prior to human impact. For Feeagh, this conclusion accorded with the results of earlier EPA-funded research (Leira et al. 2006). Nutrient enrichment with phosphorus has also been apparent in recent monitoring of water quality in Lough Feeagh. Despite these increased nutrient levels, phytoplankton production in the lake has remained relatively low, probably restricted by light availability due to the highly coloured waters from the surrounding peaty catchment (Karlsson et al., 2009).

The ILLUMINATE project also included an assessment of future climate impacts on nutrient export from the Black sub-catchment to Lough Feeagh for the period 2021–2060 (Dalton et al., 2010). Together with increases in air temperature in all seasons, a change in the seasonal pattern of precipitation was indicated, with higher rainfall between October and March and drier weather from late spring to autumn. This change was mirrored by similar seasonal changes in stream flow. Simulations of catchment phosphorus loading using GWLF resulted in increased loading of dissolved phosphorus and total phosphorus in late winter, and decreases for spring and early summer. The projected changes in dissolved phosphorus loading were driven by changes in stream flow, while that in TP was also related to changes in sediment loading. Such a reduction in nutrient loading during summer months would further reduce the risk of algal blooms occurring.

Past research on the catchment has shown that surface water temperatures (SWTs) in Lough Feeagh are highly sensitive to large-scale climatic variability (Jennings et al., 2000; George et al., 2005; Blenckner et al., 2007), while more recent research, undertaken as part of the EPA-funded ILLUMINATE project, indicates that lake SWT may increase by over 2°C by 2071 (McGinnity et al., 2009). Both the EU CLIME and EPA ILLUMINATE projects have also highlighted the potential for significant increases in DOC export from the Burrishoole catchment based on future climate projections for the period 2071–2100, together with changes in seasonal patterns of soil moisture and streamflow (Jennings et al., 2006; Naden et al., 2010; Dalton et al., 2010) (Box 1). In addition, an examination of high-frequency measurements of DOC compounds has demonstrated the association between high-flow events and pulses of DOC export from catchment soils (Jennings et al., 2010).

1.3. Context of the Report

> *Regional changes in the distribution and productivity of particular fish species are expected due to continued warming and local extinctions will occur at the edges of ranges, particularly in freshwater and diadromous species (e.g., salmon)...*
>
> (IPCC, 2007b: 275)

Previous research identified a scientific gap in knowledge in terms of understanding the implications of present and projected future changes in stream flow, water temperature, pH levels and DO concentrations on fish productivity in the catchment. To address this, a multidisciplinary team of scientists from the National University of Ireland Maynooth (NUIM), TCD and the Marine Institute, undertook an analysis of both present and likely future climate impacts on the catchment with a view to furthering the understanding of the interlinkages between climate, climate change, and the freshwater ecosystem. This report, entitled *RESCALE: Review and Simulate Climate and Catchment Responses at Burrishoole*, builds on the wealth of scientific endeavours previously undertaken on the catchment and represents the collaborative efforts of the multidisciplinary research team.

The layout of the report follows a defined structure (Figure 1), initially, providing an in-depth assessment of the climate and environmental datasets from the catchment to establish if changes have occurred over the period of record. In order to assess the likely impacts of future changes in climate on the catchment, regional climate projections were developed and subsequently employed to simulate likely responses in stream flow and temperature, DOC and DO for the present century. The projected changes in both the climate and water-quality parameters were then used to provide a basis for assessing impacts on fish growth and survival rates, of salmonid and eel species, in the catchment.

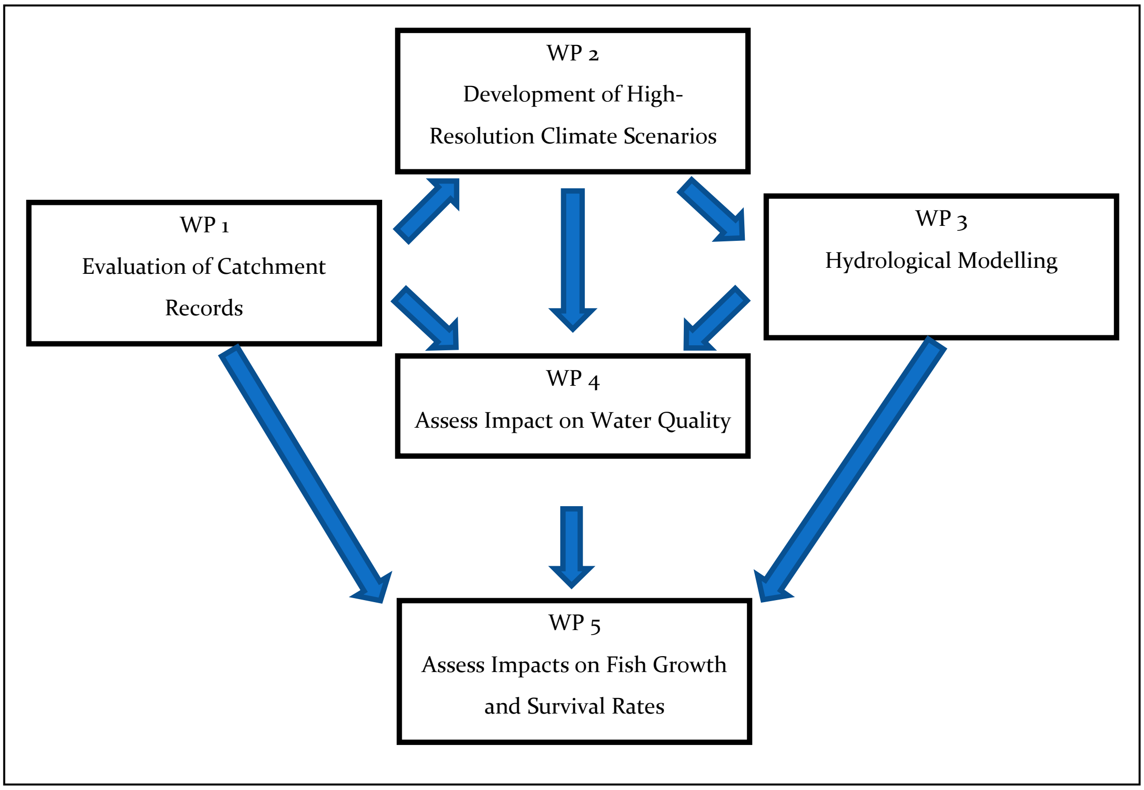


Figure 1: Schematic overview of RESCALE and work package (WP) interlinkages.

The research is intended to contribute to the wider scientific literature on climate change impacts at the catchment, ecosystem and species scale. In addition, the report provides a useful template for future studies, not just in the Burrishoole but for other ecologically important catchments. The findings from the report are relevant to policy makers at the national scale; catchment managers at the regional scale; and, specifically, to stakeholders in the Burrishoole catchment, in developing adaptive responses to climate change.

2. Observed Changes in the Climate System

2.1. Introduction

The latest IPCC (2007) assessment, the *Fourth Assessment Report*, showed clear evidence that terrestrial and aquatic ecosystems are being strongly affected by climate change, particularly in the form of regional temperature increases. The *Fourth Assessment Report* also presented observational evidence that climate change poses a significant threat to biodiversity, species distribution, and the functioning of ecosystems.

Over the instrumental period of record since 1880, global average temperatures have increased by approximately 0.8°C (GISS, 2010), along with concurrent warming of freshwater systems (Winder and Schindler, 2004; Hari et al., 2006; Arvola et al., 2010). Similar trends have been observed in Ireland where climate-induced changes in freshwater systems are of a greater magnitude and occurring at a faster rate than has been observed in the last thousand years, according to the dendro-chronological record (Stefansson et al., 2003).

Temperature is a significant driver of ecological change in aquatic environments, because of its effect on the rate of key chemical and biological processes in water – e.g. respiration, photosynthesis and DO saturation – and on metabolism (Harley et al., 2006). The most immediate effects of climate change on aquatic ecosystems are expected to occur as alterations in lake and river water temperatures (RWT) (Hammond and Pryce, 2007). As regional air temperatures have risen over the last 100 years, so have water temperatures. The EEA has observed 1°C to 3°C increases in water temperature in major European rivers, such as the Rhine and the Danube (EEA, 2007). Langan et al. (2001) have found that, in an upland Scottish river, winter and spring maximum RWTs have increased by 2°C in the last thirty years, most likely because of rising air temperature.

As temperature influences the rates of nearly all chemical and biological processes in water, water temperature is a major determinant of habitat in rivers and streams (e.g. Elliott, 1984; Eaton and Scheller, 1996). Riverine ecosystems are therefore highly susceptible to any changes in temperature. Moreover, the effects of shifts in RWT are likely to be exacerbated by alterations in precipitation patterns, which, in the case of prolonged droughts, may exacerbate extreme RWTs (Graham and Harrod, 2009). The timing of fluctuations in RWT is particularly important since the occurrence of extreme temperature events during critical stages in fish development can have negative impacts on fish populations (McGinnity et al., 2009).

Recent studies have shown that the effects of climate change on regional weather will be far more complex than simply altering temperature patterns (Parry et al., 2007). In particular, changes in the magnitude and seasonality of precipitation are expected to have significant effects on water quality (Jennings et al., 2009; Naden et al., 2010; Whitehead et al., 2009). Although relatively few studies have considered the effects of climate change on Irish freshwaters, Burrishoole was one of two sites included in a project on climate change impacts on European lakes and catchments (Arvola et al., 2010; Jennings et al., 2010; Naden et al., 2010). The project assessed impacts of climate on DOC exports from the Glenamong catchment (a sub-catchment of the Burrishoole), highlighting potential increases in export rates, and also trends in lake water temperature in Lough Feeagh. Additional work on climate change impacts in the Burrishoole catchment has identified potential negative effects of higher winter temperatures on salmon survival (McGinnity et al., 2009; Dalton et al., 2010).

Observed and projected increases in air temperature will also affect the rates of the biological and chemical processes that influence water quality (e.g. biological oxygen demand, DO saturation, DOC degradation) (Whitehead et al., 2009). Shifts in precipitation patterns may alter river flow and discharge, affecting residence times and dilution of pollutants, plus water temperature (Arnell, 1998; Mohseni et al., 2003). Increased occurrences of extreme precipitation events could increase the likelihood of acid pulses and DOC release through post-drought floods (Arnell, 1998; Whitehead et al., 2009). Finally, alterations in soil temperature and structure may modify the transport of pollutants to water, affecting water chemistry and primary production (Whitehead et al., 2009).

The impacts of climate change on aquatic ecosystems are complex and difficult to predict because of confounding factors, such as natural variability, physiological adaptation by organisms, and changes in food–web dynamics (Graham and Harrod, 2009). A large body of evidence shows, however, that the warming of freshwaters and the resulting changes in water quality have had an impact on fish physiology (Fry, 1971; Stefansson et al., 2003); fish phenology (Zydlewski et al., 2005; McGinnity et al., 2009); species distributions (Friedland et al., 2003; Davidson and Hazelwood, 2005); and survival (King et al., 2007; McGinnity et al., 2009). Increased temperature affects fish at all life stages (Friedland et al., 2003), although the response varies for species and fish life stage (Elliott, 1991; Planque and Frédou, 1999). In many cases, global climate change represents an additional stress on fish populations that are already subject to human-induced pressures (Allan and Flecker, 1993). This is particularly true in Ireland, where most freshwater bodies have long been impacted by anthropogenic activity, such as eutrophication and deforestation (Stefansson et al., 2003; Cummins and Farrell, 2003). Observational evidence suggests that many Irish populations of both Atlantic salmon and brown trout are already in decline (Stefansson et al., 2003; Peyronnet et al., 2007). Furthermore, McGinnity et al. (2009) showed that while Atlantic salmon may be able to adapt to future changes in water temperature in an ideal situation, additional stressors, such as the supplementation of populations with hatchery fish, might cause catastrophic population collapses within a relatively short period of time.

2.2. Global Climate Change

> *… warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures …* (IPCC, 2007a: 5)

Over the 100-year period from 1906–2005, mean global surface air temperatures increased by 0.74°C ±0.18°C, with a doubling of the warming trend evident in the latter half of the period (IPCC, 2007a) (Figure 2). However, global temperature changes also exhibit significant spatial variations with greater increases evident for land areas in the mid to high latitudes in the northern hemisphere, while parts of the Antarctic continent and Pacific Oceans show little or no evidence of warming.

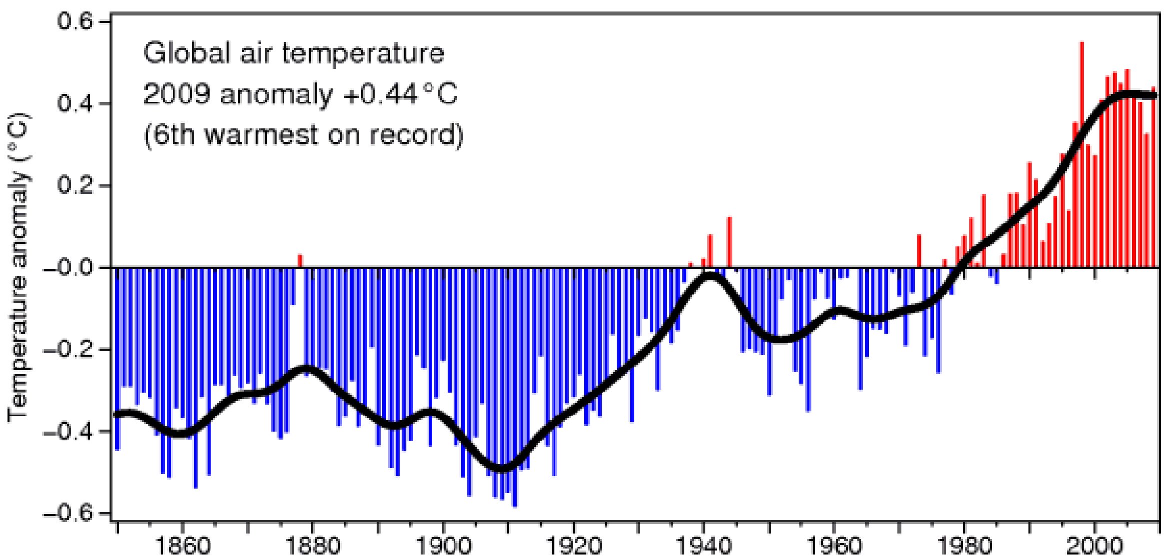


Figure 2: Global temperature anomaly for the period 1850–2008 with respect to the 1961–1990 period (Jones, 2009).

According to instrumental records analysed by researchers at the Climate Research Unit in East Anglia, 1998 was the warmest year during the period 1890–2009, with a temperature anomaly of 0.55°C above the baseline mean (Figure 2 and Figure 3). However, with the inclusion of additional station data from the Arctic, the Goddard Institute for Space Studies (NASA/GISS) found that warming in 2005 may have exceeded that of 1998 (Hansen et al., 2006). While natural factors, such as El Niño, are likely to have contributed to the warming experienced in 1998, no such natural contribution can be attributed to the warming experienced in 2005.

Fifteen of the warmest years on record have all occurred since 1990 (Figure 3). According to GISS, warming in 2009 is tied as the second warmest year in the instrumental record along with 1998, 2002, 2003, 2006 and 2007. While this ranking contrasts slightly with that from the World Meteorological Organisation (Figure 3), the decade 2000–2009 has replaced the 1990s as the warmest decade of the instrumental record. With the inclusion of the additional years of data, global average temperatures have increased by approximately 0.8°C since 1880 (GISS, 2010).

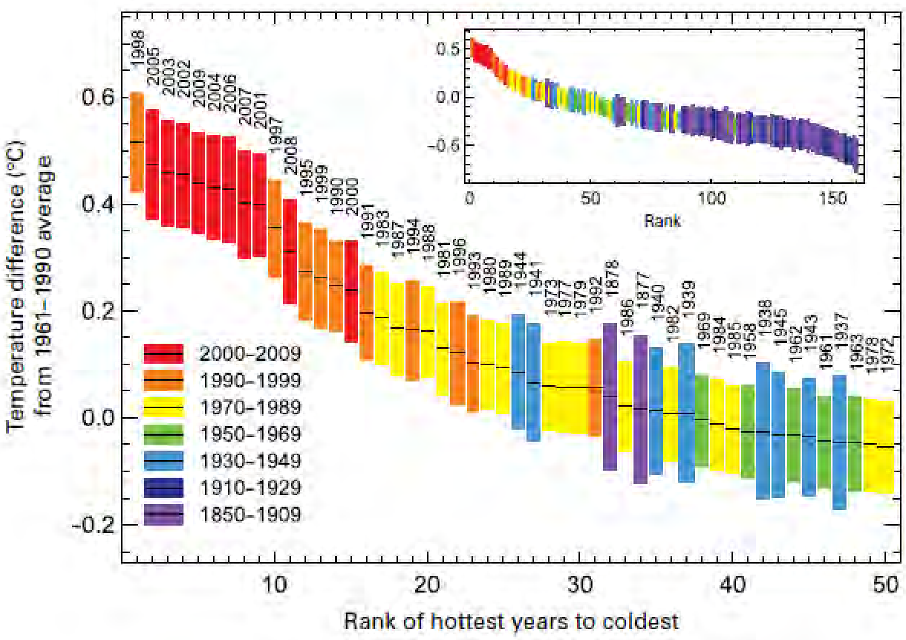


Figure 3: Global ranked surface temperatures for the warmest 50 years. Inset shows global ranked surface temperatures from 1850. Size of the bars indicates the 95% confidence limits associated with each year. Source data are blended land surface air temperature and sea surface temperature from HadCRUT3 series (Brohan et al., 2006). Values are simple area-weighted averages for the whole year (Data Source: Met Office Hadley Centre, UK, and Climatic Research Unit, University of East Anglia, UK) (WMO-No. 1055).

Changes have also been detected in precipitation with a general tendency for wetter conditions in many areas around the world (Alexander et al., 2005), including the northern hemisphere as a whole (Zhang et al., 2007), western Europe (Bardossy et al., 2003; Haylock and Goodess, 2004), regions in South America (Haylock et al., 2006), the USA (Karl and

Knight, 1998), the Arctic (Min et al., 2008), northern Taiwan (Yu et al., 2006), the UK (Osborn and Hulme, 2002; Bardossy et al., 2003) and Ireland (Hoppe and Kiely, 1999; Kiely, 1999; McElwain and Sweeney, 2007). However, many of these regions display significant seasonal variability with increased rainfall evident during winter months and decreases during the summer months. For example, an increase in total precipitation was found in the UK in winter but a marked decrease was found in summer in association with an increased frequency of droughts (Osborn and Hulme, 2002). Similarly, in an analysis of rainfall data from Germany, a number of authors detected an increase in winter rainfall, with decreases evident in summer over the period 1958–2001 (Hundecha and Bardossy, 2005) and 1851–2006 (Hansel et al., 2009).

Changes in heavy precipitation events are likely to have a greater impact than changes in the total or mean precipitation (Aguilar et al., 2005; Groisman et al., 2005; Klein Tank et al., 2006) (Box 2). Analyses of extreme precipitation trends from around the globe have in general reported an increase in extremes towards wetter conditions. A number of authors have reported an increase in the contribution of extreme heavy precipitation events to annual totals in the USA (Karl and Knight, 1998) and China (Liu et al., 2005); precipitation intensity has increased in the South Pacific (Griffiths et al., 2003) and eastern Mediterranean (Kostopoulou and Jones, 2005); there is more intense daily rainfall in winter in the UK and heavy rainfall events have increased in frequency (Osborne and Hulme, 2002). In Scotland, heavy rainfall events have also increased in frequency with 50-year events now occurring every 8 years in the east of the country (Fowler and Kilsby, 2003). Zhang et al. (2007) showed that anthropogenic forcing had a detectable influence on observed precipitation changes in the northern hemisphere: increased GHG emissions will give rise to an increased probability of intense precipitation events for many extra-tropical regions (Groisman et al., 2005).

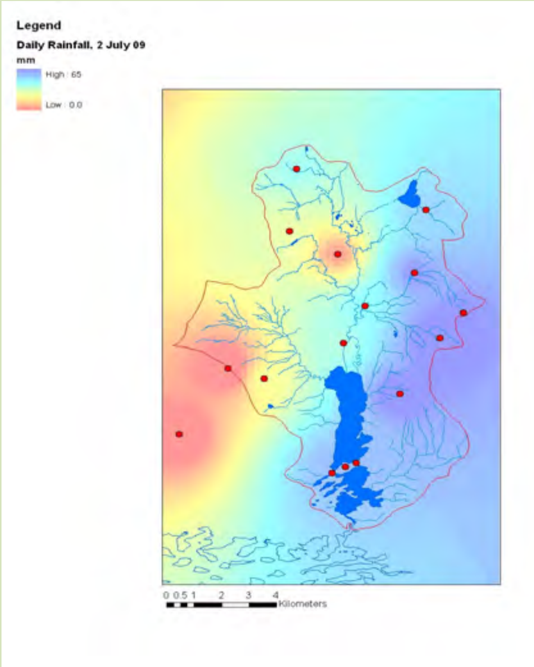
2.3. Indicators of Climate Change

An analysis of extreme temperature and precipitation in Europe was undertaken as part of an EU Framework-funded Statistical and Regional dynamical Downscaling of Extremes for European regions (STARDEX) project. This research examined trends in extreme weather events, and developed modelling techniques to assess likely changes in such events in the future. Among the project results was a key set of indices that can be used to examine trends in the mean and extremes of temperature and precipitation. The indices are based on a percentile method that provides data that are comparable across different climate regimes (http://www.cru.uea.ac.uk/projects/stardex/).

The study found that, in addition to increases in maximum and minimum temperatures across Europe, there have also been increases in extreme temperatures and precipitation events. A generally warming trend was found in western Europe, associated with an increase in hot temperature 'indices', such as heatwave duration and a decrease in cold temperature indices, such as the number of frost days (Hundecha and Bardossy, 2005; STARDEX Final Report 2005). For example, a 0.5 days/year decrease in winter frost days coupled with a hot day threshold increase of 0.04°C/year in winter and a 0.06°C/year summer increase has been reported in the UK (Haylock, 2003). A similar study in Ireland by McElwain and Sweeney (2007) found that frost days have decreased by 0.2 days/year in winter, heatwaves have increased by 0.23 days/year and cold-wave duration has decreased by 1.1 days/year. However, the heatwave duration and cold-wave duration indices used in the study by McElwain and Sweeney (2007) were not percentile based, relying instead on a 5°C threshold deviation from the long-term mean. The appropriateness of using fixed-threshold approaches for use in maritime-dominated climates, such as Western Europe, has been questioned by some authors (Bardossy et al., 2003). For this reason, percentile-based indices are now the preferred method for calculating heatwave and cold-wave duration indices.

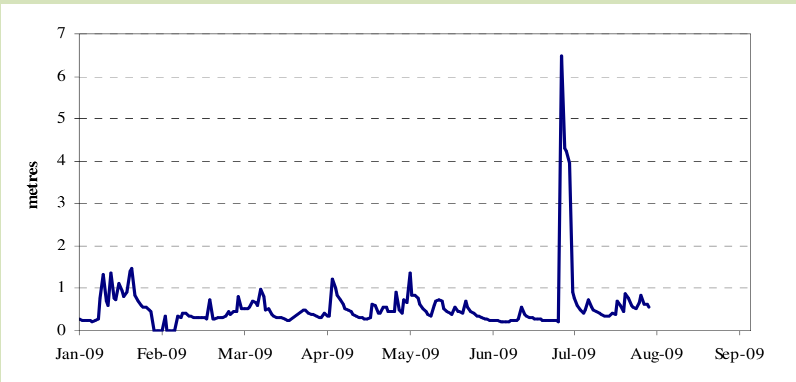
Box 2: Case study on the extreme rainfall event which occurred in the Burrishoole catchment, 2 July 2009.

Between 7 p.m. and 9 p.m. on Thursday 2 July, 2009, *c.* 50 mm of rain fell on the east side of the Burrishoole catchment, centred on the Buckagh mountain and the valley between the Skerdagh and Srahrevagh catchments (inset Fig. 1). The Glenisland area was also affected. Three of the data-logging rain gauges on the east side of the catchment recorded a 2-hourly rainfall event in excess of 44.7 mm, which has an expected return time of more than 250 years. In fact, the rain gauge at the top of the Lodge river catchment recorded a 2-hour rainfall of 52.4 mm between 7 p.m. and 9 p.m. The rain was very localised, with rain gauges on the west side of the catchment recording as little as 16 mm in the same 2-hour period.



Inset Fig. 1: Daily rainfall in the Burrishoole catchment, 2 July 2009.

The intensity of the rainfall, combined with the fact that the flood was preceded by approximately 6 weeks of dry settled weather meant that the flood water was unable to soak into the ground, and resulted in the water draining straight down the river valleys. The Black and Srahrevagh river water-level recorders reached highs of 6.48 m and 4.86 m respectively, although the water levels experienced were likely outside the ranges that the recorders are rated for. Normal floods in these rivers would be in region of 1.2 to 2 m (inset Fig. 2). The rise of the flood was very fast, and almost concurrent with the rainfall.



Inset Fig. 2. Daily maximum water level (m) in Black river, 2009.

(Cont.)

The floods in the Srahrevagh, Lodge, House, Cottage and Yellow rivers carried a significant amount of sand, gravel, boulders, trees and debris with them, blocking culverts, bridges and roads. The harbour in Lough Feeagh was infilled with material from the House river and the nephelometer on the automatic water quality monitoring stations (AWQMS) in Lough Feeagh recorded turbidity values 4 times higher than the annual maxima. Animal and plant life was undoubtedly affected, although it may take one or two annual cycles for the impacts to become apparent. Initial surveying of the Srahrevagh river indicated massive mortality among juvenile salmonids, and involuntary downstream migration of adult trout.

Inset Fig. 3. Site of An Oige hostel, Treanlaur harbour, 3 July 2009.

The numbers and species richness of invertebrate taxa were considerably reduced in the upstream sections of the affected rivers. Farmers reported losses of sheep, fences and silage and the foundations of the An Oige hostel at Treanlaur were undermined (inset Fig. 3). Some of the Marine Institute's environmental monitoring equipment was also damaged or destroyed. Much of the river beds in affected rivers were eroded, and sand and gravel accumulated in downstream deposition areas. The long-term biological impacts of the flood will continue to be monitored by the Marine Institute, and while the impacts of this event were significant and unwelcome, it is important that this extreme event is used as a research opportunity to quantify the resilience and recovery of a catchment in these circumstances.

2.4. Burrishoole Catchment: Site Details and Catchment Description

The Burrishoole catchment forms part of the Irish Western Region Basin District (WRBD) and is located in the Nephin Beg mountain range near Newport, Co. Mayo (9° 34' 20" W, 53° 55' 22" N) (Figure 4). The total area of the freshwater catchment is 89.5km^2, and comprises seven lakes of various sizes and about 45 kilometres of interconnecting rivers and streams (Whelan et al., 1998) (Figure 5). The lakes cascade in a southerly direction from upland headwaters to tidal transitional waters. Part of the catchment (the western and upper parts) has Special Area Conservation (SAC) status (Site name Owenduff/Nephin Complex; Site Code 000534). The bedrock geology of the catchment is characterised by metamorphic rocks of late Precambrian age, consisting of quartzites (44%), schists/gneiss (44%), Silurian quartzite (11%) and small areas of sandstone and limestone (1%) (Parker, 1977; Long et al., 1992; Irvine et al., 2000). As a result of geological and edaphic differences, the western and eastern sub-catchments of the Burrishoole catchment are quite distinct. Rivers and streams on the western side (Glenamong, Altahoney and Maumaratta subcatchments) are generally more acidic, with low buffering capacity (alkalinities in the order of -2.7 to 7.5 mg L^{-1} $CaCO_3$) and low aquatic production (Marine Institute, unpublished data). The geology is more varied on the east side of the catchment (Rough, Lodge, Goulaun and Cottage sub-catchments), with quartzite/schist interspersed with veins of volcanic rock, dolomite, wacke and pure schist. Rivers draining these eastern subcatchments are nearer circumneutral with alkalinities in the order of 15–20 mg L^{-1} $CaCO_3$, with consequently higher aquatic productivity. In the lower parts of the catchment, towards Clew Bay, metamorphic rocks dip below Devonian Old Red Sandstone and Carboniferous limestone. A terminal moraine, marking the boundary between metamorphic and sedimentary rock-types, separates the largest freshwater lake, Feeagh, from the tidal Furnace (Figure 5). Deglaciation left the area blanketed with a sandstone-bearing till (Newport till) (Kiely *et al*., 1974; Poole, 1994). The overlying soils are mainly poorly drained gleys and peaty podsols, with blanket peatlands covering the mountain slopes to the north.

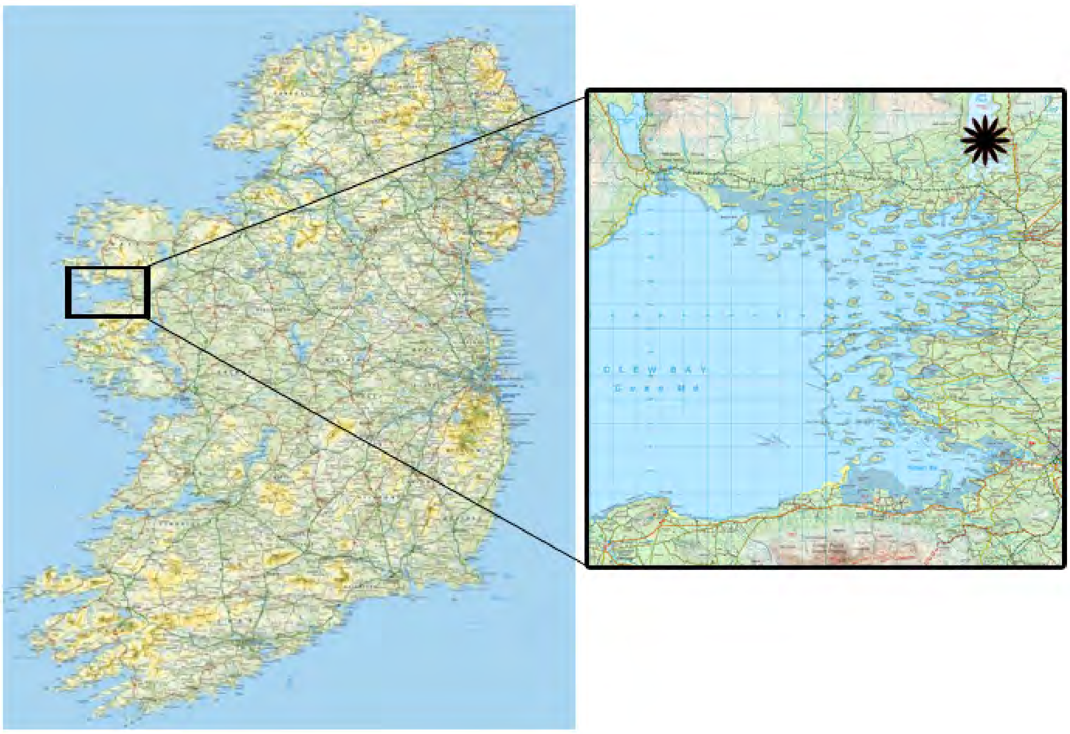


Figure 4: Location of Furnace/Burrishoole catchment near Newport, Co. Mayo on the west coast of Ireland. Site shown by asterix.

Land cover in the catchment comprises 64% peat bog, 23% forestry, with the remaining 13% being made up of smaller pockets of transitional woodland and scrub, natural grasslands and agricultural land (CORINE, 2000). Much of the peat bog area is commonage, and is used for sheep grazing (Weir, 1996). Vegetation cover on the blanket peats is characterised by *Molinia caerulea, Schoenus nigricans* and *Scirpus caespitosus* (O'Sullivan, 1993). Commercial afforestation schemes, commencing in 1951, account for the vast majority of the 23% of land cover that is forested (Coillte pers. comm.; FIPS database, Forest Service), although there are very small areas of native oak woodlands. Afforestation expanded between 1960 and 1969; the main taxa are Sitka spruce (*Picea sitchensis*) (26%) and Lodgepole pine (Pinus contorta) (70%) (Coillte, unpublished data; Dalton et al., 2010). Clearfelling of planted trees commenced in the early 1990s: approximately 672 hectares (or c. 30% of the total plantation area) have been removed (Marine Institute, unpublished data).

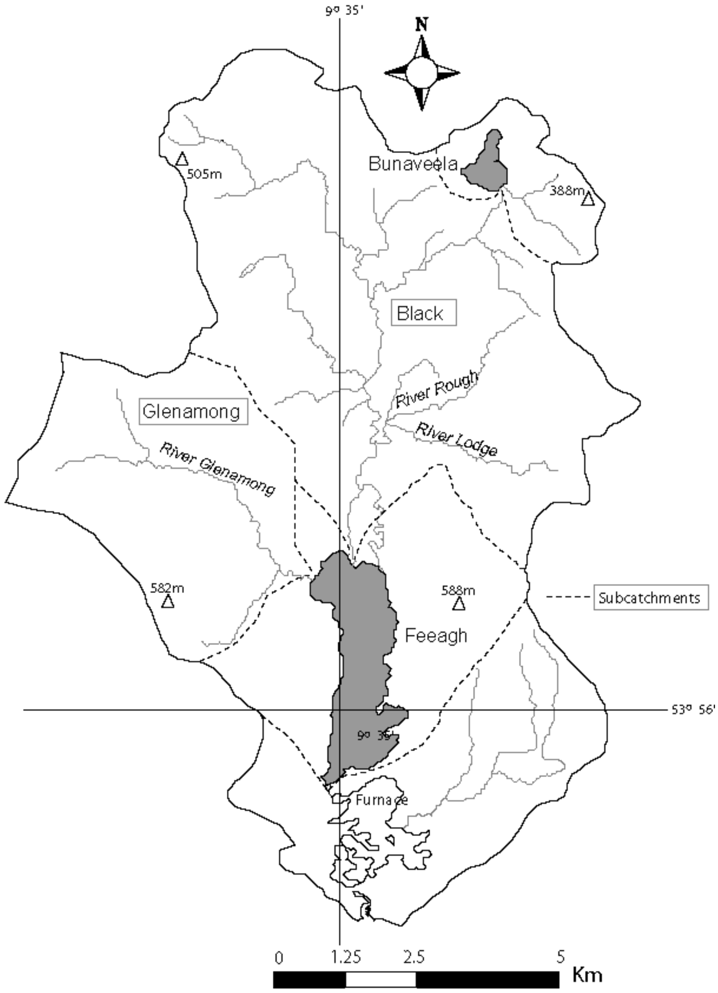


Figure 5: Burrishoole catchment showing the locations of Bunaveela and Feeagh and the main sub-catchment boundaries (Glenamong and Black) (Dalton et al., 2010).

Trap installations between Loughs Furnace and Feeagh (Figure 5) monitor all movements of fish migrating to and from the catchment. These traps enable full censuses to be carried out on wild salmon, sea trout and eels, and records in some cases extend back to 1959. Since records commenced, numbers of wild salmon, sea trout and eels returning to the catchment have declined (ICES, 2009a; 2009b; Poole *et al.*, 2007). The catchment is of national and international importance as an index site for salmonid monitoring. Data collected from the Burrishoole fish trapping facilities are used extensively by the International Council for the

Exploration of the Seas (ICES) to gauge the overall status of salmon, sea trout and eel stocks in the North Atlantic region.

Bunaveela and Feeagh are the two largest freshwater lakes in the catchment. Feeagh is an Environmental Protection Agency (EPA) typology class 4 lake (deep, >50 ha and low alkalinity) and is oligotrophic, distinctly coloured, with a pH of 6.7. Bunaveela is also an EPA typology class 4 lake and is an oligotrophic, acid-neutral, headwater lake. According to Anon (2005), Feeagh is regarded as 'probably not at significant risk' (category 2a), while in 2003 the lake was classed by the EPA Ireland as a Candidate Reference Lake. Neither concurs with work carried out on the Burrishoole catchment over the past two decades. Several studies have highlighted degradation of the Burrishoole catchment associated with afforestation and overgrazing (e.g., Allott et al., 2005; May et al., 2005; Leira et al., 2006; Dalton et al., 2010) in the past five decades, but the impacts of this degradation on fish stocks is unknown. This is partly because the catchment degradation has occurred concurrently with changes in marine survival (salmon and sea trout) and recruitment (eel) and also climate change. Possible links between climate variability and reduced numbers of Atlantic salmon in the catchment have recently been explored (McGinnity et al., 2009).

2.5. Instruments and Data

The Burrishoole catchment is a highly instrumented and intensively monitored catchment (Figure 6). Datasets available for the catchment include long-term data such as air temperature, precipitation and water temperature, measured since the late 1950s, along with more recent high-resolution data from a monitoring platform installed on Lough Feeagh in 1996, which include meteorological data, pH, DO and lake-temperature profiles. More recently, a number of new instrument platforms have been deployed within the catchment, such as the automatic river monitoring systems (ARMS), which has been in operation for approximately 6 years (Table 3). These record high temporal resolution measurements of river water parameters, with readings taken at sub-daily or sub-hourly frequency – for example, in-stream pH is measured every two minutes.

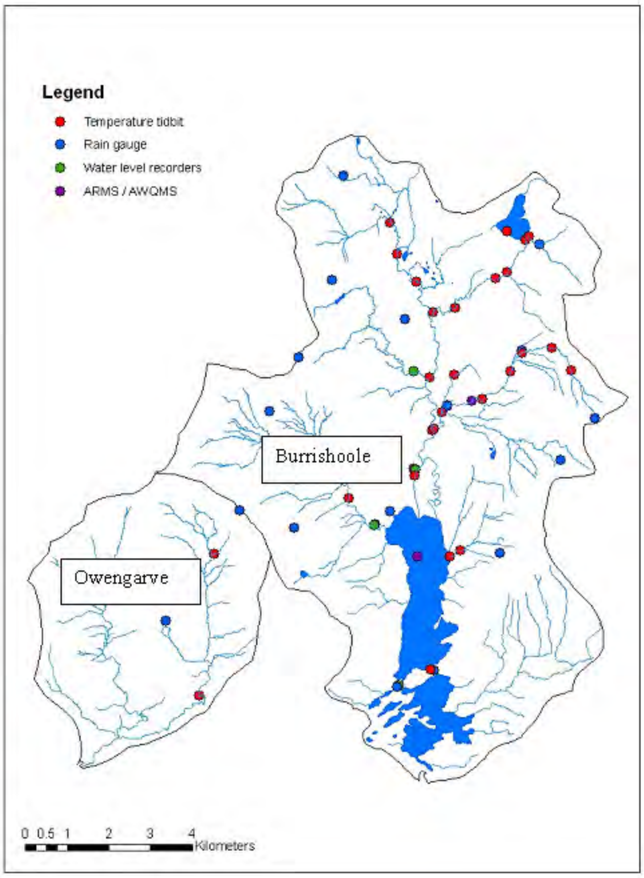


Figure 6: Monitoring equipment currently deployed in the Burrishoole and Owengarve catchments and maintained by the Marine Institute.

Data used in this report were derived from seven main sources, including instrumented platforms and observation stations (Figure 6):

- automatic water quality monitoring stations (AWQMS) on Lough Feeagh
- automatic river monitoring systems (ARMS) on Glenamong, Srahrevagh and Black rivers
- data logging rain gauges
- water-level recorders
- temperature recorders (data loggers and paper chart)
- Furnace manual weather station (WS operated by Met Éireann/Marine Institute)
- Newport automatic synoptic weather station (AWS operated by Met Éireann/Marine Institute) located at Furnace.

Table 3: List of data sources from Burrishoole catchment used in the RESCALE project. AWS = automatic weather station; manual WS = Manual weather station; AWQMS = automatic water quality monitoring system; ARMS = automatic river monitoring system; OTT = Orphimedes water-level recorder.

Parameter	Equipment Type	Quantity	Year from	Year to	Duration (years)
Air temperature	Manual WS	1	1959	----	50
	AWQMS	1	1996	----	13
	AWS	1	2005	----	4
Precipitation	Rain gauge	19	2000	----	9
	WS	1	1959	----	50
Water temperature	Chart Recorder	1	1960	2004	44
	AWQMS	1	1996	----	13
	ARMS	3	2001	----	8
	Tidbit	8	2001	----	8
Humidity	WS	1	1960	----	49
	AWQMS	1	1996	----	13
Wind speed	WS	1	1968	----	41
	AWQMS	1	2003	----	6
	AWS	1	2005	----	4
Wind direction	WS	1	1968	----	41
	AWQMS	1	2003	----	6
	AWS	1	2005	----	4
Water level	OTTs	12	2001	----	8
pH	AWQMS	1	2003	----	6
	ARMS	3	2003	----	6
Dissolved oxygen (DO)	AWQMS	1	2003	----	6
	ARMS	3	2004	----	5
Dissolved organic matter (DOM)	ARMS	1	2004	----	5

2.6. Primary Indicators of Climate Change

This section provides an overview of the analysis of the long-term observational climate records, outlined in Table 3, using the STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions) indicators. A description of indicators employed in the research is outlined in Table 4. The magnitudes and direction of all trends were assessed for statistical significance employing the Kendall tau statistical test.

Table 4: List of indices used categorised into general trends and extreme trends for air temperature, precipitation and water temperature (* indicates comparison made with McElwain and Sweeney [2007] sites for the period 1960–2005).

Code	Index	Description
	General trends	
	Air temperature	
ATA	Air temperature anomaly	
tmax*	Mean maximum temperature	
tmin*	Mean minimum temperature	
tmean*	Mean temperature	
DTR*	Diurnal temperature range	
	Water Temperature	
wtmean	Mean water temperature	
	Precipitation	
PA	Precipitation anomaly	
pmean	Mean precipitation	
	Extreme trends	
	Air temperature	
tx90	tmax 90th percentile	Hot-day threshold
tn10	tmin 10th percentile	Cold day threshold
tnfd*	number days tmin <0	Frost days
hwd	6 consecutive days >90th percentile	Heatwave duration
tx90per	days >90th percentile	Frequency at extreme high temperatures
tn10per	days <10th percentile	Frequency at extreme low temperatures
	Precipitation	
cdd*	Consecutive dry days	Longest dry period
pfl90	% rainfall >long-term 90th percentile	Heavy rainfall proportion
pnl90*	no. events >long-term 90th percentile	Heavy rainfall days
sdii	Simple daily intensity	Average wet-day rainfall
px5d*	Greatest 5-day rainfall	Greatest 5-day rainfall
pq90	90th percentile rain-day amounts	Heavy rainfall threshold

2.6.1. Air temperature indicators: mean, maximum and minimum temperatures

Analysis of air temperature trends at the Furnace weather station in the Burrishoole over the period 1960–2009 (50 years) indicates that there has been considerable warming over the period of record, with mean annual air temperatures displaying a significant increase of 1.48°C ($p<0.001$) over the instrumental period of record (Figure 7). When compared with Irish temperature anomalies over a comparative time period (1960–2005), the increase in mean annual air temperature at Furnace of 1.1°C exceeds that for Ireland as a whole (0.9°C). The increase in mean annual air temperature anomalies at Furnace over the period 1960–2009 is also greater than that reported for global mean surface average temperatures. Seasonal mean temperatures have also increased, with the greatest increase of 1.8°C evident in spring, followed by winter (1.7°C), summer (1.5°C) and autumn (1.4°C) (Table 5).

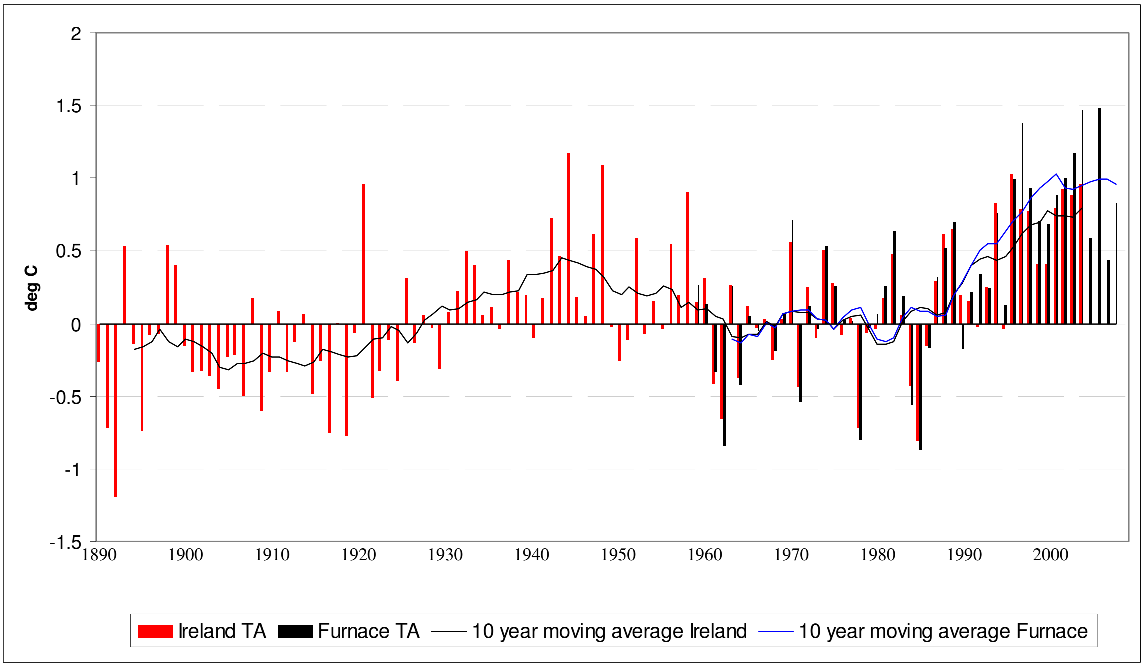


Figure 7: Air temperature anomalies for Furnace and Ireland (after McElwain and Sweeney, 2007), calculated with respect to 1961–1990 reference period. The time periods are 1890–2005 for Ireland and 1960–2009 for Furnace. Bars are annual air temperature anomalies and lines are 10-year moving averages.

Increases in maximum temperatures were also found to have occurred, with increases evident in all seasons, but most pronounced during spring (1.8°C) and winter (1.8°C) (Figure 8). Minimum temperatures also increased during all seasons, with the greatest increases occurring during winter and summer of respectively 1.1°C and 1.3°C (Table 5 and Figure 8). Maximum temperatures have increased more than minimum temperatures in all seasons and annually, resulting in an increased diurnal temperature range (DTR).

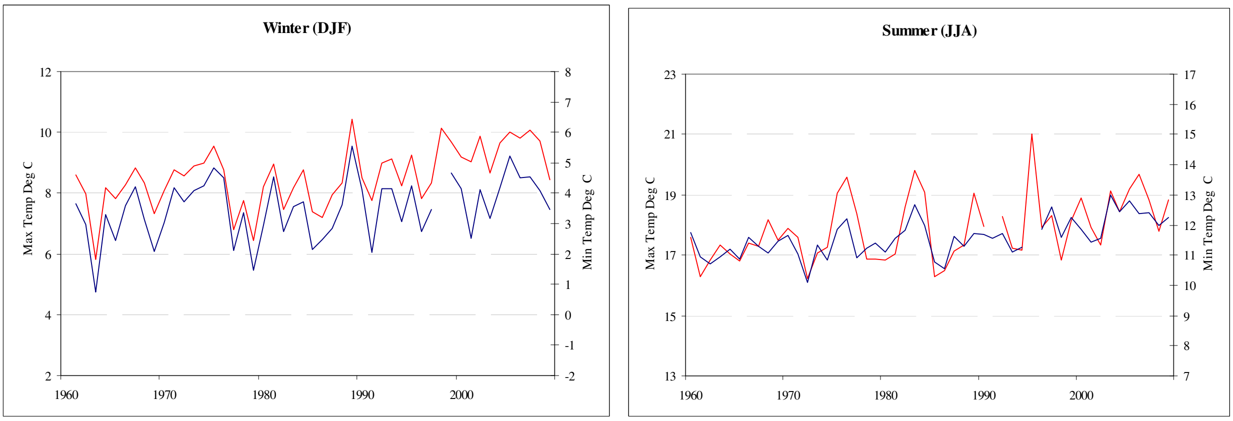


Figure 8: Winter (DJF) and summer (JJA) mean maximum and minimum temperatures for 1960–2009 at Furnace. Red line = mean maximum temperature and blue line = mean minimum temperature. Gaps relate to missing data due to equipment fault in late 1990s.

Table 5: Summary results for extreme temperature indices. Values change over period 1960–2009. tx90 = hot-day threshold, tn10 = cold-day threshold, tfnd = number of frost days, hwd = heatwave duration, tx90per = percentage frequency of extreme high (above 90th percentile) temperatures and tn10per = percentage frequency of extreme low (below 10th percentile) temperatures (* indicates significance at the 95% level, ** indicates significance at the 99% level). All values have been rounded to the nearest 0.1°C.

	Mean	Max.	Min.	DTR	tx90	tn10	tnfd	hwd	tx90per	tn10per
	°C	°C	°C	°C	°C	°C	days	days	% days	% days
Winter (DJF)	1.7**	1.8**	1.1*	0.6*	1.3**	1.6*	-8.9	3.5**	17.0**	-9.5*
Spring (MAM)	1.8**	1.8**	1.0*	0.8*	2.6**	0.5	-1.1	4.0**	19.5**	-4.5
Summer (JJA)	1.5**	1.6**	1.3**	0.3	1.7*	0.9*	---	2.2	8.0	-5.0*
Autumn (SON)	1.4**	1.4**	0.9*	0.5*	1.3**	1.3*	---	2.2*	15.0**	-0.5
Annual	1.5**	1.6**	1.0**	0.6**	1.9**	1.0*	-8.9*	4.6**	15.0**	-5.0**

Analysis of extreme temperatures also indicated an increase in hot-temperature related indices and a decrease in cold-temperature related indices. This was particularly apparent during the spring and winter. In spring the hot-day threshold (tmax 90th percentile) increased by 2.6°C over the period; however, no significant increase in cold-day threshold (tmin 10th percentile) was found for this season, indicating that warming in spring is confined to the upper end of the temperature distribution. In winter, both the hot-day threshold and cold-day threshold were found to have increased significantly, by 1.3°C and 1.6°C respectively, indicating that warming in this season is occurring at both the upper and lower ranges of the temperature distribution. This is further seen in winter with an increase in frequency of extreme high temperatures (number of days where maximum temperatures exceed the 90th percentile) and a decrease in the frequency of extreme low temperatures (number of days where minimum temperatures go below the 10th percentile). In spring there was a significant increase in the extreme high temperature, but a non significant decease in extremes of low temperature. These changes indicate not just a trend of increasing temperature, but also a change in the frequency distribution with warmer warm-periods lasting longer as well as warmer, less frequent cold-periods.

2.6.2. Precipitation indicators: mean precipitation and intensity

An increase in the frequency and intensity of extreme precipitation in winter and annually was found to have occurred at Furnace over the 50-year period 1960–2009. In winter there was an increase of 3.3 events over the period analysed, while an analysis of the annual precipitation records indicated an increase of 7.5 events. While an increase in extreme precipitation frequency and occurrence was found to have taken place, no significant trends were found to have occurred in seasonal mean precipitation. A small significant increase of 0.01 mm/year in mean precipitation was found in the annual precipitation records ($p = 0.023$; Figure 9).

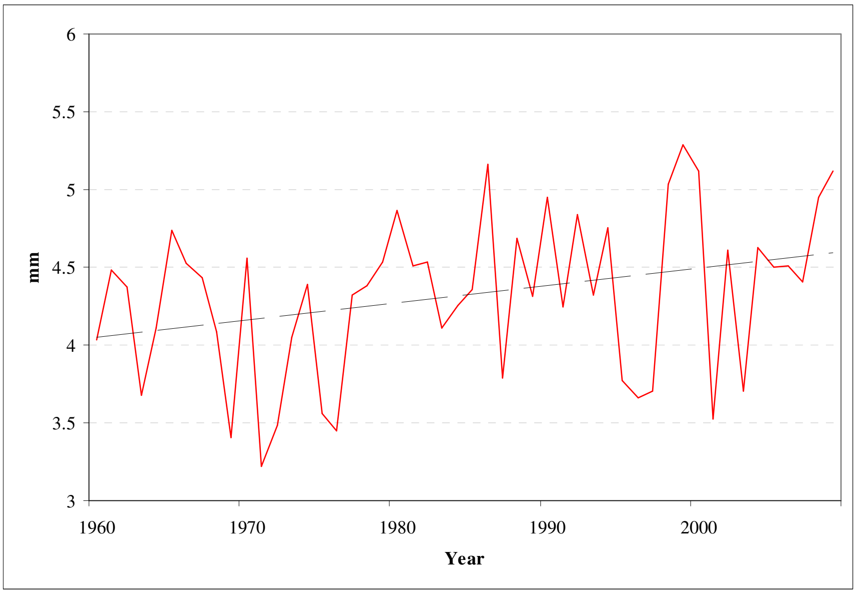


Figure 9: Increasing trend in annual average rainfall over the period 1960–2009.

The intensity of heavy rainfall (90th percentile of rain-day amounts) was also found to have increased in winter and annually. This result is consistent with the findings of McElwain and Sweeney (2007) who found that extreme rainfall intensity has increased in the west of Ireland. Although increases were seen in all seasons, the only significant change was found in the annual records that displayed an increase of 1.19 mm/day over the period ($p = 0.03$; Figure 10).

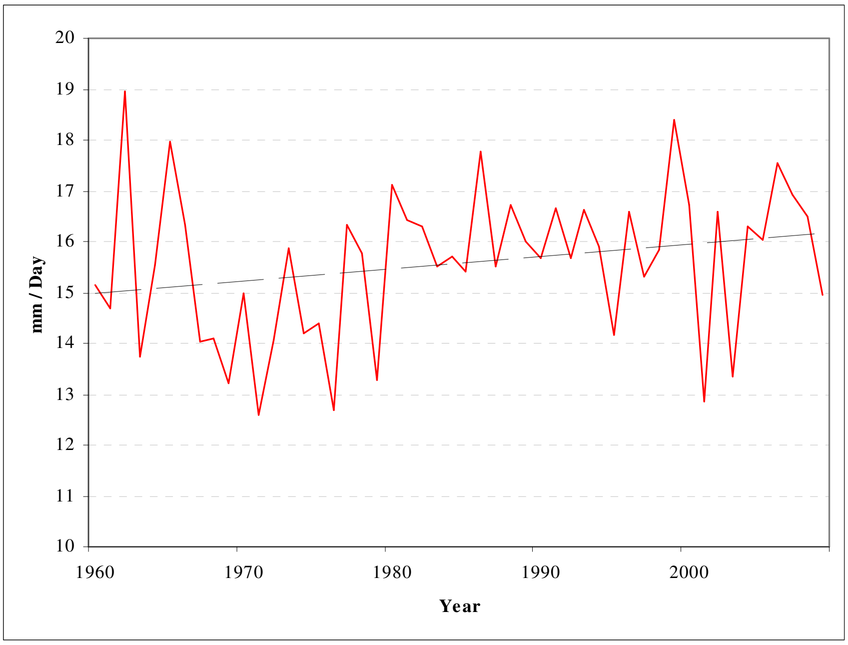


Figure 10: Significant increases in 90th percentile of annual rain-day amounts over the period 1960–2009.

2.6.3. Lake Water Temperature

An analysis of annual midnight lake water temperatures from the catchment indicate the occurrence of a cool period from the early 1960s to 1970s, which was followed by warmer temperatures from late 1970s–1980s. Cooling in the mid 1990s was followed by a period of overall higher temperatures until present. Seven of the 10 warmest years on record occurred since 1990, of which four were recorded in the 1990s and three in the 2000s. A notable feature of the midnight lake water temperature record was the occurrence of an anomalously high value in the spring of 1990 (+3.6°C) which represented the highest water temperature anomaly for all seasons over the period of record.

Trends in midnight lake water temperature were examined for each season and annually for the period 1960-2009. An increase in midnight lake water temperature was found to have occurred in all seasons and annually. The greatest seasonal increase in midnight water temperature was found to have occurred in winter and spring with an increase of 1.8°C ($p<0.01$). The smallest increase occurred during autumn (1.1°C, $p<0.01$) and summer (1.2°C, $p<0.01$) (Figure 11). Annually midnight water temperature increased by 1.3°C ($p<0.01$).

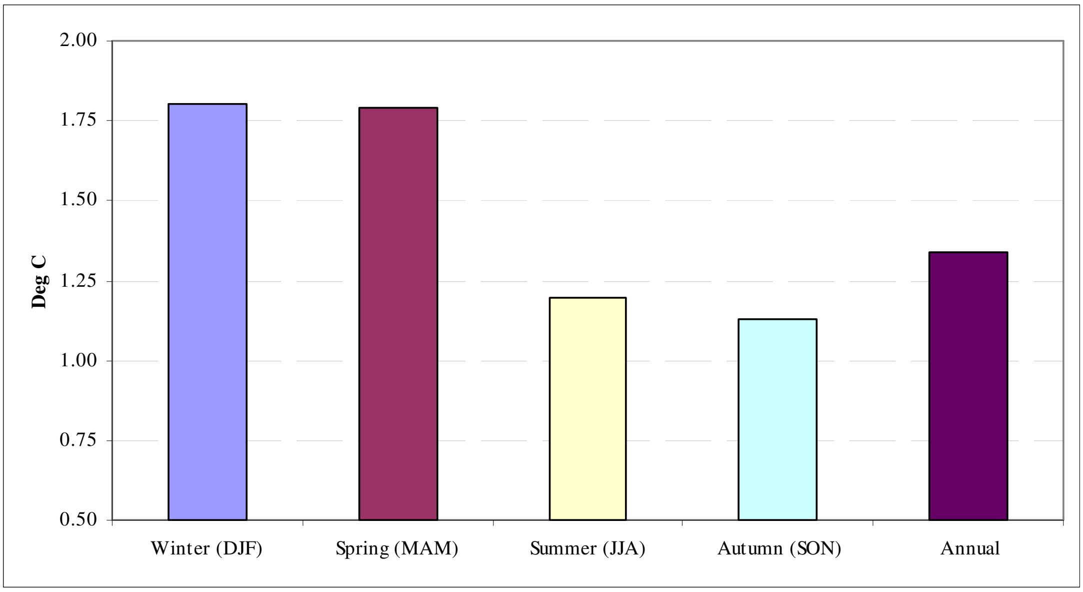


Figure 11: Increases in midnight water temperatures for each season and annually over the period 1960-2009. All results are significant at 99% level. Note Y-axis scale.

2.7. Key Results

- Air temperatures were found to have increased significantly at Furnace over the 1960–2009 period. This increase is apparent in both maximum and minimum temperatures, with maximum temperatures increasing more than minimum in all seasons and annually. Temperature increase is particularly evident in winter and spring which have seen an increase in maximum temperature of 1.8°C over the period of record.
- The diurnal temperature range (DTR) has also increased, contrary to global trends for this index. However, significant regional variations can occur in the diurnal temperature range with contradictory trends apparent within regions.
- The frequency distribution of temperature was also found to have changed, with warmer hot days now and an increase in the number of consecutive hot days while cold days have become warmer but less frequent.
- Indices relating to warming, for instance, heatwave duration, hot-day threshold, cold-day threshold, have increased, while those relating to cooling, for example, number of frost days have decreased.
- There has also been an increase in the frequency and intensity of annual extreme precipitation, similar to changes found in the UK, Europe and other extra-tropical regions around the globe.
- Midnight lake water temperatures increased in all seasons and annually over the 1960-2009 period. The greatest increase was found in winter and spring with an increase of 1.8°C and 1.79°C respectively.

3. CLIMATE AND WATER QUALITY IN THE BURRISHOOLE CATCHMENT

3.1. River Water Temperature and Salmonids

Fish responses to changes in temperature are complex because of their ability to adapt to higher temperatures, and because of confounding factors such as increased susceptibility to disease and additional temperature-related changes in their habitats. The latter include, for example, changes in the DO concentration of water, primary production levels and prey availability (Magnuson and Destasio, 1997; Whitehead et al., 2009). The timing of any change in water temperature is particularly important, as the occurrence of extreme temperature events may coincide with critical life stages in fish development (Elliot, 1991; Byrne et al., 2003; McGinnity et al., 2009).

The response of aquatic ecosystems in general and salmonid species in particular, to climate change is still unclear, but will likely differ on a regional basis and by species. Some sensitive coldwater-adapted fish, such as brown trout, may encounter RWTs close to their thermal limits, while more flexible coldwater species like Atlantic salmon may not be as strongly affected or may adapt to temperature changes (Graham and Harrod, 2009). There is, however, clear observational evidence that changes in water temperature affect salmonid fish species at all life stages through influences on phenology, growth, and metabolism. Atlantic salmon and brown trout exhibit distinct thermal tolerances during each life-cycle stage, with the tolerances for salmon being about 3°C higher than the corresponding values for trout (Elliott, 1991). In addition, major phases of fish development, such as egg hatching, parr growth, smoltification, and migration are linked directly with specific ranges in water temperature (Table 6).

The highest temperature limits for feeding and survival of any salmonid species have been recorded for Atlantic salmon parr (Elliott, 1991; Crisp, 1996). In laboratory studies of salmon from two northern England populations, Elliott (1991) showed that the upper mean incipient lethal level (survival over 7 days) for acclimatised parr was 27.8°C $\pm$ 0.2°C and that the lower incipient level was below 0°C. The tolerance range varied according to the acclimation temperature of the parr – parr acclimatised in warmer water tolerated higher water temperatures at the upper extreme, for example, but could not tolerate the coldest water at the lower extreme. Although fish can survive at these extreme temperatures, the optimum temperature ranges for growth have been defined as 16°C to 19°C for Atlantic salmon

(Peterson and Martin-Robichaud, 1989) and 13°C to 14°C for brown trout (Elliott, 1975), with the lower limit for growth occurring around 7°C to 9°C for both species (Allen, 1969).

Table 6: Selected thermal tolerance limits for Atlantic salmon (*S. salar*) and brown trout (*S. trutta*).

Parameter	Atlantic salmon *S. salar* (°C)	Brown trout *S. trutta* (°C)	References
Ultimate lethal level (parr)	30–33	26–30	Elliott, 1991; 1981
Upper incipient lethal temp. (parr)	25–28	22–25	Elliott, 1991; 1981
Lower critical range (parr)	0–7	0–4	Elliott, 1994
Seek refugia (parr)	<9 and 22–24	<9, undefined	Gardiner, 1984; Cunjak et al., 1993
Egg hatching	2.4–12	1.9–11.2	Crisp, 1982
Feeding (parr)	7–22.5	4–19	Elliott, 1991; 1981
Optimum growth (parr)	16–19	13–14	Peterson and Martin-Robichaud, 1989; Elliott, 1975
Smolt run	5.5–15.5	5–13	Byrne et al., 2003

Recent studies on Atlantic salmon have also shown that changes in water temperature during key seasons can have significant effects on fish growth and survival. For example, McGinnity et al. (2009), using data from the Burrishoole catchment, found that higher water temperatures in the first winter when eggs are incubating in gravel beds and during the second winter when fish are in the parr stage had negative impacts on survival. Higher temperatures in the first winter may be problematic because earlier hatching in a warmer winter is not always correlated with earlier phytoplankton or zooplankton production; hence, hatchlings face insufficient food supply. In the case of parr survival, higher water temperatures increase fish metabolism, so juvenile fish may deplete their energy reserves before the spring food supply becomes available (McGinnity et al., 2009). Similarly, earlier, more rapid increases in RWT can lead to faster growth and earlier smoltification of juvenile salmon and migration to sea, but before an adequate food supply is available in the marine environment (Zydlewski et al., 2005).

3.1.1. Observed changes in RWTs in the Burrishoole catchment

River water temperatures in the Burrishoole catchment are influenced by the temperate, maritime climate of the region. In an analysis of high-frequency RWT data from six sites in the catchment over the 2004–2007 period, maximum daily mean RWT was found to have exceeded 20°C in less than 1% of days (Table 7). While high-frequency (2-minute) RWT readings did show maxima and minima beyond the thresholds presented in Table 6 (temperatures of 34.9°C and -0.7°C were recorded in the high-frequency data for the Black river, for example), these values reflected rare and extreme events. In the Glenamong river, the site experiencing the highest annual mean RWT in the catchment, water temperature exceeded 20°C and 25°C in only 1.66% and 0.12% respectively of all 2-minute high-frequency measurements.

Table 7: Maximum and minimum daily mean river water temperature (RWT) values recorded at each of six sites in the Burrishoole catchment. Daily mean values were calculated from high-frequency data. Table also shows counts of the number of days with mean RWT above 20°C and the percentage of days with mean RWT over 20°C.

	Altahoney	Black	Goulaun	Glenamong	Glendahurk	Tarsaghaun
Date	18/07/06	10/06/07	18/07/06	13/07/06	10/06/07	18/07/06
Max. temperature (°C)	18.5	22.5	20.8	21.4	22.0	21.9
Date	07/02/07	07/02/07	07/02/07	02/02/07	04/01/08	08/02/07
Min. temperature (°C)	2.3	2.4	2.0	1.4	2.6	1.8
No. of days over 20°C	0	10	4	8	18	3
Total number of days	1073	1372	1282	1288	1457	1455
% of days over 20°C	0.00	0.73	0.31	0.62	1.24	0.21

Both the Altahoney and the Goulaun rivers showed different RWT behaviour than other sites in the Burrishoole catchment. Water temperatures in the Altahoney were consistently lower, particularly in warm seasons, due to the location of the temperature logger in a deep, shaded pool (Figure 12). The Goulaun exhibited a more smoothed daily temperature record because it is influenced by an upstream lake. These two sites are important in terms of fish growth and survival because deep pools and stream reaches with buffered temperatures have been shown to serve as cooler water refuges for fish during episodes of extreme temperatures.

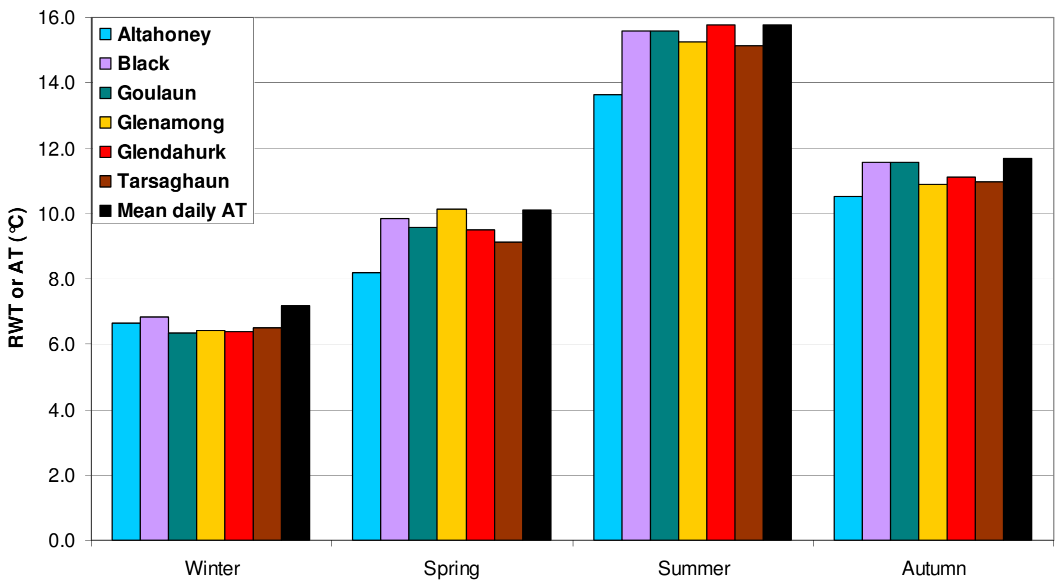


Figure 12: Mean daily river water temperature (RWT) for each season for the six Burrishoole catchment sites over the period 2004–2007, together with mean seasonal air temperature (AT) recorded at the Millrace Meteorological Station.

A very high degree of spatial coherence in RWT was observed for the remaining monitoring sites in the Burrishoole catchment (Figure 12). A more detailed analysis of coherence on a seasonal basis showed that the highest coherence occurred in winter (monthly mean r2 >92%), while the lowest coherence was in the spring and summer (r2 = 74% to 96%). Of the rivers included in the analyses, the Glenamong was the most representative of the catchment mean RWT, while the Black river was the least. The low level of coherence for the Black river with the catchment mean may be because the logger was in the slow-flowing final stretch of the river above Lough Feeagh. All other loggers are situated in fast-flowing upland streams.

3.2. Dissolved Oxygen Habitat Requirements for Salmonids

Fish in general and salmonids in particular are extremely sensitive to low DO concentrations (Alabaster and Gough, 1986; Crisp, 1996; Armstrong et al., 2003; Solomon and Sambrook, 2004; Youngson et al., 2004; Greig et al., 2007). Stream DO concentration is a function of water temperature, together with rates of in-stream primary productivity and decomposition of organic carbon. Inputs of carbon from human-related pollution (e.g. silage, slurry and sewage effluents) are not considered to be a major factor in the Burrishoole catchment; however, peat soils do produce large amounts of coloured DOC compounds. Decomposition of DOC can result in lower oxygen levels in streams and can also decrease levels in deep lake waters, that is, below the thermocline, providing a refuge for prey species less sensitive to oxygen availability than fish (Wissel et al., 2003).

The solubility of oxygen is governed by atmospheric and hydrostatic pressure, turbulence, and temperature (Wetzel, 2001). The relationship with temperature is non-linear with solubility increasing considerably in colder water (Wetzel, 2001). Freshwater is considered to be saturated at 14.6 mg O_2 L^{-1} at 0^{o}C. Super-saturation can also occur when the concentration exceeds the equivalent atmospheric pressure during periods of high primary productivity or water turbulence. Dissolved oxygen also exhibits a diurnal cycle driven by photosynthesis and respiration. This cycle is most evident during summer months and results in the lowest DO levels occurring at night (Wetzel, 2001).

Dissolved oxygen habitat requirements for fish vary considerably by fish species and life stage (Table 8) (Alabaster and Lloyd, 1982; Crisp, 1996; Louhi et al., 2008). Fish sensitivity to DO levels is also significantly affected by other water quality parameters, such as temperature (Bilby, 1984; Crisp, 1996; Matthews and Berg, 1997), flow velocity (Grieg et al., 2007), and the amount of silt in the water column (Chapman, 1988; Louhi et al., 2008). Greig et al. (2007)

demonstrated that the mortality of salmonid eggs in redds was not dependent on the oxygen content of water alone, but also on flow velocity of water through redds. Similarly, Chapman (1988) noted that the infiltration of fine sediments into river bed gravels reduced the permeability of salmonid redds and lowered the oxygen supply to developing ova, resulting in an increased mortality of eggs. As a result, many researchers have defined salmonid habitat quality by ranges of DO concentration, rather than as absolute thresholds associated with fish mortality or specific sub-lethal effects (Marty et al., 1986 in Crisp, 1996; Kondolf, 2000; Armstrong et al., 2003; Greig et al., 2007) (Table 8).

Table 8: Habitat requirements for Atlantic salmon and brown trout as defined by dissolved oxygen (DO) concentrations.

Salmonid life stage	DO (mg L^{-1}) Habitat requirement	Species	References
Early eggs	0.8	Salmon	Lindroth (1942) from Louhi et al. (2008)
Eyed eggs	2.0–2.5	Salmon	Marty et al. (1986); Crisp (1996)
Eggs near hatching	4.0	Salmon	Crisp (1996)
Critical level for egg survival in redds	5.0	Salmon	Greig et al. (2007)
Critical level for egg survival in redds	>83% saturation	Trout	Witzel and MacCrimmon (1983)
Hatching eggs	5.0–7.0	Salmon	Crisp (1996)
Hatching eggs	7.1–10.0	Salmon	Lindroth (1942), Hayes et al. (1951) from Louhi et al.(2008)
Alevins	2.0–8.0	Salmon; trout	Kondolf (2000)
Critical level for adults	3.0	Salmon; trout	USEPA (1986)
Spawning adults	5.0 (50th percentile), 2.0 (5 percentile)	Salmon; trout	Alabaster and Lloyd (1982)
Optimum conditions for adults	9.0 (50th percentile), 5.0 (5th percentile)	Salmon; trout	Alabaster and Lloyd (1982)

Oxygen deficit has been observed to affect many aspects of fish physiology and ecology – causing, for instance, reduced growth, premature hatching, changes in morphology, decreased reproductive success, slowed activity, and increased predation risk (Crisp, 1996; Armstrong et al., 2003; Graham and Harrod, 2009). Oxygen consumption per unit of body weight decreases as fish size increases (Crisp, 1996). Fish oxygen demands also increase as metabolic rates rise with water temperature (Pörtner, 2001). Most relatively unpolluted upland streams, like those in the Burrishoole catchment, tend to be fast flowing with high turbulence, and hence have sufficient DO concentrations to support fish life (Sinokrot et al., 1995). Since the solubility of oxygen in water is temperature dependent, however, projected increases in stream water temperature may be accompanied by decreases in stream DO concentrations (Graham and

Harrod, 2009). Some studies have suggested that increased fish metabolism and oxygen consumption may become problematic when DO contents of surface waters are already depleted and this may lead to habitat restrictions or increased fish mortality (Caissie, 2006).

High-frequency measurements of stream DO concentrations are available from *in situ* monitoring stations at several sites in the Burrishoole catchment. Trends in DO concentrations in the Glenamong river were assessed for the period of September 2005 to November 2006. Dissolved oxygen concentrations showed a distinct seasonal pattern, with values above 12 mg DO L^{-1} between October and May and between 8 and 12 mg DO L^{-1} for the months of June to September, when temperatures and DOC levels were higher. The minimum daily mean DO value was 6.9 mg DO L^{-1}, recorded on 7 June 2006, while the minimum high-frequency value on that date was 5.3 mg DO L^{-1} and was registered at midnight. Dissolved oxygen levels were strongly dependent on RWT throughout the year (Figure 13). The dependence of DO solubility on temperature alone explained between 75% and 90% of the variability between September and May. In the months between June and August 2006, DO concentrations were still highly dependent on RWT, but were also related to rising DOC levels. Dissolved oxygen levels were not dependent on flow in any month during the 2005 to 2006 record.

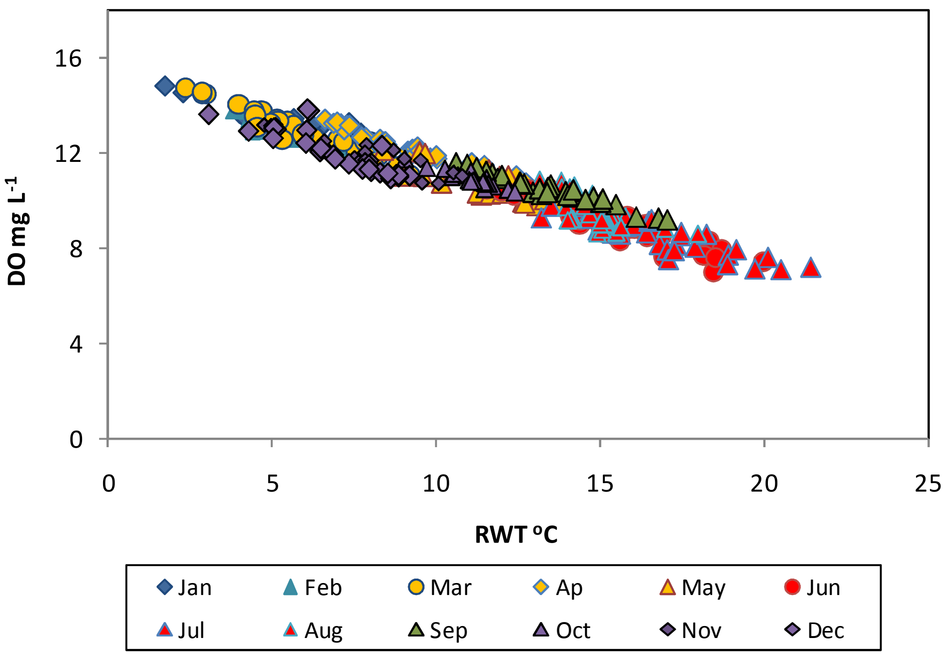


Figure 13: Dissolved oxygen (DO) concentrations (mg L^{-1}) in the Glenamong river, January–December 2006 plotted against river water temperature (RWT) for each month.

3.3. Episodic Acidification and Local Weather

pH is a measure of the concentration of acidifying ions (e.g. H^+, hydrogen ion) in a solution. The pH scale is based on the logarithm of the reciprocal of hydrogen ion. The lower the pH value, the higher the H^+ ion concentration. It is important to note that since the pH scale is a logarithmic scale, a drop of one pH unit at the higher (e.g. alkaline) end of the scale is equivalent to a much larger drop than one pH unit at the lower (acidic) end of the scale. This can have a large effect on aquatic ecosystems as a drop in pH of already acidic water (e.g. pH 5) is a much more significant increase in acidity than the same pH drop in neutral (e.g. pH 7) waters. Acid deposition, associated with increases in industrial emissions during the latter half of the twentieth century, was linked with decreases in stream pH and associated fish mortality at sites throughout Europe and North America. Stream pH in areas not affected by atmospheric pollution from acid deposition is primarily a function of catchment geology and soil processes (Davies et al., 1992). The pH of surface waters is usually lower than pH 7 in areas with acid geology and acid soils (e.g. granite bedrock or upland peat soils). Streams running through areas with basic geology (e.g. limestone bedrock) will normally have a neutral or basic pH, above pH 7.

The lowest (most acidic) pH values recorded in streams are generally *c.* pH 4, but these values are extreme. Most of the extreme low values have been measured in stream-draining areas of upland bog in Sweden, Finland, Scotland, and Wales, often in catchments with non-calcareous bedrock and a high percentage of coniferous forest (e.g. Laudon et al., 2004; Monteith and Evans et al., 2005; Kowalik et al., 2007; Buffam et al., 2008; Ormerod and Durance, 2009). These areas have been affected by transboundary acid deposition as a result of fossil fuel burning in locations that are often remote from the site. They also tend to have natural acidity and poor buffering capacity because of acid bedrock and soils, while the scavenging of H^+ ions from polluted air is exacerbated by the presence of coniferous trees (Evans and Monteith, 2001; Davies et al., 2005).

Maritime regions of western Europe, in particular, have been severely affected by acidification. Large rainfall volumes have magnified anthropogenic sulphur (S) and nitrogen (N) deposition onto poorly buffered soils and surface water bodies (Ormerod and Durance, 2009). In Wales, for example, over half of the 24,000-km stream network has been acidified to pH values between 4.0 and 5.7, with lower values occurring during peak acid episodes (Edwards et al., 1990). In Ireland, the impacts of acid deposition have been greatest in naturally occurring acid-sensitive waters chiefly located in areas with acid bedrock, and including the Burrishoole catchment (Aherne and Farrell, 2000; Allott and Brennan, 2000). The acidification of stream waters constitutes a considerable pressure on aquatic ecosystems, causing loss of species at all trophic levels, including the collapse of entire salmonid populations in severely acidified catchments (e.g. Milner and Varallo, 1990; Hesthagen et al., 1999).

Salmonid fish species, such as Atlantic salmon and brown trout, are very sensitive to low pH stream water (Table 9). Exposure to acidic waters has a wide range of effects on salmonids, from delayed hatching of eggs, decreased feeding and slowed growth of fry (Atlantic Salmon Trust, 1991); to tail deformities in adults (Campbell, 1987); migration of fish to higher-pH refugia (Baker et al., 1996); and increased mortality of all life stages (eggs to adults) (EIFAC, 1969; Baker et al., 1996; McCartney et al., 2003; Finn, 2007; Monette and McCormick, 2008).

Table 9: Approximate ranges of pH observed to cause negative effects on Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*).

pH range	Effect on salmonids	References
3.0–4.0	Range lethal to all salmonids	EIFAC (1969) Atlantic Salmon Trust (1991)
4.0–4.5	Total mortality of salmonid eggs, alevins, and fry	EIFAC (1969) Atlantic Salmon Trust (1991)
<5.0	Increased mortality of alevins	Atlantic Salmon Trust (1991)
	No nest digging by female trout	Kitamura and Ikuta (2001)
<5.2	Triggers migration of all species to refugia	Baker et al. (1996)
	Inability of fry to feed	Atlantic Salmon Trust (1991)
<5.5	Prevention of egg hatching	Peterson et al. (1980)
	Decreased abundance of salmonid smolts	Monette and McCormick (2008)
<6.5	Toxic effects for embryos – reduced fertilisation, lower embryonic growth	Finn (2007)
	No nest digging by female salmon	Kitamura and Ikuta (2000)
6.5–8.5	Maximum productivity for salmonids	Orsanco (1955) in EIFAC (1969)

Although concentrations of atmospheric S and N, and hence acid deposition, have been reduced in the last few decades, the recovery of UK surface waters from acidification has been sporadic and inconsistent in terms of pH increase or the reappearance of acid-sensitive taxa (Davies et al., 2005; Monteith et al., 2005; Ormerod and Durance, 2009). Kowalik et al. (2007) showed that periodic acid episodes in acid-sensitive areas of Scotland and Wales prevented the return of acid-sensitive organisms even in streams where mean pH had increased to circumneutral levels. Conversely, across a 250,000-km^2 expanse of northern Sweden, a 65% decline in sulphur deposition between 1970 and 1990 reduced the area of chronically acidified spring floods by 75% (Laudon and Bishop, 2002). Although it was long thought that chronic acidification of streams was the most significant threat to biodiversity, it is now believed that episodic acidification, single or recurrent low-pH episodes lasting hours to several days, is a major cause of slowed recovery from acidification in both the UK and Scandinavia (Kowalik et al., 2007; Laudon, 2008) and a possible contributor to the decline of the Atlantic salmon population (Monette and McCormick, 2008).

Acid episodes in upland areas most commonly occur during heavy precipitation and flooding events and have been linked to the flushing out of historical S and N oxides derived from fossil-fuel burning, the inputs of natural organic acids (e.g. humic acids) derived from the degradation of peatlands and the deposition of sea-salts in maritime regions (Davies et al., 1992; Farrell et al., 1998; Evans and Monteith, 2001; Kowalik et al., 2007; Laudon, 2008; Vuorenmaa and Forsius, 2008; Ormerod and Durance, 2009). The degree to which acid deposition is modified by the vegetation, soils, and geology of a catchment is dependent upon the length of time that acidic water has been in contact with the physical catchment features (e.g. the buffering capacity of ion-exchange with limestone bedrock). During storm events, a large percentage of event water enters surface water bodies through overland flow or percolation into the topsoil. This rapid flow allows for only minimal soil/water contact, resulting in negligible buffering capacity, and hence 'pulses' of acidity to streams (Davies et al., 1992; Wigington et al., 1996; Lawrence, 2002).

3.3.1. Association between episodic acidification and weather types

High-frequency pH data are available from *in situ* monitoring stations that have been located on river sites in the Burrishoole catchment since 2003. These data were used to assess the relationship between low pH events and both regional weather conditions and high river flows. Weather on the date of acid episodes and in the periods leading up to acid episodes in the Glenamong sub-catchment of the Burrishoole was classified using the Lamb-Jenkinson weather type (LJWT). This classification of weather types describes weather patterns across the region of Britain and Ireland. Originally based on subjective analysis of daily synoptic charts (Lamb, 1972; Jenkinson and Collinson), it was later automated to classify weather types based on grid-point mean sea-level-pressure differences around Britain and Ireland (Jones et al., 1993).

The majority of low-pH events in the Glenamong river occurred on days dominated by southerly (S) (31%) or westerly (W) (34%) weather types, reflecting an association with high rainfall when the main airflow is coming in from the Atlantic. In contrast, the dominant LJWT type on the weekly, fortnightly, and monthly run-ups to low pH events was anticyclonic (A). This pattern was observed in 30% of weekly run-ups, in 41% of fortnightly run-ups, and in 45% of monthly run-up periods. The frequency of A weather-type in all run-up periods was greater than expected when compared with the long-term LJWT record. This was in agreement with earlier studies in the west of Ireland that attributed an association between low pH episodes and antecedent A conditions to the dry deposition of pollutants from eastern Ireland and Britain (e.g. Allott and Brennan, 2000). These acidifying pollutants build up in the soil during periods of dry easterly weather; they are then washed from the soil when rainfall occurs. These results imply that, despite regional reductions in emissions levels, such deposition is still occurring during periods of easterly air flow.

High-resolution pH data from the Glenamong river were examined from 2005 to 2009 to assess both the magnitude and nature of acid episodes in the river. The minimum and maximum high-frequency pH values recorded in the Glenamong over 2008 to 2009 were pH 3.90 and pH 7.04 respectively. That range in pH was found to be comparable to other upland, peaty catchments in Ireland, the UK, Sweden, and the north-east USA. Daily mean pH values ranged from pH 4.04 to pH 6.81, with the highest frequency of measurements falling between pH 6.00 and pH 6.50. The daily mean pH in the Glenamong river was less than or equal to pH 5.50 for 45% of the 2008 to 2009 record. Increased mortality and other sub-lethal effects on salmonids have been observed when fish are exposed to waters with pH less than 5.50, indicating that salmonids in the Glenamong river may periodically be exposed to potentially harmful low pH levels. The low-pH events documented in the Glenamong river occurred both as single and multiple depressions in pH, ranging in magnitude from 0.50 to 2.30 pH units. Acid episodes in the Glenamong most commonly occurred on days dominated by westerly and south-westerly (precipitation-bearing) weather over the Burrishoole catchment when the river was experiencing high flows. Of the 10 low-pH events analysed in the 2008 to 2009 record in the Glenamong river, 6 occurred as single drops in pH and 4 were composed of multiple decreases in pH over 1- to 2-day periods. Recovery to pre-episode pH after the multiple-drop events was complete after 3.5 to 7 days.

Critical ranges of pH observed to have negative effects on salmonid species are listed in Table 10. An analysis was conducted on the frequency of Glenamong river daily mean pH measurements within these thresholds (Table 10). No daily mean pH values of pH 3.0 to pH 4.0, the range lethal to all salmonid species and life stages, were recorded in the Glenamong river during the October 2008 to October 2009 period. Only 17% of Glenamong daily mean pH readings fell between pH 4.5 and pH 5.0, the range where total mortality of salmonid eggs, alevins, and fry is observed (EIFAC, 1969; Atlantic Salmon Trust, 1991). A more significant 45% of daily mean pH readings were below the threshold of pH 5.5, the level of acidity below which marked deleterious effects on salmonid fish is observed (Peterson et al., 1980; Atlantic

Salmon Trust, 1991; Monette and McCormick, 2008). This suggests that fish in the Glenamong river may have been exposed to potentially harmful levels of acidity for 45% of the 2008 to 2009 record.

Table 10: Frequency of pH values recorded in the Glenamong river within critical thresholds for fish survival during the period 30 October 2008–20 October 2009.

pH range	Frequency (%)
3.0–4.0	0.00
4.5–5.0	17.50
<5.5	44.60
>6.0	37.90
>6.5	11.40

3.4. Key Results

- The Burrishoole catchment has a temperate maritime-influenced climate where river water temperatures rarely exceed 23°C in summer and rarely fall below 1°C in winter. Daily mean RWT values within the catchment exceeded 20°C on <1.25% of occasions. However, highest and lowest single RWTs were recorded in the Black river at 34.9°C on 7 June 2007 and -0.7°C on 17 February 2008.
- There was a high degree of coherence across the catchment between RWT measured in different streams. This coherence was higher in winter, with lower coherence occurring in the spring and summer.
- Dissolved oxygen (DO) concentrations in the Glenamong river over the period September 2005 to November 2006 exhibited an expected seasonal pattern, with values above 12 mg L^{-1} between October and May and between 8 and 12 mg L^{-1} between June and September when river temperatures and DOC levels were higher.
- Dissolved oxygen (DO) levels were found to be strongly dependent on RWT throughout the year. The dependence of DO solubility on temperature alone explained between 75% and 90% of the variability between September and May. In the months between June and August 2006, DO concentrations were still highly dependent on RWT, but were also related to rising DOC levels.
- The dominant weather type on the weekly, fortnightly, and monthly run-ups to low pH events was Anticyclonic (A). This result was in agreement with earlier studies in the west of Ireland which attributed an association between low pH episodes and antecedent A conditions to dry deposition of pollutants from eastern Ireland and Britain.

- The 10 low-pH episodes in the Glenamong River in 2008 to 2009 were associated with increased precipitation in the Burrishoole catchment and increased flow. Of the 10 events, 6 occurred as single drops in pH and 4 were composed of multiple decreases in pH over 1- to 2-day periods.
- No daily mean pH values of 3.0 to 4.0 (the range lethal to all salmonid species and life stages), were recorded in the Glenamong river during the October 2008 to October 2009 period. However, 17% of daily mean pH readings in the Glenamong River fell between pH 4.5 and pH 5.0, the range where total mortality of salmonid eggs, alevins, and fry is observed.
- A more significant 45% of daily mean pH readings were below the threshold of pH 5.5, the level of acidity below which a range of deleterious effects on salmonid fish are observed.
- Recovery to pre-episode pH after the multiple-drop events was complete after 3.5 to 7 days.

4. Climate Scenarios for the Burrishoole

4.1. Introduction

Global climate models (GCMs) are the most sophisticated models presently available for studying the complexities of the Earth's climate. These models are physically based, three-dimensional numerical representations of the structure and behaviour of the global climate system. Global climate models account for the complex workings and interactions of various sub-systems of the Earth's climate, including the atmosphere, oceans, sea ice and land-surface processes. Climate models have become a key tool for exploring the possible evolutionary pathways of the climate system under prescribed anthropogenic forcings. Projections from GCM experiments provide a primary source of information used to carry out impacts modelling, to develop climate-change adaptation strategies and to inform future policy planning.

Global climate models are currently run at a relatively coarse spatial resolution, typically of the order of 300 to 500 km^2. Operating at this scale is necessary given the constraints of currently available computing power and the highly dynamic nature of the climate system. At this resolution, the influence of important sub-grid scale features, which have a strong bearing on local climate conditions, cannot be accounted for explicitly. Considering local-scale forcings in any plausible future scenario is particularly important where land–surface conditions significantly influence the characteristics of regional and local climate. This is especially true for regions that present highly heterogeneous environments such as coastal zones, regions with complex topographies and areas with diverse land types (Wilby et al., 2004). Furthermore, their coarse resolution and limited physics prohibits them from resolving important climate processes which occur at a sub-grid scale level (e.g. cloud formation, evaporation, convective rainfall). Many of these processes are either omitted or approximated in the model structure using various parameterisation schemes or empirical approximations. Sub-grid scale processes strongly affect the local climate at the scales of the ecological and human environment and as such are often those with the greatest relevance to impact modellers (Zorita and von Storch, 1999).

4.2. Development of High-Resolution Scenarios

It is widely acknowledged that while GCMs demonstrate skill at reproducing the large-scale features and dynamics of the Earth's climate system, the coarse resolution at which they operate restricts their capacity to provide a realistic description of both the workings and condition of the system at finer spatial scales (Grotch and MacCracken, 1991; Zorita and Von Storch, 1999). This aspect of GCMs severely limits the direct use of their output in local or regional scale impact applications where higher-resolution climate projections are required (Giorgi and Mearns, 1991; Wilby and Wigley 1997; Mc Guffie et al., 1999; Giorgi et al., 2001).

This necessitates 'downscaling' coarse resolution model output to the finer spatial scales relevant for studying the impacts of climate change. This may be to higher-resolution grids (~25 to 50 km) or point-specific locations on the Earth's surface commensurate with instrumental stations. Downscaling is based on the principle that local or regional climate is primarily determined by climate conditions on a much larger scale. Developing models that capture this relationship allows changes in key local-scale climate variables – such as temperature and precipitation – to be explored using low-resolution GCM projections.

Box 3: Special Report on Emissions Scenarios (SRES) illustrating four scenario 'families' (IPCC, 2001 after Nakicenovic et al., 2000).

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, with a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in the other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with a continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Climate scenarios for the Burrishoole catchment were statistically downscaled from grid-scale projections from three GCMs, namely the HadCM3 from the Hadley Centre for Climate Prediction and Research (Met Office, UK); CCGCM2, from the Canadian Centre for Climate Modelling and Analysis (CCCMA) and CSIRO-MK2 from the Commonwealth Science and

Industrial Research Organisation (CSIRO, Australia), each run using two different emission scenarios (A2 and B2) (Box 3).

The models, which link a suite of large-scale atmospheric predictors to local-scale meteorological variables, were empirically derived and independently tested using observed data representing current climate conditions (1961–2000). However, shortcomings and limitations associated with the application of any downscaling technique represent an additional source of uncertainty in local-scale projections of climate change. To address this, and in recognition that no one optimal statistical method exists, both linear regression and generalised linear models (GLMs) were employed to develop future scenarios (Table 11).

Table 11: List of variables and statistical downscaling techniques applied. (* Separate GLMs were developed for both precipitation occurrence and amounts). †Variables discussed in main report.

Variable	Linear regression (SDSM)	Generalised linear regression (GLM)
Temperature (minimum and maximum) (°C)	√	
Precipitation (mm) (*occurrence and amounts)	√	√
†Wind speed (kt)	√	√
Relative humidity (%)	√	
Solar radiation (Mj m^{-2})	√	
†Potential evapotranspiration (PET) (mm)	√	

Linear regression was implemented using Statistical DownScaling Model (SDSM) software, a package used to downscale multiple-scenarios of surface-weather variables at individual sites on a daily time-step using grid resolution reanalysis and GCM data. The model had previously been applied to a host of meteorological, hydrological and environmental assessments within a range of geographical contexts (Hassan et al., 1998; Wilby et al., 1999, 2000; Hay et al., 2000). Statistical DownScaling Model software is best described as a 'hybrid' of the stochastic weather generator and regression-based downscaling methods (Wilby et al., 2002). A key advantage of SDSM is its ability to generate multiple realisations for each variable. In the current study, 100 individual realisation or individual scenario members were developed for each season and variable employing SDSM. While each realisation is deterministic in nature, the addition of a stochastic element offers a significant improvement over more traditional techniques.

A generalised linear model (GLM) was the second method employed – these models can be thought of as a flexible generalisation or expansion of the standard linear regression models. This approach to regression analysis can be used to overcome some of the limitations associated with ordinary least squares regression. Where the conventional linear model requires the response variable to be normally distributed, GLMs have the advantage of being able to model probability distributions from the exponential family (e.g. binomial, Poisson, gamma). As a result of this, the use of GLMs obviates the need for data transformation. This is desirable given the loss of information which can occur when altering a variables distribution through rescaling or normalisation.

All the derived (seasonal and parameter) statistical models were calibrated and validated on observed data (Figure 14; Figure 15). They were then employed in conjunction with an equivalent set of GCM modelled large-scale 'predictors' to provide the downscaled scenarios for the catchment. Changes in each of the downscaled variables are considered over three future time-horizons: the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099), with the model control period of 1961–1990 used to represent baseline conditions. Thirty years is the standard period, as defined by the World Meteorological Organisation (WMO), over which 'climate' is generally defined, allowing for inter-decadal variability to be considered when determining defined changes in the system.

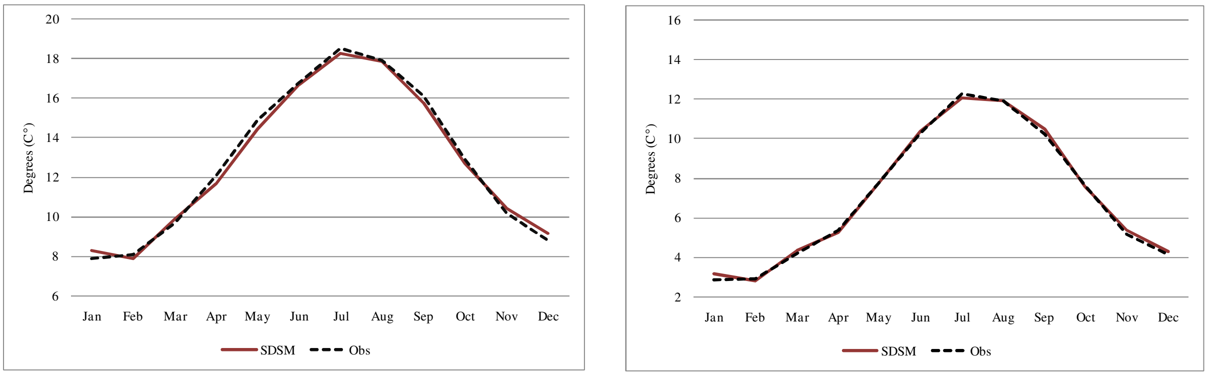


Figure 14: Correspondence between observed and National Centre for Environmental Prediction (NCEP) modelled monthly mean for maximum (left) and minimum (right) temperatures over the independent validation period of 1979–1993.

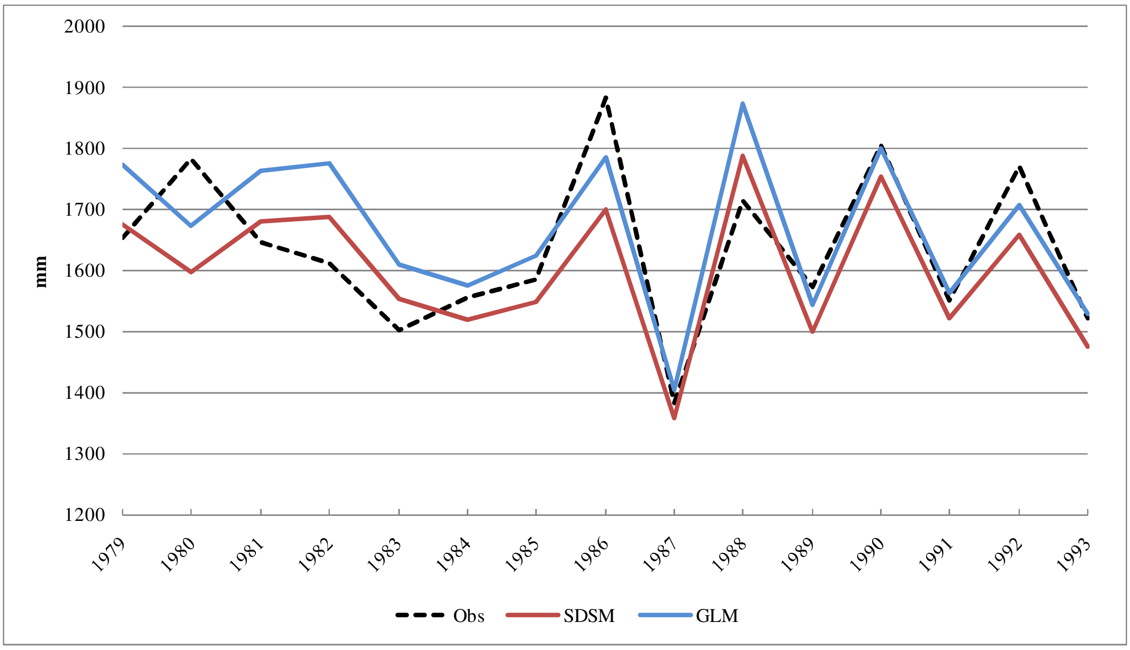


Figure 15: Correspondence between interannual variability for the observed and downscaled precipitation series over the 1979–1993 validation period. SDSM – statistical downscaling model. GLM – Generalised linear model.

4.3. Climate Scenarios

Climate scenarios developed for the Burrishoole catchment suggest that for each season and future time-horizon average temperatures are likely to be higher than reference conditions (1961–1990) with the summer and autumn months projected to experience the greatest absolute increase. Each GCM and emission scenario is in agreement that temperatures are likely to progressively increase through the 21st century with the greatest amount of warming occurring in the 2080s. Although there is a general consensus between the models in relation to temperature rise, inter-model differences exist regarding the exact magnitude and time-evolution of model-projected increases through the century. Significant differences between emission scenarios – i.e. the same model run using different forcing conditions – are notable from the 2050s onwards, and become most apparent over the 2080s for all models. Intra-model differences are also evident with the HadCM3 model generally producing cooler projections when compared to the CSIRO-MK2 and CGCM2 climate models.

Figure 16 shows a comparison between observed mean annual temperature from Furnace weather station, represented as a 10-year moving average over the period 1961–2008, and the downscaled climate scenarios for each GCM and emissions scenario, represented as a 10-year moving average for the model period of 1961–2099. While the warming between both observed and modelled series are consistent for much of the period up to 1990, observed mean annual temperatures increase at a greater rate than suggested by any of the individual GCMs over the period up to 2008.

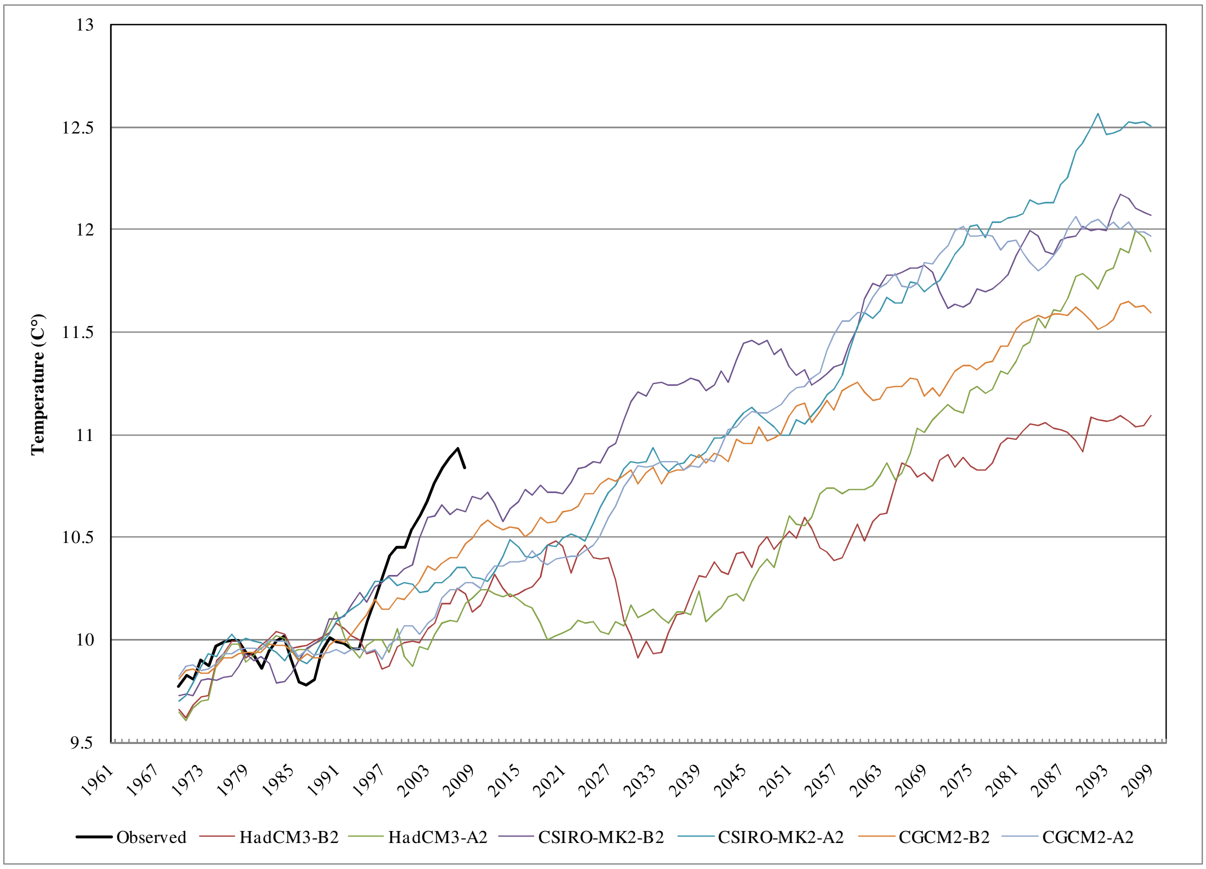


Figure 16: Comparison between observed mean annual temperature data from Furnace (10-year moving average calculated over the 1961–2008 period) and climate scenarios for each GCM and emissions scenario (10-year moving average calculated over the model period of 1961–2099).

4.3.1. Maximum temperature

Table 12 lists the projected changes in mean maximum temperature for each future horizon on a monthly and seasonal basis. Based on the downscaled HadCM3-A2 scenario, average summer maximum temperatures for the 2080s are projected to increase by 1.9°C above the baseline period of 1961–1990. The same downscaled temperature scenario suggests an increase in mean autumn maximum temperatures of 2.3°C. In accordance with this, the downscaled output from the CSIRO-MK2 model and A2 emissions scenario, over the 2080 period, also suggests an increase in mean summer (2.1°C) and autumn (2.8°C) maximum temperatures respectively.

Table 12: Projected changes in mean maximum temperature for each future horizon on a monthly and seasonal basis modelled using output from three GCMs each run using both the A2 and B2 scenarios.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Winter	Spring	Summer	Autumn
HadCM3-A2																
2020s	0.3	0.3	0.3	0.3	0.4	0.3	0.1	0.6	0.4	0.4	0.2	-0.7	0	0.3	0.3	0.3
2050s	1	0.9	0.7	0.7	0.7	0.4	1.2	1	1.5	1.1	0.9	0	0.7	0.7	0.8	1.2
2080s	1.5	1.4	1.8	1.5	1.6	1.3	2.2	2.3	2.4	2.6	1.8	1	1.3	1.6	1.9	2.3
HadCM3-B2																
2020s	0.3	0.6	0.3	0.6	0.3	0.1	0.3	0.6	0.7	0.9	0.6	-0.4	0.2	0.4	0.4	0.7
2050s	0.8	0.2	0.4	0.6	0.8	0.6	0.7	1.1	0.8	1	1.2	0.2	0.4	0.6	0.8	1
2080s	0.8	0.8	0.9	1.2	1.1	1.1	1.2	1.4	1.4	1.9	1.4	0.3	0.7	1	1.2	1.6
CSIRO-MK2-A2																
2020s	0.5	0.5	0.9	1.3	0.6	0.6	0.6	0.6	1	1.1	1.3	0.9	0.6	0.9	0.6	1.1
2050s	1.2	1.2	1.5	1.7	1.5	0.9	1.2	1.5	1.8	1.8	1.9	1.5	1.3	1.6	1.2	1.9
2080s	2.2	1.8	2.6	2.9	2	1.5	2.2	2.4	2.8	2.7	3	2.5	2.2	2.5	2.1	2.8
CSIRO-MK2-B2																
2020s	1.1	1.1	1.3	1.2	0.9	1	0.7	1	1.5	1.2	1.4	0.8	1	1.1	0.9	1.4
2050s	1.5	1.4	1.9	1.7	1.7	1.3	1.2	1.5	2	1.7	2.4	1.4	1.4	1.8	1.3	2.1
2080s	1.8	1.8	2.3	2	1.8	1.3	1.5	2	2.5	2.4	2.8	1.7	1.8	2	1.6	2.6
CGCM2-A2																
2020s	0.6	0.5	0.9	1	1.1	0.9	0.9	0.9	0.8	0.6	0.5	0.8	0.6	1	0.9	0.6
2050s	1.3	1.2	1.8	1.6	1.7	1.5	1.9	1.7	1.8	1.8	1.8	1.4	1.3	1.7	1.7	1.8
2080s	1.4	1.4	2	2.2	2.3	2.2	2.5	2.2	2.5	2.5	2.3	1.8	1.5	2.2	2.3	2.4
CGCM2-B2																
2020s	1	0.7	1	0.9	0.8	0.8	1	0.8	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.8
2050s	1	0.8	1.4	1.5	1.5	1.2	1.5	1.3	1.4	1.3	1.2	1	1	1.5	1.3	1.3
2080s	1	1.2	1.8	2	1.9	1.7	1.8	1.7	2.1	2.1	1.7	1.2	1.1	1.9	1.7	2

Similarly, the temperature scenarios developed using the output from the CGCM2 model, driven using the A2 scenario, indicate an increase in average summer maximum temperatures of 2.3°C with an accompanied increase of 2.4°C for the autumn period. On a monthly basis, model projections suggest that the greatest absolute increase in average maximum temperature is associated with November and April (CSIRO-MK2-A2) with increases of 2.9°C and 3°C respectively.

Figure 17 displays a probability density function, constructed using the downscaled output from each GCM and emission scenario, depicting the projected change in temperature for all months. A progressive increase in temperature through the century is suggested for each month. The spread in the range of projections is much greater for the winter months, and generally increases towards the end of the century as the divergence between the A2 and B2 emissions pathways increase.

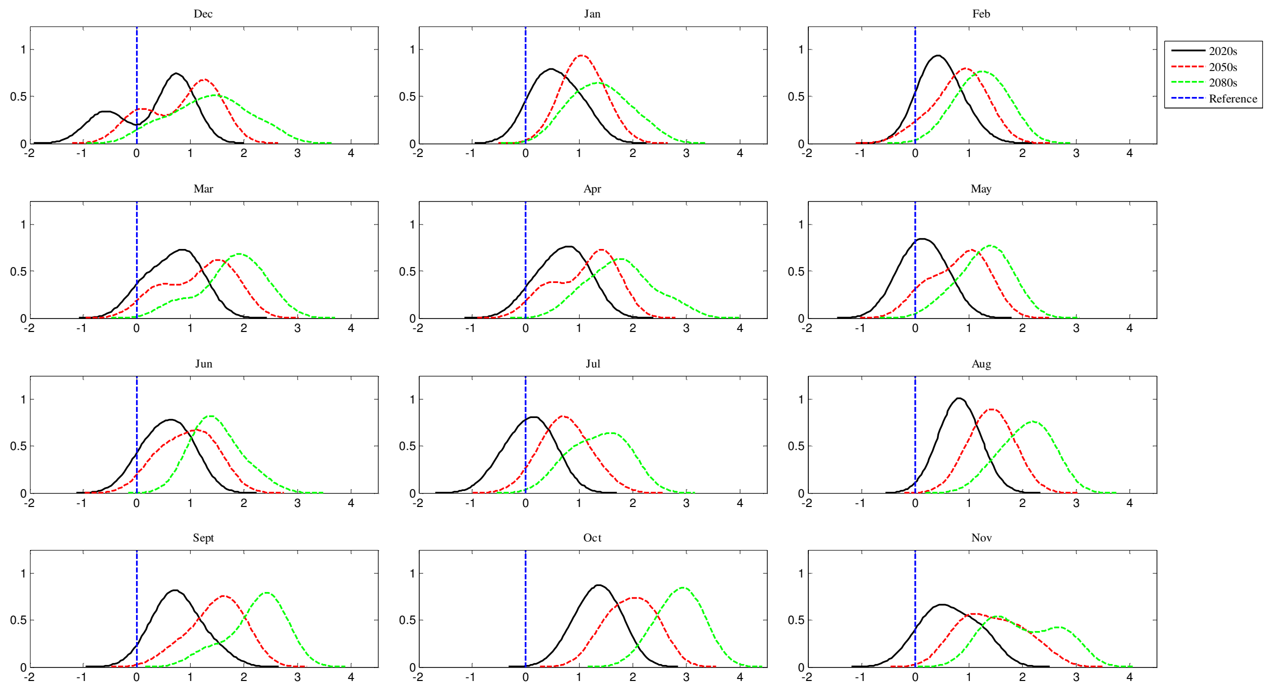


Figure 17: Probability density functions, constructed using the downscaled output from each GCM and emission scenario, depicting the projected change in maximum temperature for all months. The vertical line represents the baseline mean.

4.3.2. Minimum temperature

Projected changes in average minimum temperatures largely follow those exhibited by maximum temperature (Table 13). However, increases for other seasons are more notable. Scenarios derived using the output from the HadCM3 model, forced using the A2 scenario, indicate an increase in average autumn minimum temperatures of 2.2°C for the 2080s. Under this scenario, minimum temperatures for each of the remaining seasons are projected to be 1.6°C to 1.7°C greater than that experienced over the 1961–1990 baseline period. Projected changes in minimum temperature, estimated using the output from the CSIRO-MK2 model, suggest that the greatest warming is likely to occur during the winter, with a 2.7°C increase in average conditions by the end of the century. This increase in winter minimum temperatures is more extreme (3.1°C) when compared against all other seasons and models. According to the downscaled output from the CGCM2 model and A2 emissions scenario, minimum temperatures are projected to experience the greatest increase during the autumn with a 2.3°C increase by the 2080s. For the same horizon this model also suggests that average winter minimum temperatures will increase by 2.1°C compared to the reference period. On a monthly basis the greatest increases in minimum temperature are associated with January (3.3°C) and December (3.4°C), downscaled from the CSIRO-MK2 model under the A2 emissions pathway.

Table 13: Projected changes in mean minimum temperature for each future horizon on a monthly and seasonal basis modelled using output from three GCMs each run using both A2 and B2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Winter	Spring	Summer	Autumn
HadCM3-A2																
2020s	0.4	0.4	0.1	0.3	0.5	0.4	0	0.3	0.4	0.4	0.1	-0.8	0	0.3	0.2	0.3
2050s	1.3	1.2	0.4	0.5	0.7	0.6	0.8	0.8	1.4	1	0.8	0.1	0.9	0.5	0.8	1.1
2080s	1.9	1.7	1.7	1.6	1.7	1.3	1.8	1.8	2.3	2.5	1.8	1.3	1.7	1.7	1.6	2.2
HadCM3-B2																
2020s	0.4	0.7	0.1	0.6	0.5	0.3	0.2	0.3	0.7	0.9	0.6	-0.4	0.3	0.4	0.3	0.7
2050s	1	0.3	0.2	0.7	0.9	0.6	0.6	0.7	0.7	0.9	1.2	0.4	0.6	0.6	0.6	0.9
2080s	1.2	1	0.7	1.2	1.2	1.1	1	1.1	1.4	1.8	1.4	0.5	0.9	1	1.1	1.5
CSIRO-MK2-A2																
2020s	0.8	0.5	0.9	1.2	0.6	0.4	0.5	0.5	0.9	1.1	1.3	1.3	0.9	0.9	0.5	1.1
2050s	1.7	1.5	1.3	1.5	1.4	0.8	1	1.1	1.8	1.7	1.9	2.1	1.8	1.4	1	1.8
2080s	3.3	2.4	2.2	2.5	1.9	1.3	1.8	2	2.6	2.6	2.9	3.4	3.1	2.2	1.7	2.7
CSIRO-MK2-B2																
2020s	1.6	1.6	1.2	1	0.8	0.9	0.6	0.9	1.5	1.1	1.4	1.1	1.4	1	0.8	1.3
2050s	1.9	1.9	1.7	1.5	1.4	1.2	1	1.3	2	1.7	2.4	1.8	1.9	1.5	1.1	2
2080s	2.6	2.4	2.1	1.8	1.5	1.2	1.3	1.6	2.4	2.3	2.8	2.5	2.5	1.8	1.4	2.5
CGCM2-A2																
2020s	0.8	0.6	0.6	0.9	0.7	0.8	0.6	0.7	0.7	0.6	0.5	0.9	0.8	0.8	0.7	0.6
2050s	1.8	1.6	1.5	1.3	1.4	1.4	1.4	1.5	1.7	1.8	1.8	1.8	1.7	1.4	1.4	1.8
2080s	1.9	1.9	1.6	1.8	1.7	1.9	1.9	2	2.4	2.4	2.3	2.6	2.1	1.7	1.9	2.3
CGCM2-B2																
2020s	1.3	1.1	0.7	0.9	0.6	0.7	0.6	0.7	0.8	0.8	0.8	1.1	1.2	0.7	0.7	0.8
2050s	1.3	1	1.1	1.3	1.2	1	1	1.1	1.2	1.3	1.2	1.4	1.2	1.2	1.1	1.2
2080s	1.3	1.5	1.4	1.7	1.5	1.5	1.4	1.5	2	2.1	1.6	1.8	1.6	1.5	1.5	1.9

The combined projections for minimum temperature, represented by the probability density functions in Figure 18, indicate a steady increase in minimum temperatures through the 21st century. Model projections suggest that September, October and November are likely to experience the greatest relative warming with increases of 2.1°C, 3.0°C and 1.9°C respectively by the 2080s.

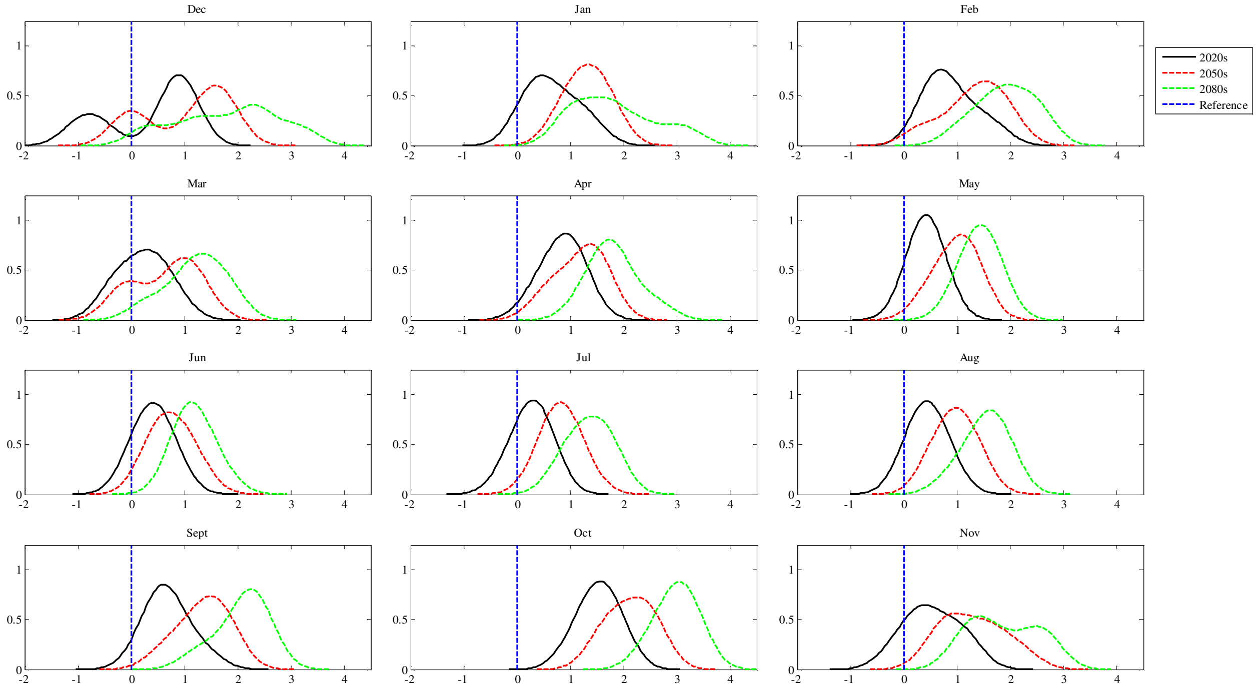


Figure 18: Probability density functions, constructed using the downscaled output from each GCM and emission scenario, depicting the projected change in minimum temperature for all months. The vertical line represents the baseline mean.

4.3.3. Precipitation

When compared to temperature, projected changes in the precipitation regime of the catchment differ to a much greater degree depending on the time-horizon, climate model and emissions pathway considered. There is also the added complication of the dissimilarity between the downscaling techniques used to derive local-scale precipitation (Table 14). There are however broad commonalities across the downscaled series. Each GCM and emission scenario suggests a reduction in summer rainfall amounts accompanied by an increase in winter, with this trend likely to become more extreme as the century progresses. The divergence between projected changes arising from emission scenarios alone increases towards the end of the century. For the 2020s and in some cases the 2050s differences between the A2 and B2 emissions pathway are negligible; this applies primarily to the HadCM3 model. The 2080s exhibit the greatest difference between the A2 and B2 pathways. Significant differences also arise due to downscaling technique. This is most notable for the summer months where the GLM approach estimates greater reductions when compared to SDSM. Although both are based on regression analysis, differences arise due to individual model structure and predictor selection.

Table 14: Percentage change (from simulated 1961–1990 control period) in rainfall for each future horizon (2020s, 2050s and 2080s) on a seasonal basis downscaled using both linear (e.g. SDSM) and generalised linear (e.g. GLM) techniques modelled using output from three GCMs and both the A2 and B2 emissions scenario.

	SDSM				GLM			
	Winter	*Spring*	*Summer*	*Autumn*	*Winter*	*Spring*	*Summer*	*Autumn*
HadCM3-A2								
2020s	-1.5	-3.8	-2	-1.5	-0.7	-3.3	-3.8	0
2050s	3.8	-7.4	-2.8	-6.6	5.3	-5.4	-10.5	-5.9
2080s	17.3	3.7	-18	-5	20.2	1.9	-34.2	-4.5
HadCM3-B2								
2020s	0.9	1.5	1.3	1.7	1.2	3.2	-1.8	2.9
2050s	8.2	-2.4	-9	-2.9	8.8	-3	-15.2	-2.2
2080s	9.7	4.7	-7.9	-2.9	11.1	4.4	-18.2	-2.7
CSIRO-MK2-A2								
2020s	10	3.9	-7.6	1.6	10.7	1.3	-15.2	-1
2050s	13.1	1.3	-17	-4.3	14.1	-3.6	-34.3	-7
2080s	21.5	-1.3	-13.7	-4.7	22.5	-7.6	-38.4	-9
CSIRO-MK2-B2								
2020s	4.7	-0.8	-1.5	-6.8	4.9	-4.3	-10	-6.6
2050s	25.4	-5.6	-3.7	-2.9	24.6	-10.4	-16.3	-3.3
2080s	14.8	-0.5	-5.4	-5.4	15.6	-3.5	-22.7	-6.7
CGCM2-A2								
2020s	6.4	-7.7	-8.5	2.5	7.4	-9.8	-19.3	1.3
2050s	20.3	-18.1	-6.2	-4.2	19.7	-19.7	-23.1	-4.9
2080s	12.6	-27.7	-10.4	-9.9	14.7	-37.2	-36.9	-12.8
CGCM2-B2								
2020s	2.3	2.9	0	0.6	4.4	1.5	-7.1	0.1
2050s	9.4	-13.2	-7.6	1.8	10	-14	-21	0.5
2080s	13.1	-17.8	-6.2	0.2	13.7	-21.3	-22.9	-2.2

Based on SDSM, the projected changes in precipitation for the 2080s, derived using the output from the HadCM3 model driven using the A2 emission scenario, indicate an increase in mean winter precipitation amounts by 17.3% and a decrease in mean summer precipitation by -18% relative to the baseline period. Using the same model output, a decrease of -5% in autumn rainfall is also projected to occur over the 2080s. The scenarios derived using the GLM approach, for the same GCM and emissions pathway indicate a 20.2% increase in winter rainfall and a much more extreme decrease of -34.2% in summer. Precipitation scenarios from SDSM, derived using the model output from CSIRO-MK2 under the A2 emission scenario, suggest an increase in winter rainfall amounts by 21% and a decrease of -13.7% in summer for the 2080s. The GLM-derived scenarios suggest a similar increase in winter (22.5%), with a much greater decrease in summer (-38.4%) and autumn (-9.0%). Precipitation scenarios based on the

CGCM2 climate model output and A2 emissions scenario, downscaled using SDSM, suggest that by the 2080s, summer precipitation is projected to decrease by -10.4% whilst winter levels are expected to increase by 12.6%. The greatest relative reductions in precipitation are however projected to occur for the spring with an estimated -27.7% decrease by the 2080s. As with other scenarios, a reduction in autumn precipitation amounts (-9.9%) is also projected to occur for this horizon. The GLM-derived scenarios from the CGCM2 model are largely in line with SDSM – however, the projected changes in summer (-36.9%) and spring (-37.2%) are much greater.

The probability density functions constructed using all model predictions, including those derived using both SDSM and the GLM, provide a clearer picture of changes in the catchments rainfall regime with an increase in winter accompanied by a decrease in summer (Figure 19). This enhancement in the seasonality of the precipitation regime is projected to become more pronounced as the century progresses. For a number of months, most notably April and November, little change over reference conditions is suggested.

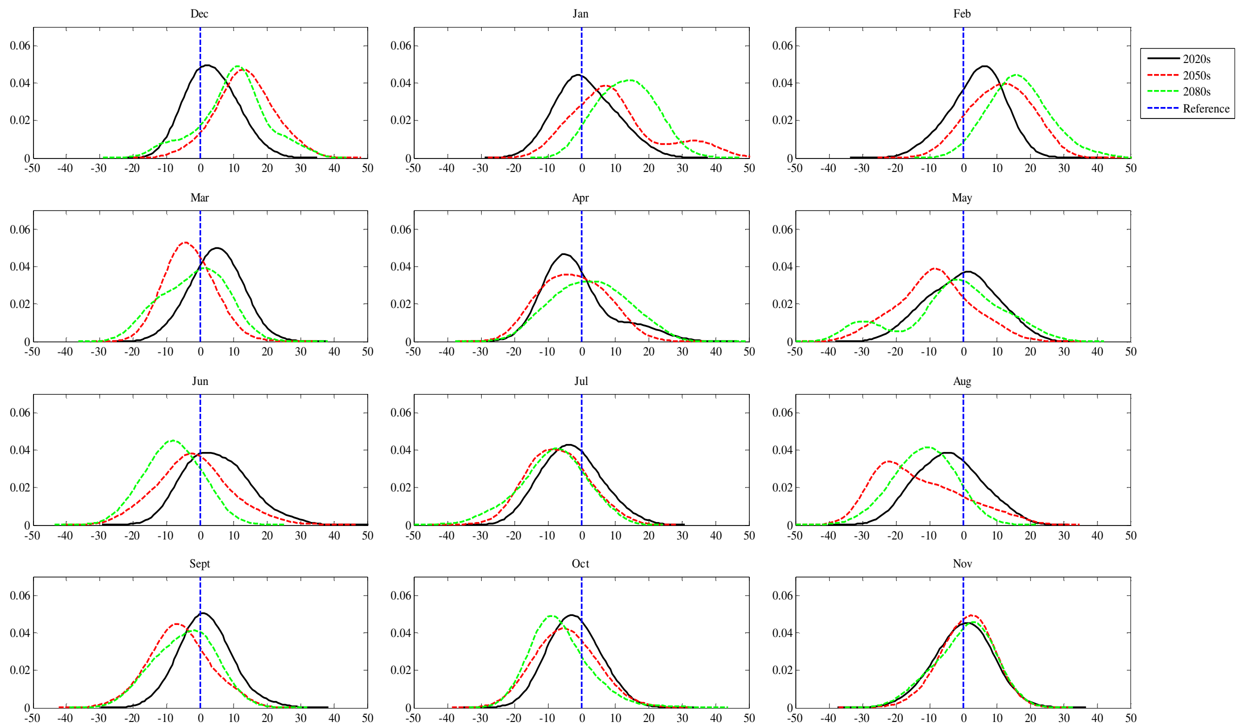


Figure 19: Probability density functions, constructed using the downscaled output from each GCM, emission scenario and both downscaling techniques, depicting the projected change in precipitation for all months. The vertical line represents the baseline mean.

4.3.4. Solar radiation and potential evaporation

Due to the influence which solar radiation has on controlling evaporation rates projected changes for both incoming radiation and potential evaporation were found to be relatively similar. Table 15 lists the projected changes in both variables relative to baseline conditions. The downscaled scenarios suggest the greatest relative increase in both variables will be over the summer period with deviations from reference conditions for this season becoming more pronounced towards the end of the century.

Table 15: Percentage change in solar radiation and potential evaporation for each future horizon on a seasonal basis downscaled using SDSM.

	Solar Radiation				Potential Evaporation			
	Winter	*Spring*	*Summer*	*Autumn*	*Winter*	*Spring*	*Summer*	*Autumn*
HadCM3 - A2								
2020s	0.6	0.0	1.1	1.2	-0.2	-0.1	1.2	1.6
2050s	-0.6	2.9	3.0	2.4	-0.1	2.8	3.3	3.0
2080s	-1.7	2.3	6.8	4.3	-1.1	2.0	7.6	4.7
HadCM3 - B2								
2020s	0.2	-0.1	1.8	0.2	-0.4	-0.3	1.7	0.6
2050s	-0.4	0.1	3.1	2.2	0.0	0.1	3.5	2.8
2080s	-0.1	1.0	4.3	2.5	-0.1	0.8	4.6	2.4
CSIROmk2 - A2								
2020s	0.2	0.1	1.5	-0.1	1.9	0.3	1.5	-0.1
2050s	-1.1	2.0	2.4	0.4	-0.5	1.9	2.5	0.7
2080s	-1.8	3.5	3.9	2.5	-1.5	3.5	4.0	2.5
CSIROmk2 - B2								
2020s	-2.1	0.8	2.1	-0.2	-4.6	1.1	1.8	-0.2
2050s	-4.5	1.7	3.1	-0.3	-4.0	1.9	3.0	-0.1
2080s	-2.4	3.6	4.3	0.1	-4.6	3.6	4.2	-0.2
CGCM2 - A2								
2020s	0.0	0.7	1.7	1.3	1.0	1.1	2.0	1.6
2050s	-0.2	2.7	1.8	2.1	1.3	3.1	2.2	2.3
2080s	0.2	1.6	3.7	3.0	0.7	2.3	4.3	2.9
CGCM2 - B2								
2020s	-0.9	2.1	2.3	1.3	-1.1	2.2	2.4	1.5
2050s	-2.5	1.4	1.7	2.2	0.8	1.7	2.1	2.4
2080s	-0.2	2.7	3.4	3.2	1.4	3.0	3.7	3.0

The greatest summer increases are suggested by the scenario downscaled from the HadCM3 model under the A2 emissions pathway. Such increases in evaporation rates are in-line with projected changes in air temperature and reductions in cloud cover suggested by a decrease in summer precipitation. Winter reductions in both variables are indicated by the model results with the greatest decreases being associated with the CSIROmk2 GCM under the B2 emissions scenario. Such decreases during the winter period are commensurate with an increase in precipitation rates indicating greater cloud cover.

4.4. Key Results

A number of general conclusions can be made regarding key projected changes in the climate of the Burrishoole catchment over the course of the present century.

- There is a general consensus between model projections that all seasons will experience an increase in both average daily minimum and maximum temperature, with deviations from baseline conditions becoming more pronounced as the century progresses.
- Projected changes in temperature are likely to be more acute under the A2 emissions pathway when compared to the less carbon-intensive B2 scenario.
- The temperature scenarios downscaled from each GCM and emissions scenario, when considered collectively (i.e. as a probability density function), indicate an increase in mean daily temperatures by the 2080s of 1.7°C, 1.8°C, 1.7°C and 2.2°C for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) respectively.
- When considered collectively the greatest relative changes in maximum temperature are associated with the months of September (+2.2°C), October (+2.9°C) and August (+2°C) over the 2080s.
- When considered collectively, the greatest relative changes in minimum temperature are associated with the months of September (+2.1°C), October (+3°C), November (+1.9°C) and February (+1.9°C) over the 2080s.
- Extreme maximum temperatures (90th percentile) are anticipated to increase as are extreme minimum temperatures (10th percentile). Both these findings are commensurate with the overall trend of increasing temperatures.
- Model simulations suggest an increasing tendency towards a more seasonal rainfall regime (i.e. higher winter and lower summer precipitation receipts) with this underlying trend becoming more pronounced as the century progresses.
- Based on the precipitation scenarios derived from each GCM and emission scenario, it is likely that winter receipts will increase by 13% over the latter half of the century, whilst decreases of 10% are projected for the summer over the 2080s.

- On a monthly basis, over the 2080s, the greatest increases in precipitation are suggested for February (+16.8%) and January (+13%) whilst the largest decreases are associated with the months of August (-11.7%), June (-8.1%) and July (-8.6%).
- Model-projected changes in wind speed do not present any clear indication of an alteration in prevailing conditions over that of the baseline period. It is likely that the changes suggested by the scenarios downscaled from each GCM are within the bounds of natural variability.
- The seasonal regime for receipts of solar radiation is expected to become more pronounced with increases during summer and decreases during the winter months.
- Owing to their close association, projected changes in potential evaporation follow the trend exhibited by solar radiation. Thus, increased losses to evaporation from the catchment system are likely over the summer months with this trend becoming more pronounced as the century progresses.

5. PROJECTED CHANGES IN CATCHMENT HYDROLOGY

5.1. Introduction

Changes in climate are likely to have significant impacts on freshwater hydrology, with increased energy resulting in an intensified hydrological cycle. Given the complex and fragile interaction between the climate system and land-surface hydrology, any changes in the primary processes of precipitation and evaporation will have considerable knock-on effects for the rest of the hydrological cycle.

In order to translate future climate scenarios into hydrological simulations, different hydrological modelling approaches were employed during the current research. Conceptual rainfall-runoff (CRR) models have been the most widely used for climate impact assessment. Central to their use is their ability to characterise the catchment system as a simplified collection of stores representing catchment processes, enabling such models to be applied to a wide variety of catchments. Conceptual rainfall-runoff models also tend to contain a small number of parameters, many of which can be measured. Consequently, simple model structures, non-linear representations of the hydrological system as well as the ability to simulate the movement and storage of water in soils have led to the widespread use of CRR models in climate-impact assessment. Despite their wide application, CRR models are associated with uncertainty because of their simplified structure and varying degrees of complexity. Broadly speaking, there are three principal sources of uncertainty in hydrological models: (i) errors associated with input data and data for calibration; (ii) imperfection in the model structure; and (iii) uncertainty in model parameters (Jin et al., 2010).

Addressing model uncertainty is an important aspect of climate-impacts assessment and in the context of this study was considered by employing two different modelling strategies. The first employed HYSIM, a CRR model previously been used in the field of climate-impacts analysis. The second modelling strategy was based on the use of artificial neural networks (ANNs). To assess model uncertainty, previous studies have used the results from several different hydrological models to produce a range of equally plausible streamflow predictions. The level of agreement exhibited between different models provides some indication of model uncertainty. In this study, the two selected modelling techniques were firstly applied to a single catchment to determine the magnitude of inter-model uncertainty and following from this, whether the application of both models to each of the remaining catchments was necessary. The Glenamong catchment, a sub-catchment of the Burrishoole, was selected as the study catchment for this analysis. To assess the relative skill of each method under observed conditions, both were used to simulate streamflow for the same calibration and validation periods. In addition, the agreement shown between the future simulations from each model under the same climate forcing scenario was examined.

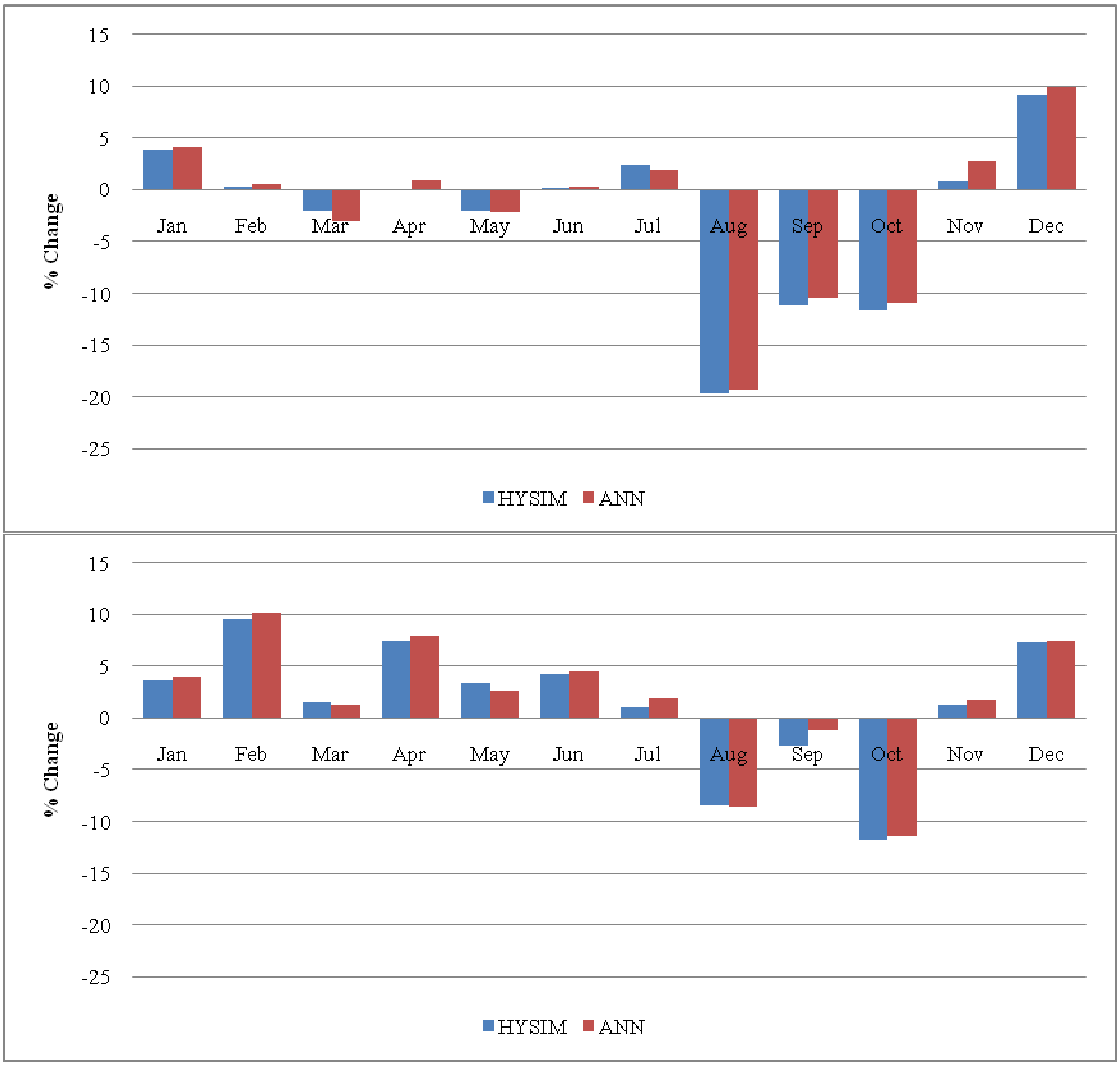


Figure 20: Percentage change (%) in mean monthly streamflow for the Glenamong catchment simulated using HYSIM, a CRR model, and ANN for the 2050s (top) and 2080s (bottom). Both models are run using data from the HadCM3 GCM under the B2 emissions scenario.

Figure 20 illustrates the monthly percent change in mean streamflow, as simulated by the selected neural network and HYSIM, using climate projections downscaled from the HadCM3 GCM under the B2 emissions scenario. Given the agreement shown between each model's simulated changes in the Glenamong flow regime it was assumed that the uncertainty associated with the final streamflow projections arising due to model choice would be negligible. Consequently, only HYSIM was employed to model future streamflow for the remaining catchments. This model was selected over the ANNs as it allows for the hydrological dynamics of the catchment to be represented explicitly in the model structure.

A second key source of uncertainty associated with CRR models is caused by limitations associated with the definition of model parameters, such as parameter stability, parameter identifiability and equifinality, each of which gives rise to uncertainty in model output. Wilby (2006) shows that uncertainty in future flow changes due to equifinality is comparable in magnitude to the uncertainty in emissions scenario. In this study the uncertainty associated with parameter identifiability is addressed and quantified using the generalised likelihood uncertainty estimation (GLUE) procedure.

Additionally, the uncertainties introduced to the analysis derived from different GCMs and GHG emissions scenarios were also accommodated. In relation to final results, the uncertainty derived from GCMs was found to be largest. By comparison, the uncertainties introduced from different emissions scenarios and the rainfall runoff model used were comparable to each other but smaller than GCM uncertainty. This highlights the importance of accounting for uncertainty in GCMs, emissions scenarios and impacts models, particularly if modelling results are to be used for policy development.

5.2. Simulated Changes in Hydrology

Projected changes in streamflow for each study catchment are considered for three future time-horizons: the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099), with the period 1961–1990 used to represent baseline or reference conditions. For each catchment, changes in the monthly flow regime and for high and low-flow events were considered. Changes in the monthly flow regime for each catchment are presented using box plots. The whiskers represent the 95% confidence intervals of projected changes, also presented are the 75th and 25th percentiles and the mean (middle line). Changes in the monthly flow regime are presented relative to the natural variability for the current climate. In total, five sub-catchments of the Burrishoole system are modelled: (i) Glenamong, (ii) Maurmatta, (iii) Altahoney, (iv) Goulan and (v) Srahrevagh. In addition, the neighbouring catchment (the Glendahurk) was also included in the analysis. Due to the similarity of response, only the indicative results for the Glenamong catchment are presented here (details for all catchments are available in Fealy et al., forthcoming).

5.2.1. Uncertainty in future hydrological simulations

As a first component of the analysis, a comparison of the sources of uncertainty considered was carried out for the Glenamong catchment. By far the largest component of uncertainty is derived from the use of different GCMs. Figure 21 shows the changes in the monthly flow regime for the Glenamong catchment for each of the GCMs considered, when all other sources of uncertainty were held constant (i.e. one emissions scenario [A2], one downscaling technique [SDSM] and one parameter set). What is evident is that there is a good deal of deviation in relative changes between climate models in relation to both the timing and magnitude of changes in the monthly flow regime. Of particular note are the large reductions in spring flow simulated by the CGCM2 climate model, particularly by the 2080s. The HadCM3 model tends to be the driest model with the largest decreases in flow associated with the 2080s. The disparities between models emphasise the importance of including multiple GCMs in impact assessment in order to increase the robustness to uncertainty of policy-making in adapting to climate change.

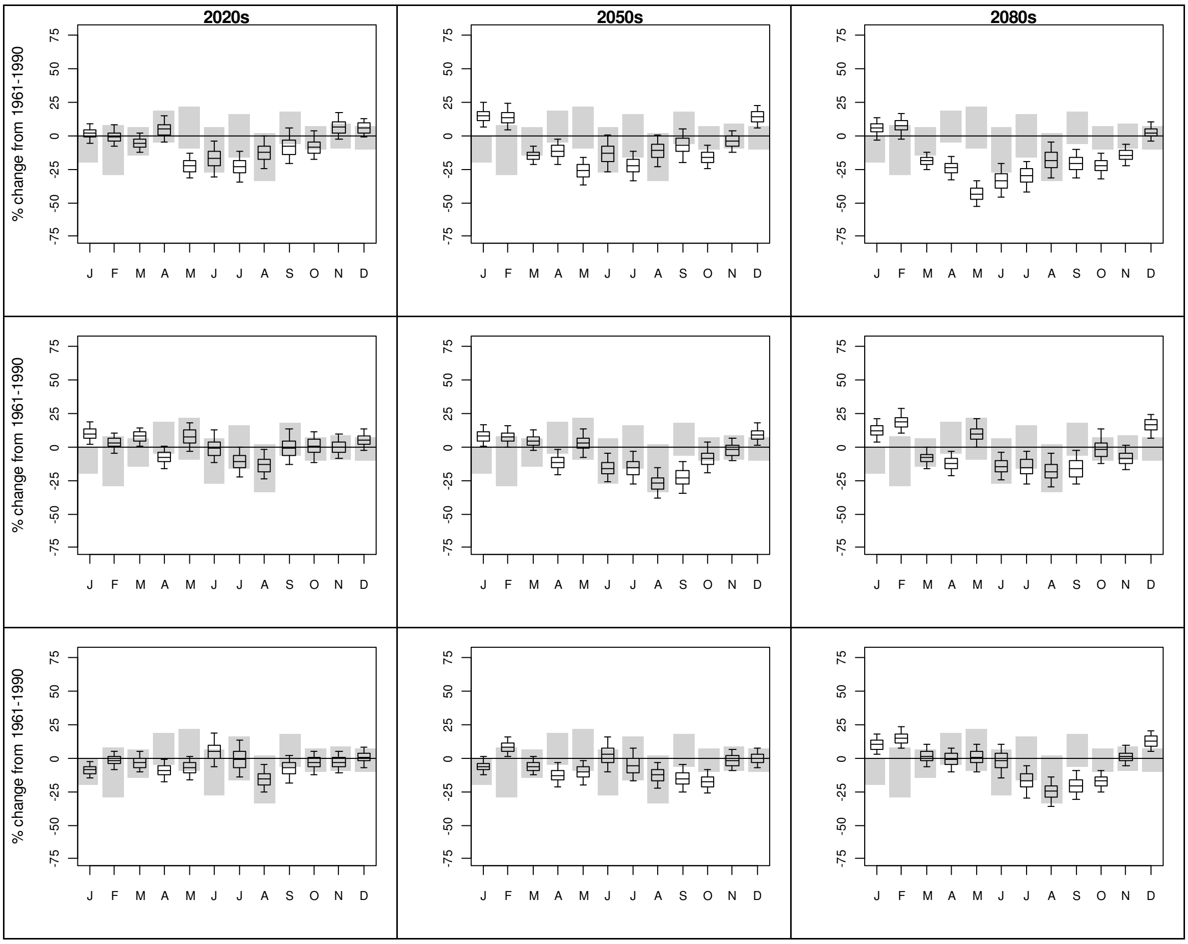


Figure 21: Uncertainty in changes in future flow regime derived from GCMs CGCM2 (top), CSIRO-MK2 (middle) and HadCM3 (bottom).

In relation to the uncertainty in future flows derived from GHG emissions, Figure 22 depicts the results for the Glenamong catchment. In assessing the contribution from this source of uncertainty, only the emissions scenario was varied between both sets of simulations. What is obvious from the results is that the A2 scenario simulates greater increases in winter flows and greater reductions for summer and autumn flows than the more optimistic B2 emissions scenario. The divergence between the scenarios is greatest after the middle of the century and largest by the 2080s. For the B2 scenario, no changes in the flow regime are significant outside of natural variability, even by the 2080s. While the uncertainty between emissions scenario is important, it is not as large as the uncertainty derived from the use of different GCMs.

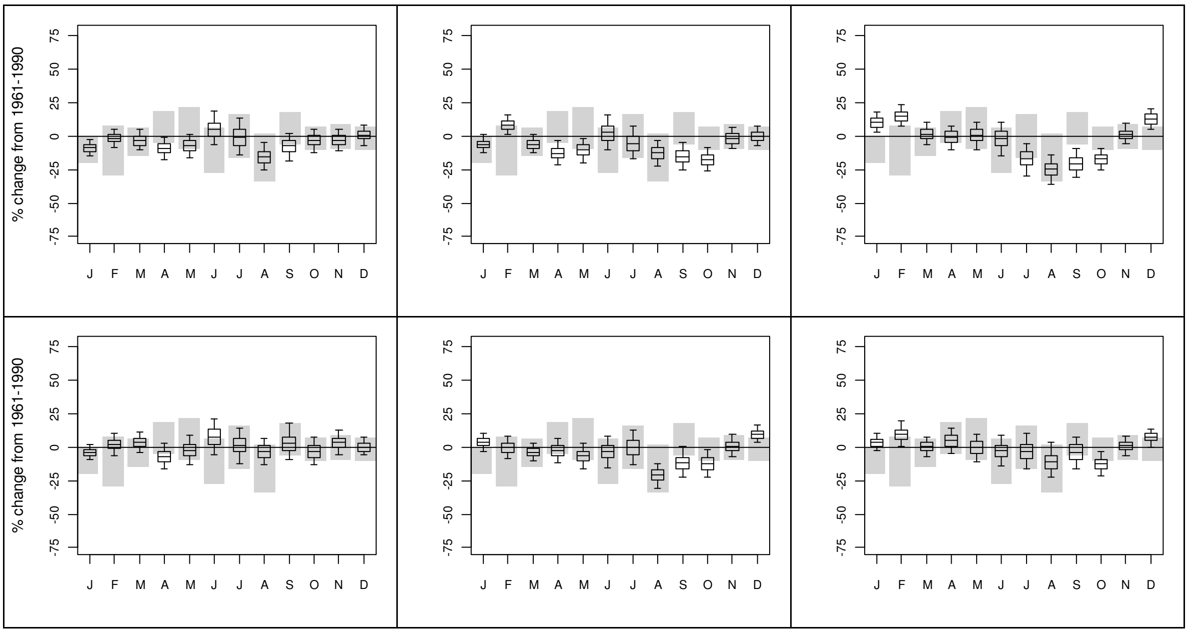


Figure 22: Uncertainty in changes in future flow regime derived from emissions scenarios. Both A2 (top) and B2 (bottom) are run using HadCM3.

A final source of uncertainty analysed here is that derived from parametric sources in the HYSIM model due to issues of non-identifiability of an optimum parameter set. Within this experiment only the behavioural parameter sets were varied. Of interest is the range of changes characterised by the box plots (Figure 23). For the winter months the range of uncertainty is small with the greatest uncertainties evident for spring and summer months. There is also an increase in uncertainty from the 2020s to the 2080s. However, in comparison to GCM uncertainty, parameter uncertainty from HYSIM is small, but can be as large as emissions scenario uncertainty during summer months. This is consistent with the findings of Wilby and Harris (2006).

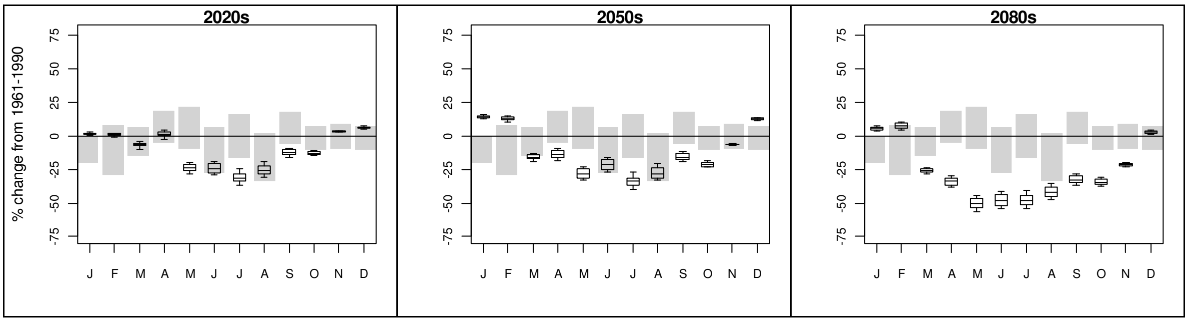


Figure 23: Uncertainty in changes in future flow regime derived HYSIM model parameters.

5.2.2. Glenamong catchment

Projected changes in the mean monthly flow regime for the Glenamong catchment are depicted in Figure 24. For the 2020s there is no clear indication of any significant changes in monthly streamflow outside the bounds of natural variability for reference climate conditions. A similar picture is produced from model simulations for the 2050s. However, the seasonality of the discharge regime does begin to become more pronounced, with significant changes in streamflow being registered for the months of January and April. By the 2080s, changes in local climate conditions (i.e. drier summers and wetter winters) become more apparent in the projected flow regime. Increases in January, February and December are deemed to be significant whilst decreases in catchment discharge are significant for September and October. For the remaining months model simulations are not considered to be significant outside natural variability.

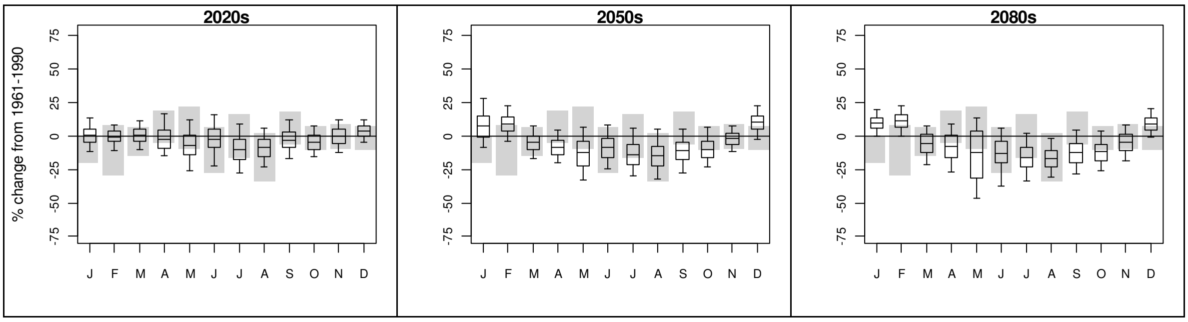


Figure 24: Changes in the monthly flow regime for the Glenamong catchment for the 2020s, 2050s and 2080s relative to the control period 1961–1990.

Model-projected changes in the full range of flow conditions for the Glenamong catchment are assessed by examining changes in the annual flow percentiles for each future time-horizon relative to the baseline period. Of particular interest are changes at the extremes of the flow distribution considered here using Q_{05} and Q_{95} flow percentiles. The cumulative distribution functions presented in Figure 25 depict the projected changes in each flow percentile. Model results suggest that an increase in high flows (Q_{05}) is likely becoming more pronounced as the century progresses. A decrease in low flows (Q_{95}) is also suggested, again with the trend becoming more acute towards the end of the century.

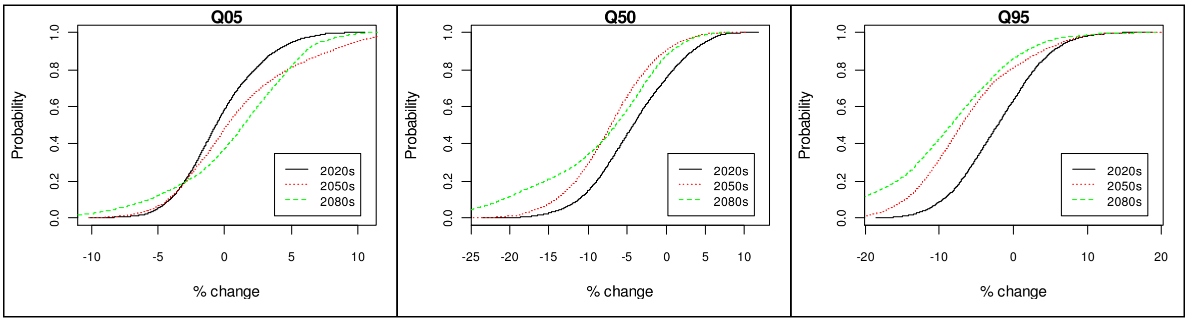


Figure 25: Cumulative distribution functions of percent changes in annual flow percentiles for the Glenamong catchment.

Changes in the frequency of low-flow events are presented in Figure 26. From the results obtained for the Glenamong catchment, an increase in the frequency of low-flow events is suggested for each future time-horizon – with increases of 15.2, 14 and 40.5 days projected for the 2020s, 2050s and 2080s accordingly. On a seasonal basis, the greatest increase in the number of low-flow days is projected to occur for the summer (18.27) over the 2080s' horizon. Uncertainty ranges are also largest for this season, particularly for the 2080s, with model projections ranging from a reduction of almost 16 days per annum to an increase of up to 52 days. The spring also exhibits a notable increase in low-flow days for the same horizon (13.43) with uncertainty bounds again spanning a sign change (-14.63 to +41.5).

Figure 27 displays the model projected changes in the duration of low-flow events for the Glenamong catchment. On an annual basis, an increase in the duration of low-flow events is evident for each future time period with increases of 1.57, 2.26 and 2.89 days for the 2020s, 2050s and 2080s respectively. The greatest increases in the duration of low-flow conditions are shown for spring and summer, with the latter showing an increase of over 6 days by the end of the century. The uncertainty bounds are also largest for these seasons, with a standard deviation of 7.07 and 6.0 in the statistical distribution of model projections for the 2080s.

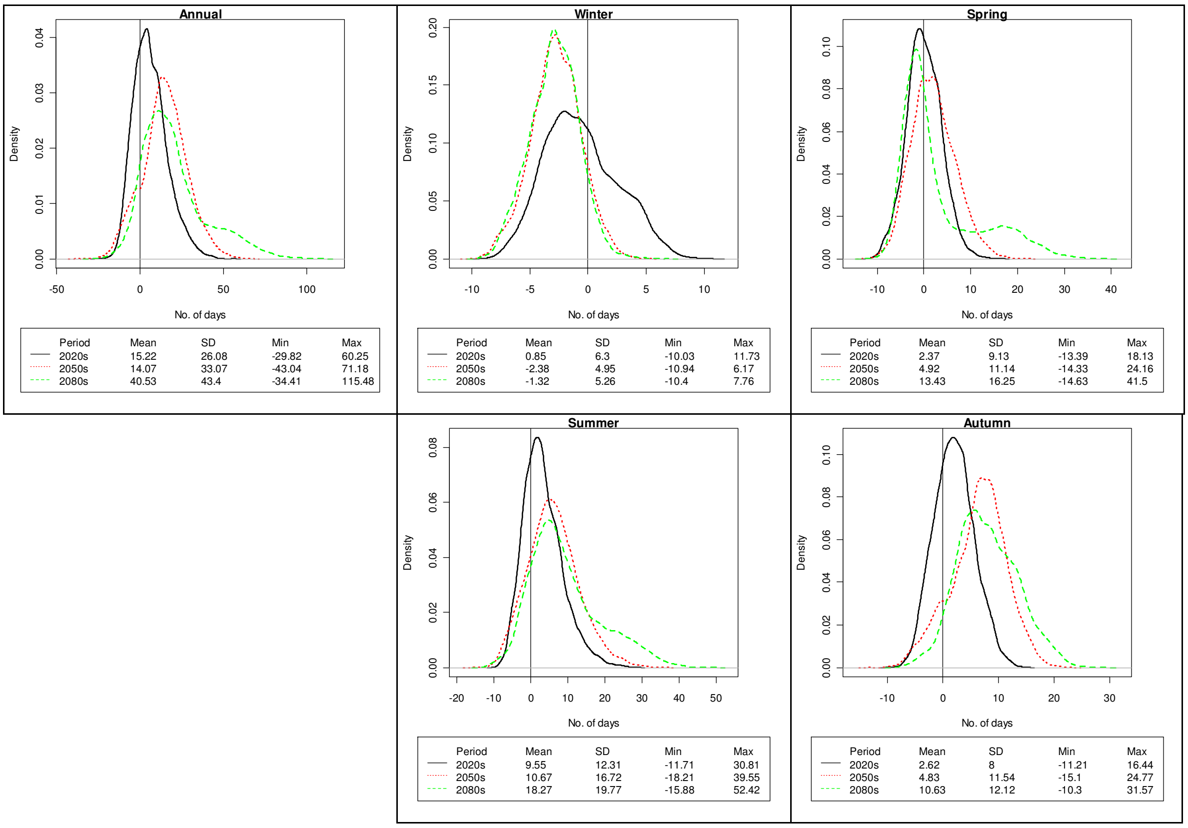


Figure 26: Simulated changes in the frequency of low-flow events on an annual and seasonal basis for each future time period in the Glenamong catchment.

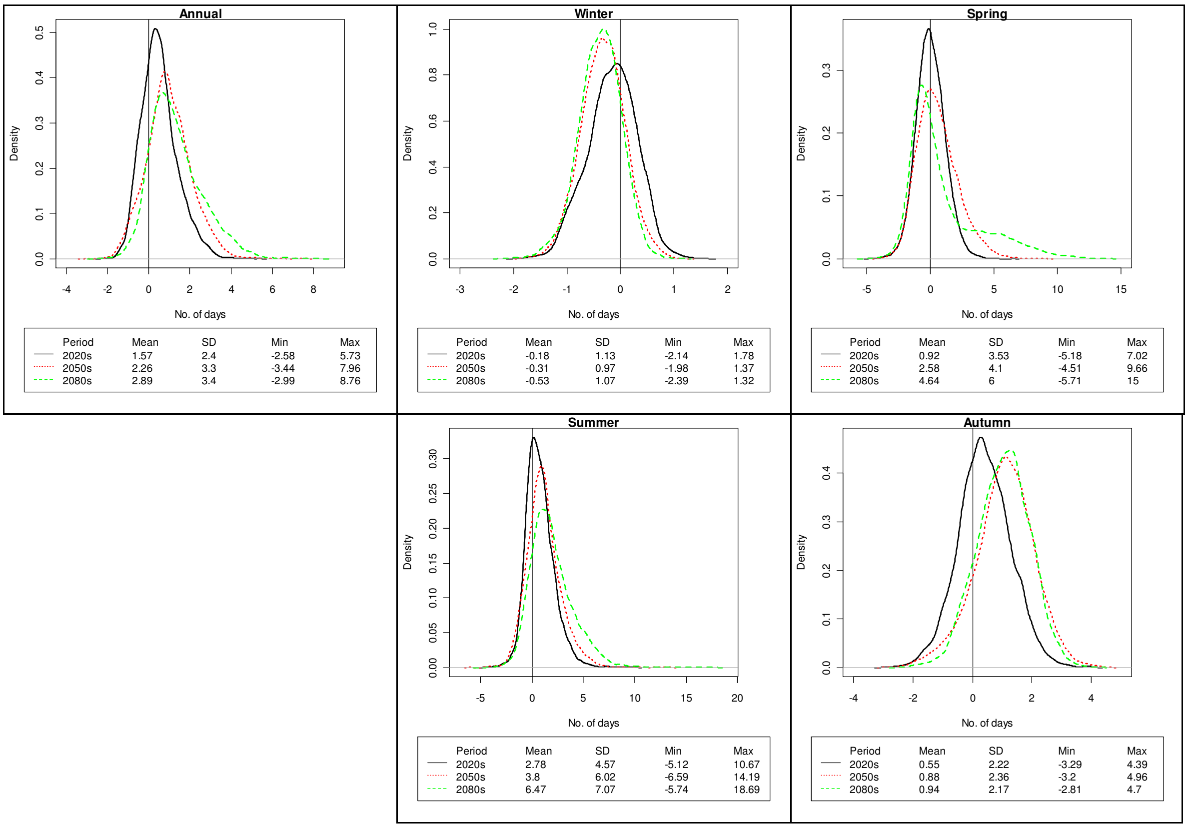


Figure 27: Simulated changes in the duration of low-flow events on an annual and seasonal basis for each future time period in the Glenamong catchment.

In order to examine changes in the frequency of flooding in each of the catchments modelled, an extreme value analysis was conducted to assess how the frequency of selected flood events for the control period are likely to change for each future time period. In total, 6 flood events were chosen: the flood expected (t) every 2, 5 10, 15, 20 and 50 years. Therefore, flood events ranging from fairly frequent (2-year) to moderately infrequent (50-year) are analysed. Because of the limited years of data, more extreme return periods were not included.
Table 16 shows the changes in frequency of these flood events simulated for mid-century. What is evident is that the majority of GCMs indicate a substantial increase in the frequency of extreme floods; in some instances, the current flood expected once every 50 years is suggested to occur more frequently than once every 10 years. However, there are uncertainties evident with two GCMs, namely CSIRO-MK2 and HadCM3, forced with the A2 emissions scenario, indicating little change or indeed less frequent flooding.

Table 16: Projected changes in the frequency of selected flood events by mid century as simulated by different GCMs and emissions scenarios.

2050s	CGCM2-A2	CGCM2-B2	CSIRO-MK2-A2	CSIRO-MK2-B2	HadCM3-A2	HadCM3-B2
t2	1	2	2	1	2	2
t5	2	3	5	3	7	3
t10	3	4	11	5	15	6
t15	4	5	17	7	24	8
t20	5	6	23	10	35	10
t50	6	9	56	26	100	21

5.3. Key Results

The key findings are outlined below.

- Projected changes in streamflow for each sub catchment were found to be relatively similar with no one catchment exhibiting deviations from the general trend in changing flow conditions found across the Burrishoole system. This is indicative of the relatively similar physical characteristics presented by each sub catchment.
- Given the dominant role runoff plays in shaping each sub catchment's hydrology, projected changes in streamflow conditions are predominantly driven by, and are sensitive to, alterations in the local precipitation regime (i.e. wetter winters and drier summers).
- An increase in the seasonality of the flow regime (i.e. higher winter flows and lower summer flows) is projected for all sub catchments with this underlying trend becoming more pronounced as the century progresses.

- Changes in mean flows for each month over the 2020s were deemed to lie within the bounds of natural variability for the baseline period and thus could not be clearly attributed to the underlying climate change 'signal'. This is a finding common to all selected sub catchments.
- By the 2050s, model simulations suggest a clear shift in mean flow conditions outside reference variability for some months. The most consistent changes across each sub catchment were found to occur for the winter (DJF) and autumn (SON) months. Comparatively fewer significant changes for the spring (MAM) and summer (JJA) months were found.
- Over the 2080s, mean monthly flows deviate further from baseline conditions and as such projected changes for a greater number of months were deemed to be significant with regards to baseline variability. Significant increases in mean flow for the months of January and December, accompanied by decreases for the months of June, October and August, are suggested for the majority of sub catchments.
- The incidence of extreme low flows, defined using the Q_{95} flow threshold, is anticipated to increase during the summer and spring seasons with this trend becoming more pronounced through the latter part of the century.
- A reduction in low flows is accompanied by an increase in the average number of consecutive days for which streamflow is equal to or less than the Q_{95} threshold. This was found to be most extreme for the spring and summer seasons over the 2080s.
- Model simulations indicate an increase in high flows (Q_{05}) as the century progresses with deviations from reference conditions being most apparent over the latter half of the century.
- Although there is a degree of inter-model variability regarding the projected return period for flooding events, it is generally evident that the occurrence of floods will increase. This is a finding common to each sub catchment.
- The absence of any significant storage capacity across the Burrishoole system suggests that it is unable to provide any natural means of flow regulation which could moderate the impact of an increasingly seasonal rainfall regime on flow conditions – thereby leaving the catchment vulnerable to changes in local climate. This is illustrated by the projected increase in low flows during the summer months when baseflow is required to sustain river levels.
- The 'flashy' nature of the streamflow response to precipitation events, a trait exhibited by all sub catchments, highlights the inability of each system to buffer or dampen the impact of heavy rainfall on peak discharge. This alludes to the sensitivity of the

catchment to any intensification in its rainfall regime under future climate forcing, a point underlined by the projected increase in high flow and flooding events.

- Projected changes in the flow regime for the Burrishoole catchment have potentially significant implications for the catchment's aquatic ecosystem.
- Management of the catchment will require explicit consideration of the likely impacts climate change will have on its hydrological regime.

6. Projected Changes In Water-Quality Parameters

6.1. Introduction

Projected changes in climate, if realised, are likely to both directly and indirectly affect a range of water-quality parameters, which in turn may have an impact on fish growth and survival. These include water temperature, DO and DOC concentrations. As outlined in Section 3, increases in RWT can have a direct influence on fish survival through an increase in the number of days when temperatures exceed critical threshold values. In addition, although most salmonid spawning and juvenile growth stages occur in rivers and streams, changes in lake water temperature may also affect survival rates. Inshore areas of Lough Feeagh, for example, provide nursery habitat for older age classes (Matthews et al., 1997). The lake is also the main feeding area for salmon during smoltification, the final months of their freshwater cycle before they migrate to sea. When thermal stratification develops in lakes during warm calm weather, warmer upper waters are separated from cooler deeper waters by a thermocline, a water layer over which temperature drops rapidly (Imberger and Patterson, 1989; Wetzel, 2001). These lower waters can provide a refuge for salmonids during periods of high surface water temperature (Tanaka et al., 2000; Mathes et al., 2010).

In addition to these direct temperature impacts, fish are also particularly sensitive to low DO concentrations (Alabaster and Gough, 1986; Youngson et al., 2004; Greig et al., 2006). Temperature is one of the key drivers of changes in DO solubility. However, DO levels are also related to decomposition of DOC and to rates of primary production. In humic lakes such as Lough Feeagh, DOC supplying the microbial portion of the food-web, may be an equal or more important source of carbon than primary production (Prairie, 2007). Both the production and transport of DOC are strongly influenced by climate and the recent large-scale increases in DOC levels have been linked, in part, to climate change (e.g. Freeman et al., 2001; Evans et al., 2006; Worrall et al., 2006; Hudson et al., 2003; Erlandsson et al., 2008) (for review see Jennings et al., 2010). More importantly these increases in the export of DOC from catchment soils represent a transfer of carbon from long-term terrestrial stores to forms that are more easily decomposed by bacteria and that can further contribute to atmospheric concentrations of CO_2 and, therefore, to global warming (Knorr et al., 2005; Davidson and Janssens, 2006). In this section the impacts of the projected changes in climate on RWT, DO solubility, DOC concentrations and lake water temperature (LWT) are explored using a range of modelling techniques. Mean monthly values were output from each model. Future climate simulations are presented as boxplots of the 5th percentile, 25th percentile, 50th percentile, 75th percentile and 95th percentile values of these monthly values. Each model was also run using historical meteorological data to give an estimate of historical variability. The 25th percentile and 75th percentile ranges for historical variability are included in all graphs to provide a common frame of reference.

6.2. Projected Changes in River Water Temperature

Increased air temperatures over the past century have caused RWTs in many river systems around the world to approach the lethal limit for coldwater-adapted fish (Eaton et al., 1995). For example, in an upland river in Scotland, Langan et al. (2001) found that winter RWT maxima have increased by 2°C since the 1980s, most likely because of rising seasonal air temperature. Under future projected global warming, it is anticipated that RWTs will increase further, altering fish habitat ranges, necessitating adaptive responses from fish and new management strategies, and possibly resulting in biodiversity loss (Schindler, 2001; Mohseni et al., 2003; Caissie, 2006).

6.2.1. Projected RWTs for the Burrishoole catchment

An exponential smoothing filter approach (Livingstone et al., 2005; Livingstone and Hari, 2008) was used to model future RWT in Burrishoole based on projected mean daily air temperature. One hundred datasets were output for each GCM-emission scenario combination described in Section 4. An increase in mean annual RWT from the baseline period (1961–1990) was projected for all three time-horizons (2010–2039, 2040–2069 and 2070–2099) for both the A2 and B2 emissions scenarios (Table 17 and Table 18).

The increase for the A2 simulations for the 2010–2039 period were +0.6°C, +1.1°C and +0.8°C for the HadCM3, CSIRO-MK2 and CGCM models respectively. The equivalent increases for the B2 scenario were also +0.6°C, +1.1°C and +0.8°C, although the results for two scenarios did differ on a monthly basis. The increases in annual RWT from the 1961–1990 baseline for both the 2040–2069 and 2070–2099 time periods exceeded those for the 2010–2039 period for all model-scenario combinations (Table 17 and Table 18). The increases for the A2 simulations were +0.8°C, +1.4°C and +1.6°C for 2040–2069 and +1.9°C, +2.3°C and +2.0°C for 2070–2099 for the HadCM3, CSIRO-MK2 and CGCM models respectively. The increases in RWT for the B2 simulations for the same time periods ranged from +0.8°C to +1.6°C (2040–2069) and from +1.3°C to +1.9°C (2070–2099). Projected increases in monthly mean RWT were higher for simulations based on the A2 scenario than those based on the B2 scenario (Figure 28 and Figure 29). Higher monthly RWTs were also indicated for all months relative to the 1961–1990 baseline (Figure 28 and Figure 29). In general, relative increases in summer RWT (June to August) were of a smaller magnitude relative to the annual increase, whereas increases in late autumn – early spring RWT (November to March) were projected to be higher than the annual increase in RWT.

Table 17: A2 scenario: river water temperature in °C for the observed period and for the 1961–1990 period for the three GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods.

A2	°C	J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**1961–1990**	**5.8**	**5.9**	**6.8**	**8.9**	**11.1**	**13.4**	**15.2**	**15.0**	**13.3**	**11.3**	**8.0**	**6.7**	**10.1**
HadCM3	1961–1990	5.9	5.5	6.9	8.6	10.9	13.3	14.9	14.8	13.2	10.9	7.8	7.0	9.7
	2010–2039	0.2	0.5	0.1	0.2	0.5	0.3	0.1	0.4	0.4	0.2	-0.2	-0.8	0.6
	2040–2069	0.9	1.1	0.2	0.7	0.7	0.5	0.9	0.9	1.7	0.9	0.7	-0.3	0.8
	2070–2099	1.5	1.7	1.5	1.4	1.5	1.4	1.8	2.0	2.2	2.6	1.4	0.5	1.9
CSIRO-MK2	1961–1990	5.4	5.5	6.6	8.5	11.0	13.4	14.9	14.8	13.2	10.9	7.7	6.4	9.8
	2010–2039	0.8	0.5	1.1	1.2	0.4	0.6	0.6	0.6	0.9	1.1	1.3	1.2	1.1
	2040–2069	1.5	1.1	1.5	1.7	1.2	1.0	1.2	1.3	1.8	1.8	1.8	1.6	1.4
	2070–2099	2.7	2.2	2.6	2.6	1.9	1.5	2.1	2.2	2.8	2.7	3.1	2.9	2.3
CGCM	1961–1990	5.5	5.4	6.9	8.6	11.1	13.5	14.9	14.9	13.2	10.9	7.5	6.4	9.9
	2010–2039	0.8	0.6	0.8	0.9	0.9	0.8	0.8	0.9	0.8	0.7	0.7	0.9	0.8
	2040–2069	1.5	1.3	1.5	1.3	1.4	1.4	1.6	1.6	1.7	1.9	2.0	1.6	1.6
	2070–2099	1.6	1.6	1.7	1.9	2.0	2.0	2.1	2.1	2.5	2.4	2.4	2.3	2.0

Table 18: B2 scenario: river water temperature in °C for the observed period and for the 1961–1990 period for the three GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods.

B2	°C	J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**1961–1990**	**5.8**	**5.9**	**6.8**	**8.9**	**11.1**	**13.4**	**15.2**	**15.0**	**13.3**	**11.3**	**8.0**	**6.7**	**10.1**
HadCM3	1961–1990	5.9	5.6	6.9	8.6	11.0	13.4	14.9	14.8	13.2	10.9	7.8	7.0	9.7
	2010–2039	-0.3	0.7	0.1	0.5	0.4	0.2	0.2	0.5	0.9	0.6	0.8	-1.2	0.6
	2040–2069	0.3	0.3	0.1	0.6	0.8	0.4	0.6	0.7	0.8	0.9	1.2	0.0	0.8
	2070–2099	0.6	1.0	0.6	1.1	1.2	1.2	1.0	1.2	1.3	1.7	1.6	-0.1	1.3
CSIRO-MK2	1960–1990	5.5	5.7	6.8	8.6	10.9	13.4	14.9	14.9	13.3	11.0	7.7	6.5	9.8
	2010–2039	1.4	1.2	1.1	0.9	0.8	1.0	0.7	0.9	1.4	1.0	1.4	0.9	1.1
	2040–2069	1.7	1.4	1.6	1.6	1.6	1.3	1.1	1.4	1.9	1.6	2.4	1.6	1.6
	2070–2099	2.2	1.9	2.1	2.1	1.8	1.4	1.4	1.8	2.3	2.4	2.9	2.3	1.9
CGCM	1961–1990	5.5	5.4	6.9	8.6	11.0	13.5	14.9	14.9	13.2	10.9	7.6	6.4	9.9
	2010–2039	1.0	1.0	0.8	0.8	0.5	0.7	0.9	0.8	0.8	0.9	0.9	1.0	0.8
	2040–2069	1.2	1.1	1.2	1.4	1.3	1.1	1.3	1.2	1.3	1.4	1.3	1.3	1.3
	2070–2099	1.1	1.4	1.3	1.7	1.4	1.3	1.4	1.7	2.2	2.4	2.3	2.0	1.7

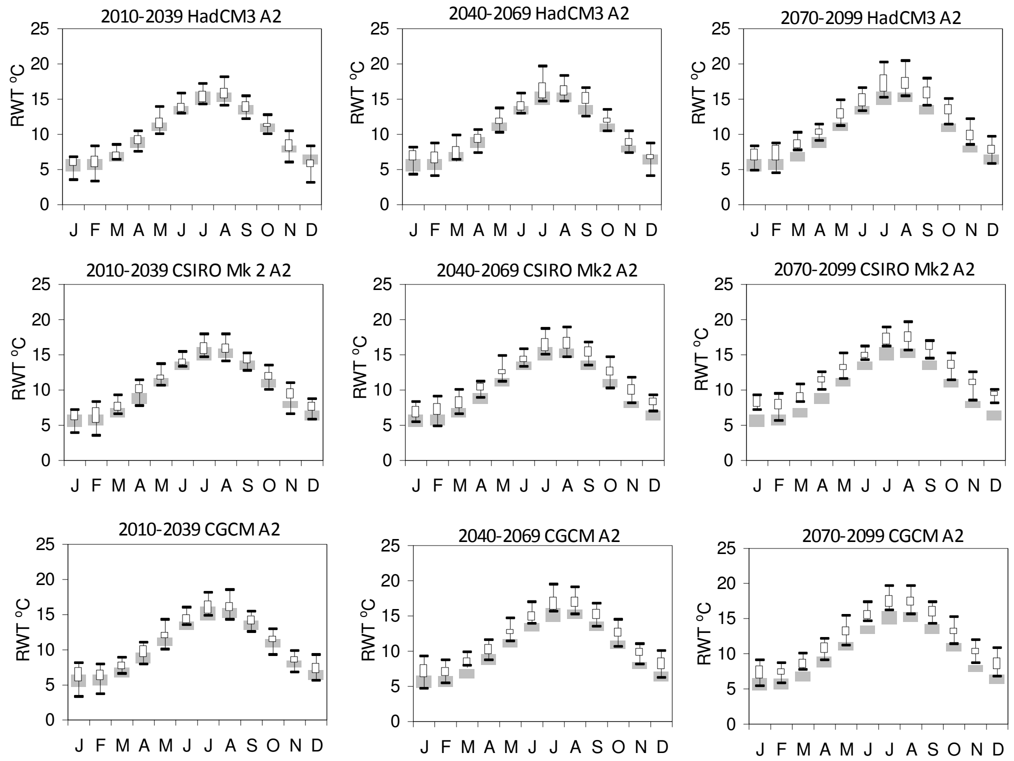


Figure 28: A2 scenario: boxplots of river water temperature (RWT) in °C for the three GCM models for three future periods: 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using historical meteorological data and are used to represent observed variability.

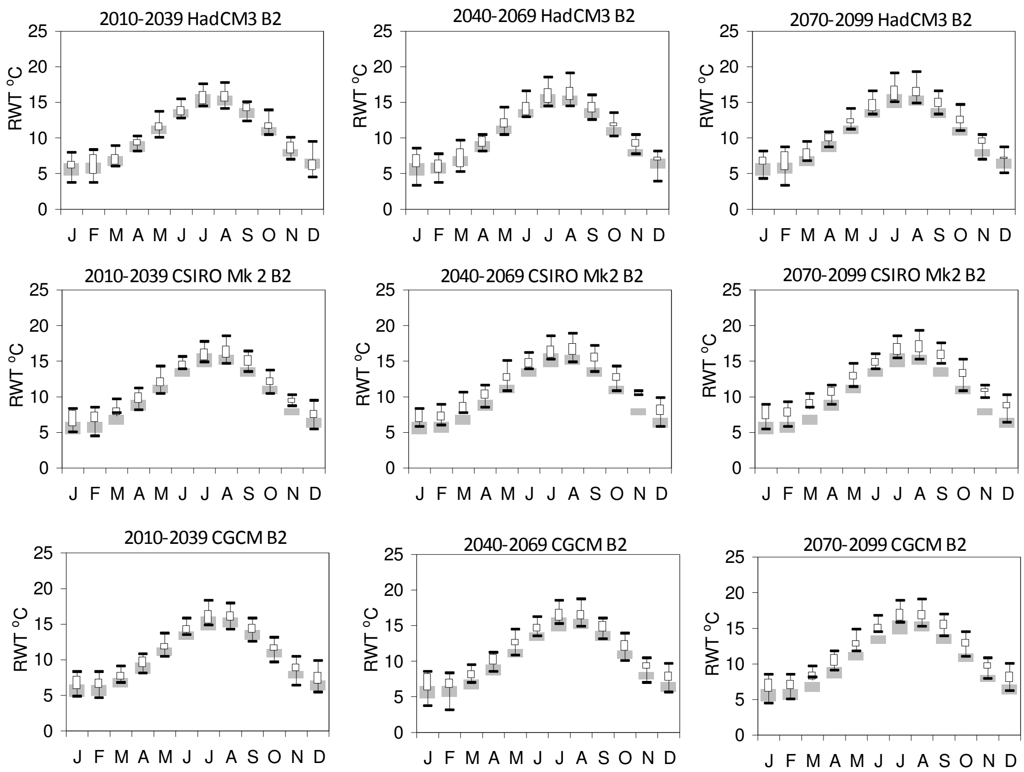


Figure 29: B2 scenario: boxplots of river water temperature (RWT) in °C based on the B2 scenario for the three GCM models for three future periods: 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using historical meteorological data and are used to represent observed variability.

6.3. Projected Changes in Dissolved Organic Carbon

6.3.1. Model description and data

The DOC model which was used in this study was originally developed in response to the user needs of water-treatment managers in the UK in the 1980s and 1990s (Naden, 1991; Naden and Watts, 1998). Based on experimental work, the release of coloured DOC compounds from peat soils was modelled as a two-stage process: peat decomposition produced soluble compounds that were then washed out of the soil. The model was then further developed during an EU project, Climate Impacts on European Lakes (CLIME), which included the Marine Institute, Newport, as partners. In that project the DOC model was dynamically coupled with the Generalised Watershed Loading Functions (GWLF) model hydrology (Naden et al., 2010). The model produces daily in-stream DOC concentrations and is driven by air temperature and precipitation. For each of the six GCM-scenario combinations, described in Section 4, one hundred datasets of air temperature and precipitation were run with each of the five selected DOC parameter sets. A single run was included using projected precipitation based on the GLM again with each of the five DOC parameter datasets. For all simulations, potential evapotranspiration (PE) was calculated within the GWLF hydrology model using the Hargreaves–Samani equation (Hargreaves and Samini, 1982), to retain the relationship between air temperature and PE in each individual simulation.

6.3.2. Projected DOC concentrations

An increase in mean annual DOC concentration from the baseline 1961–1990 period was projected for all model-scenario combinations for each of the three future time-horizons (Table 19 and Table 20). The median annual value for the observed dataset was 6.5 mg DOC L^{-1}. The median values for 1961–1990 based on the output from the GCMs ranged from 6.2 mg DOC L^{-1} to 7.1 mg DOC L^{-1}. The relative increase projected for the A2 scenario from 1961–1990 to 2010–2039 was 0.7 mg DOC L^{-1} for both the HadCM3 and CSIRO-MK2 models and 1.2 mg DOC L^{-1} for the CGCM model. The increases for the simulations based on the B2 scenario were 0.1 mg DOC L^{-1}, 0.9 mg DOC L^{-1} and 0.6 mg DOC L^{-1} for the HadCM3, CSIRO-MK2 and CGCM simulations. The overall increase from 1961–1990 to 2010–2039 based on all three GCM datasets for the A2 scenario was 0.9 mg DOC L^{-1} while that for the B2 scenario was 0.6 mg DOC L^{-1} (Table 21).

Table 19: A2 scenario: dissolved organic carbon (DOC) concentration (mg L^{-1}) for the observed period and for the 1961–1990 period for the three GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099.

A2	DOC	J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**mg L^{-1}**	**6.5**	**5.9**	**5.6**	**5.5**	**5.5**	**5.5**	**5.8**	**6.4**	**7.4**	**8.4**	**8.5**	**7.5**	**6.5**
HadCM3	1961–1990	6.9	6.2	5.9	5.7	5.8	5.8	6.0	6.6	7.5	9.0	9.2	8.1	6.9
	2010–2039	0.7	0.6	0.5	0.6	0.6	0.6	0.6	0.4	0.7	0.9	0.7	0.7	0.7
	2040–2069	1.3	1.0	0.9	1.0	0.9	0.9	1.0	0.8	0.7	0.9	1.4	1.4	1.0
	2070–2099	3.1	2.2	2.0	2.2	2.4	2.4	2.3	2.0	2.2	3.4	4.7	4.0	2.7
CSIRO-MK2	1961–1990	6.7	6.0	5.6	5.4	5.3	5.3	5.2	5.5	6.2	6.7	7.8	7.5	6.2
	2010–2039	1.1	0.7	0.6	0.5	0.5	0.6	0.6	0.6	0.5	0.6	0.9	1.1	0.7
	2040–2069	2.5	2.0	1.7	1.6	1.6	1.6	1.7	1.6	1.4	1.8	2.6	2.7	1.9
	2070–2099	2.7	2.2	1.9	1.9	1.8	1.8	1.9	1.9	1.9	2.5	3.1	3.6	2.3
CGCM	1961–1990	7.3	6.7	6.3	6.1	6.2	6.1	6.2	6.3	6.9	8.2	9.1	8.2	7.1
	2010–2039	1.4	1.1	1.1	1.1	0.9	1.0	1.1	1.1	1.3	1.4	1.9	1.8	1.2
	2040–2069	2.6	2.1	2.0	2.0	1.8	2.0	1.9	2.1	2.3	2.4	3.2	3.4	2.3
	2070–2099	5.2	4.4	4.2	4.2	4.1	4.3	4.3	4.5	4.6	4.9	6.0	6.0	4.8

Table 20: B2 scenario: dissolved organic carbon (DOC) concentration (mg L-1) for the observed period and for the 1961–1990 period for the three GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099.

B2	DOC	J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**mg L^{-1}**	**6.5**	**5.9**	**5.6**	**5.5**	**5.5**	**5.5**	**5.8**	**6.4**	**7.4**	**8.4**	**8.5**	**7.5**	**6.5**
HadCM3	1961–1990	6.2	5.6	5.3	5.2	5.3	5.3	5.5	6.2	7.0	8.3	8.5	7.2	6.4
	2010–2039	0.2	0.2	0.3	0.2	0.1	0.2	0.1	0.0	0.4	0.4	0.4	0.2	0.1
	2040–2069	1.1	0.9	0.8	0.9	0.9	0.9	0.9	0.4	0.9	1.1	1.7	1.5	1.0
	2070–2099	1.3	0.9	0.9	0.9	0.9	0.9	0.9	0.7	1.4	1.5	1.9	1.7	1.1
CSIRO-MK2	1961–1990	7.2	6.5	5.9	5.7	5.5	5.5	5.5	5.6	6.4	6.9	8.1	8.0	6.4
	2010–2039	1.0	0.9	0.9	0.8	0.8	0.8	0.8	0.7	0.9	0.8	1.0	1.3	0.9
	2040–2069	1.3	0.7	0.6	0.7	0.9	0.9	1.0	1.1	1.2	1.3	1.5	1.8	1.1
	2070–2099	2.1	1.7	1.4	1.4	1.5	1.5	1.5	1.4	1.2	1.5	2.1	2.4	1.7
CGCM	1961–1990	7.1	6.6	6.2	6.0	6.1	6.0	6.0	6.2	6.8	8.1	9.0	8.1	7.0
	2010–2039	0.9	0.7	0.7	0.7	0.4	0.5	0.4	0.5	0.8	0.7	1.1	1.2	0.6
	2040–2069	2.3	1.9	1.7	1.7	1.5	1.7	1.6	1.8	2.0	2.3	2.7	2.9	1.9
	2070–2099	2.9	2.3	2.2	2.3	2.1	2.2	2.1	2.2	2.4	2.7	3.5	3.4	2.4

The increases in mean annual DOC concentration for both the 2040–2069 and 2070–2099 horizons exceeded those for 2010–2039 for all model-scenario combinations (Table 19 and Table 20). The absolute increases for the A2 simulations from 1961–1990 to 2040–2069 were 1.0 mg DOC L^{-1} (HadCM3), 1.9 mg DOC L^{-1} (CSIRO-MK2) and 2.3 mg DOC L^{-1} (CGCM). Those for 2070–2099 were 2.7 mg DOC L^{-1} (HadCM3), 2.3 mg DOC L^{-1} (CSIRO-MK2) and 4.8 mg DOC L^{-1} (CGCM). The increases for the B2 simulations for the same time periods ranged from 1.1 DOC mg L^{-1} to 1.9 mg L^{-1} (2040–2069) and from 1.1 mg DOC L^{-1} to 2.4 mg DOC L^{-1} (2070–2099). The overall increase from the 1961–1990 baseline to 2040–2069 for all three GCM models for the A2 scenario combined was 1.8 mg DOC L^{-1} while that for the B2 scenario was 1.4 mg DOC L^{-1} (Table 21 and Figure 30). The overall increase from 1961–1990 to 2070–2099 for the A2 scenario was 2.4 mg DOC L^{-1} while that for the B2 scenario was 1.8 mg DOC L^{-1}. All were significantly different from the simulated annual means for 1961–1990. Significant increases in DOC concentrations were indicated for all months for each of the three time-horizons (Table 21). While these were generally of a similar magnitude to the increases in annual values, the increase was always lower in the late summer and highest in November/December.

Table 21: Dissolved organic carbon (DOC) concentration (mg L^{-1}) for the observed period (1961–1990) and for the 1961–1990 control period for the combined GCM models for the A2 and B2 scenarios together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099.

DOC		J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**mg L^{-1}**	**6.5**	**5.9**	**5.6**	**5.5**	**5.5**	**5.5**	**5.8**	**6.4**	**7.4**	**8.4**	**8.5**	**7.5**	**6.5**
A2	1961–1990	6.9	6.3	5.9	5.7	5.7	5.7	5.7	6.1	6.8	7.9	8.6	7.9	6.6
	2010–2039	1.1	0.8	0.7	0.8	0.7	0.8	0.8	0.7	0.9	1.0	1.2	1.2	0.9
	2040–2069	2.2	1.8	1.6	1.6	1.5	1.5	1.6	1.5	1.5	1.8	2.5	2.6	1.8
	2070–2099	3.6	2.0	1.7	1.9	1.9	1.9	1.9	1.8	1.9	2.5	3.6	3.6	2.4
B2	1961–1990	6.8	6.2	5.8	5.6	5.6	5.6	5.7	6.1	6.7	7.9	8.5	7.8	6.6
	2010–2039	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.6	0.5	0.8	1.0	0.6
	2040–2069	1.7	1.2	1.1	1.2	1.1	1.2	1.2	1.0	1.3	1.4	2.0	2.1	1.4
	2070–2099	2.2	1.8	1.6	1.6	1.5	1.6	1.5	1.4	1.7	1.9	2.5	2.6	1.8

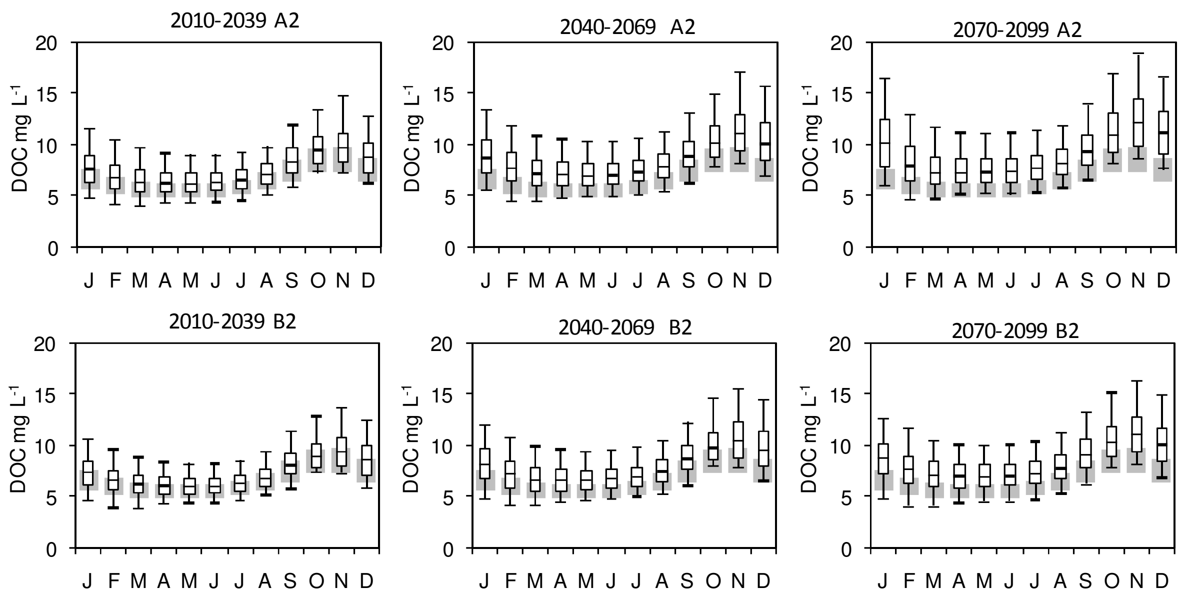


Figure 30: Boxplots of mean monthly and annual DOC concentration (mg L^{-1}) for the overall A2 and B2 scenarios for 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using historical meteorological data and are used to represent observed variability.

This seasonal pattern in DOC concentrations was driven in the model by the seasonal patterns in temperature, soil moisture levels and flow and replicated the currently observed pattern. The data for the overall A2 simulations for 2070–2099 are used to illustrate the combined impact of these three driving variables (Figure 31). In the model, decomposition of peat soils is driven by temperature and by the depth of the soil-unsaturated zone, a measure of soil moisture levels.

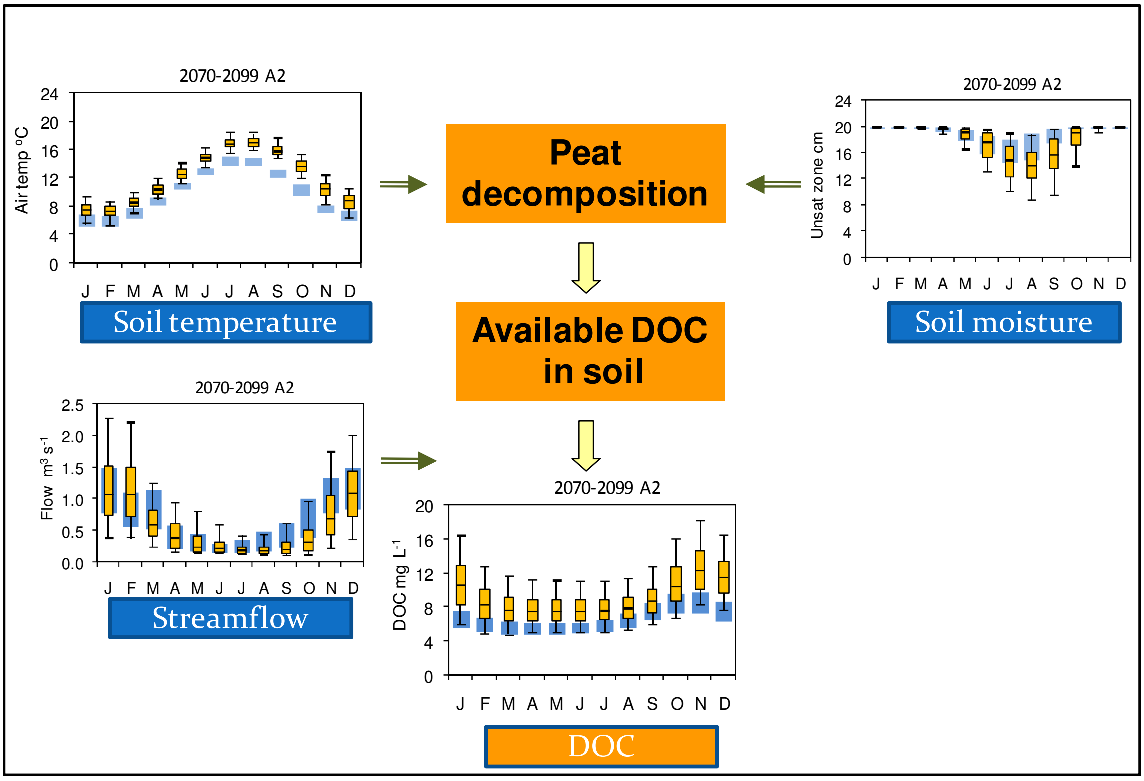


Figure 31: Diagram of dissolved organic carbon (DOC) model structure showing boxplots of air temperature, the depth of the unsaturated zone (soil moisture), streamflow and DOC concentration for the overall A2 scenario. The yellow boxes are the 25 percentile to 75 percentile range for future projections: the blue boxes are the 25 percentile to 75 percentile range for runs using historical meteorological data and are used to represent observed variability.

The impact of low soil moisture levels is confined to the summer months, when evapo-transpiration exceeds precipitation and the soil-unsaturated zone deepens. Soil temperatures, which are a function of air temperature in the model, are also at their highest during summer. These two factors result in a seasonal peak in the store of available DOC in the soil and were a major factor in the projected increases in stream DOC concentrations. The median depth of the unsaturated zone in July in the observed dataset, for example, was 2.7 cm. The projected value for 2070 to 2099 for the overall A2 scenario was 5.1 cm. In addition, while the unsaturated zone in the soil had recharged by October in the observed dataset based on the historical weather data, soil moisture levels were depleted until November in the simulations for 2070–2099. The store of DOC produced by these seasonal drivers was then washed out by higher surface and sub-surface runoff in November and December. While there is no overall increase in annual streamflow in these simulations, there was a reduction in flow rates in the late summer and autumn. This reduction would also contribute to higher available soil carbon stores in the November/December period.

6.4. Impact of Projected River Water Temperature on In-Stream Dissolved Oxygen Levels

Equations modelling DO concentrations in water include estimation using a physical equation based on the relationship of DO solubility to temperature (Cox, 2003). This equation calculates DO concentrations in the absence of the biological processes of photosynthesis and respiration. In the current project, the impact of the projected changes in RWT on DO solubility alone was assessed. However, as illustrated in Section 3, temperature is the major driver of DO concentrations in rivers and streams in the Burrishoole catchment. A more comprehensive assessment of future climate impacts on in-stream DO levels would require more detailed data on biological and chemical parameters in catchment streams and could form the basis of a future study.

The projected increases in RWT generally led to a decrease in mean annual DO concentration from the baseline period (1961–1990) to the 2010–2039 time-horizon for all GCM model scenario combinations (Table 22 and Table 23). These changes ranged from 0 mg DO L^{-1} to -0.2 mg DO L^{-1} for the simulations based on the A2 scenario. The differences for the same time period for the B2 scenario ranged from -0.1 mg DO L^{-1} to -0.3 mg DO L^{-1}.

The decreases in annual mean DO concentration for both the 2040–2069 and 2070–2099 time periods exceeded those for 2010–2039 (Table 22 and Table 23). The decreases in annual mean DO concentrations for the A2 simulations were -0.2 mg L^{-1}, -0.4 mg L^{-1} and -0.4 mg L^{-1} for 2040–2069 and -0.4 mg L^{-1}, -0.6 mg L^{-1} and -0.5 mg L^{-1} for 2070–2099 for the HadCM3, CSIROMk2 and CGCM models respectively. The decreases for the B2 simulations for the same time periods ranged from -0.2 mg DO L^{-1} to -0.4 mg DO L^{-1} (2040–2069) and from -0.3 mg DO L^{-1} to -0.5 mg DO L^{-1} (2070–2099). For the 2070–2099 period, the simulations based on the combined output for the A2 scenario gave larger decreases than the B2 scenario (Table 24). The currently observed seasonal pattern, with lower concentrations in summer and highest concentrations in winter, was replicated in all future simulations (Figure 32 and Figure 33). The relative decrease was always lower in the late summer and highest in late autumn to mid-winter (November to January). This seasonal pattern in DO concentrations was driven by the seasonal patterns in RWT.

Table 22: A2 scenario: dissolved oxygen (DO) concentration (mg L-1) for 1961–1990 for the three GCM models and absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods.

A2		J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**mg L-1**	**12.5**	**12.5**	**12.2**	**11.6**	**11.0**	**10.5**	**10.1**	**10.1**	**10.5**	**11.0**	**11.9**	**12.3**	**11.3**
HadCM3	1961–1990	12.5	12.6	12.2	11.7	11.1	10.5	10.1	10.2	10.5	11.1	12.0	12.0	11.4
	2010–2039	-0.1	-0.2	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0
	2040–2069	-0.3	-0.3	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2	-0.4	-0.2	-0.2	-0.2	-0.2
	2070–2099	-0.4	-0.5	-0.4	-0.4	-0.4	-0.3	-0.4	-0.4	-0.5	-0.6	-0.4	-0.4	-0.4
CSIROMk2	1961–1990	12.6	12.6	12.3	11.7	11.0	10.5	10.1	10.1	10.5	11.1	11.9	11.9	11.4
	2010–2039	-0.3	-0.2	-0.3	-0.3	-0.1	-0.1	-0.1	-0.1	-0.2	-0.3	-0.4	-0.4	-0.2
	2040–2069	-0.5	-0.3	-0.4	-0.5	-0.3	-0.2	-0.2	-0.3	-0.4	-0.4	-0.5	-0.5	-0.4
	2070–2099	-0.8	-0.7	-0.7	-0.7	-0.4	-0.3	-0.4	-0.4	-0.6	-0.7	-0.9	-0.9	-0.6
CGCM	1961–1990	12.6	12.6	12.2	11.7	11.0	10.4	10.1	10.1	10.5	11.1	12.0	12.0	11.4
	2010–2039	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
	2040–2069	-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6	-0.4
	2070–2099	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.5	-0.6	-0.7	-0.7	-0.5

Table 23: B2 scenario: dissolved oxygen (DO) concentration (mg L-1) for 1961–1990 for the three GCM models and absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods.

A2		J	F	M	A	M	J	J	A	S	O	N	D	Year
Observed	**mg L-1**	**12.5**	**12.5**	**12.2**	**11.6**	**11.0**	**10.5**	**10.1**	**10.1**	**10.5**	**11.0**	**11.9**	**12.3**	**11.3**
HadCM3	1961–1990	12.5	12.6	12.2	11.7	11.1	10.5	10.1	10.2	10.5	11.1	12.0	12.0	11.4
	2010–2039	0.1	-0.2	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.2	-0.1	-0.3	-0.3	-0.1
	2040–2069	-0.1	-0.1	0.0	-0.2	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2
	2070–2099	-0.2	-0.3	-0.2	-0.3	-0.3	-0.3	-0.2	-0.2	-0.3	-0.4	-0.5	-0.5	-0.3
CSIROMk2	1961–1990	12.6	12.6	12.3	11.7	11.0	10.5	10.1	10.1	10.5	11.1	11.9	11.9	11.4
	2010–2039	-0.5	-0.5	-0.4	-0.3	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.3
	2040–2069	-0.6	-0.5	-0.5	-0.5	-0.4	-0.3	-0.2	-0.3	-0.4	-0.4	-0.7	-0.7	-0.4
	2070–2099	-0.7	-0.6	-0.6	-0.6	-0.4	-0.3	-0.3	-0.4	-0.5	-0.6	-0.8	-0.8	-0.5
CGCM	1961–1990	12.6	12.6	12.2	11.7	11.0	10.4	10.1	10.1	10.5	11.1	12.0	12.0	11.4
	2010–2039	-0.3	-0.3	-0.2	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
	2040–2069	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.3	-0.2	-0.3	-0.3	-0.4	-0.4	-0.3
	2070–2099	-0.3	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.5	-0.5	-0.6	-0.6	-0.4

Table 24: Deviation from the 1961–1990 period for the overall A2 and B2 scenario (mg DO L-1).

		J	F	M	A	M	J	J	A	S	O	N	D
A2	2010–2039	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
	2040–2069	-0.4	-0.4	-0.3	-0.3	-0.3	-0.2	-0.2	-0.3	-0.4	-0.4	-0.4	-0.4
	2070–2099	-0.6	-0.6	-0.5	-0.5	-0.4	-0.3	-0.4	-0.4	-0.6	-0.6	-0.7	-0.7
B2	2010–2039	-0.2	-0.3	-0.2	-0.2	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3
	2040–2069	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4
	2070–2099	-0.4	-0.5	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6

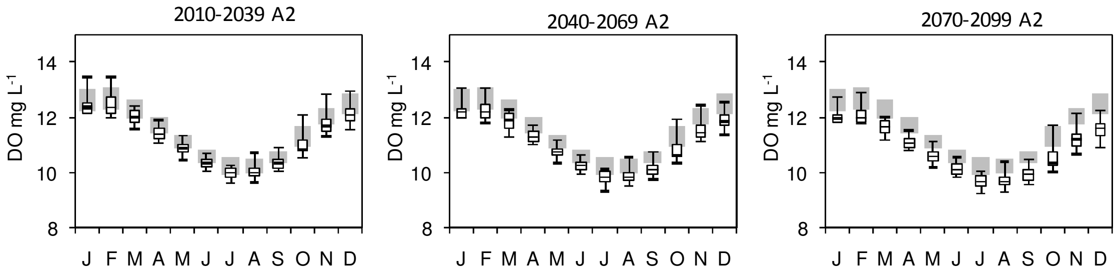


Figure 32: A2 scenario: boxplots of dissolved oxygen (DO) concentration (mg L^{-1}) for the combined GCM models for three periods: 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using historical meteorological data and are used to represent observed variability.

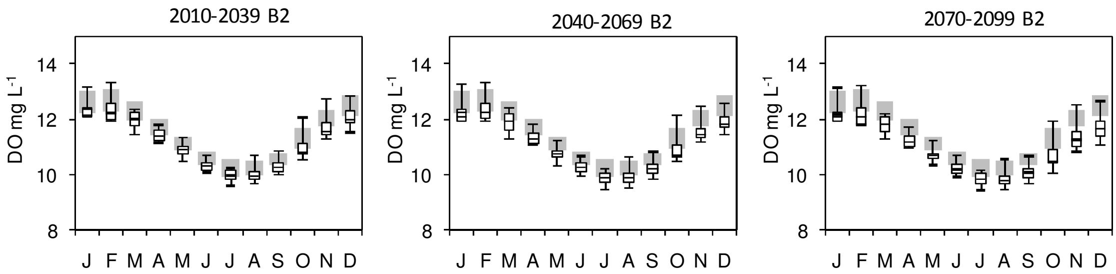


Figure 33: B2 scenario: boxplots of dissolved oxygen (DO) concentration (mg L^{-1}) based on the B2 scenario for the combined GCM models for three periods: 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using historical meteorological data and are used to represent observed variability.

While the overall decreases were greater in winter months, reflecting seasonal patterns in temperature increases (Table 24; Figure 32 and Figure 33), these would not be expected to have an impact on fish survival as catchment streams are well aerated during that period of the year. Dissolved oxygen levels during the summer are the most biologically relevant, because minimum concentrations generally occur in this period. These result from both decreased DO solubility due to higher temperatures and net respiration from primary producers and decomposers. To compare these temperature-driven impacts on DO concentrations to observed DO decreases that result from both temperature and biological impacts, the projected decreases for the 2071–2099 period were subtracted from the measured daily DO values for the Glenamong river for May to September 2006 (Figure 34). The measured monthly average DO levels for the months during which DO levels were lowest (namely June and July) were 8.4 mg DO L^{-1} and 8.5 mg DO L^{-1} while minimum daily values recorded were 6.9 and 7.0 mg DO L^{-1}. By subtracting the DO reduction due to temperature alone in those months from the measured values, it was estimated that biological activity accounted for an average reduction of -1.3 mg DO L^{-1}. The additional projected decreases due to the impact of RWT on solubility were -0.3 to -0.4 mg DO L^{-1} for June and July respectively. Even with these additional decreases, it was estimated that DO concentrations would remain above all critical values for salmonids described previously in Section 3. It should be noted, however, that DO levels can exhibit lower night-time levels during summer months depending on rates of in-stream primary production. The lowest measured DO concentrations in the Glenamong river between 2004 and 2006 occurred at midnight on 6/7 June 2006 (5.3 mg DO L^{-1}). The projected decrease due to higher RWTs would reduce a similar DO concentration to between 4.9 and 5.0 mg DO L^{-1}, close to the lower threshold for adult salmon (Alabaster and Lloyd, 1982).

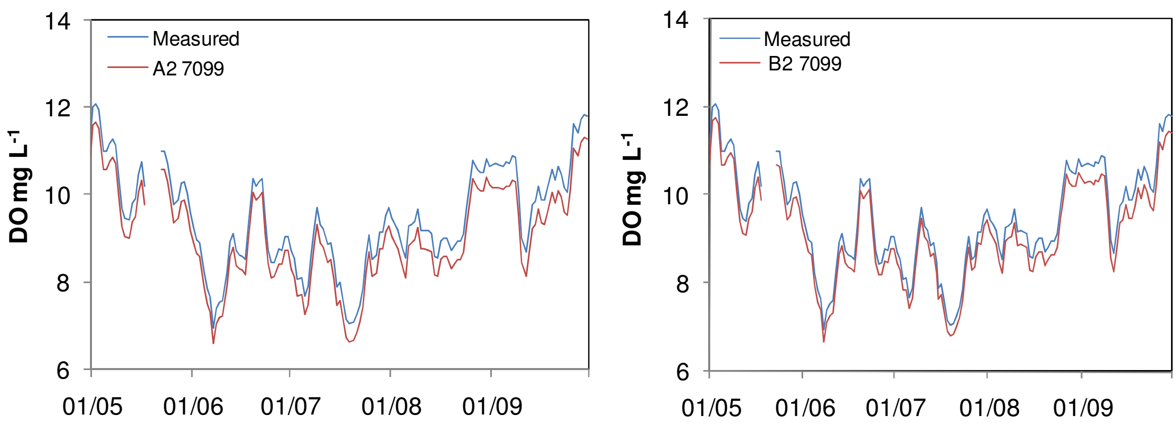


Figure 34: Measured dissolved oxygen (DO) concentration (mg DO L^{-1}) Glenamong river, May–September 2006.

6.5. Projected Changes in Lake Water Temperature

The one-dimensional hydrodynamics model DYRESM was used to predict the vertical distribution of temperature in Lough Feeagh. The model and software are currently available from the Centre for Water Research (CWR), University of Western Australia (http://www.cwr.uwa.edu.au). Model input data requirements include daily solar radiation, cloud cover, wind speed, vapour pressure, air temperature, and precipitation. Ten simulations were carried out for each GCM-emissions scenario combination. Water temperatures were output for 0.5 m (surface water temperature: SWT) and 40 m (deep water temperature: DWT).

Mean annual SWT in Lough Feeagh was projected to increase under both the A2 and B2 scenarios for all time-horizons (Table 25). The median increase was greater for each A2 scenario than for the equivalent B2 scenario. The greatest increase in annual temperature was projected when the model was run using input data based on the CSIROMk2 model and the A2 emissions scenario: these increases were 1.0°C, 1.6°C and 2.5°C for the 2010–2039, 2040–

2069 and 2070–2099 time periods respectively (Table 25). The increases for the CSIROMk2 B2 simulations for these same time periods were 1.1°C, 1.7°C and 2.1°C. The lowest increases were for the CGCM simulations: for the A2 scenario these were 0.8°C, 1.5°C and 1.9°C, while for the B2 scenarios they were 0.8°C, 1.3°C and 1.6°C. The overall increases for the A2 scenario for the three time-horizons 2010–2039, 2040–2069 and 2070–2099 were 0.6°C, 1.5°C and 2.1°C (Table 26), while those for the B2 scenario were 0.8°C, 1.3°C and 1.5°C (Table 27).

Table 25: Lake surface water temperature (SWT) in °C (0.5 m) for the observed period and for the 1961–1990 period for the three GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods for the A2 and B2 scenarios.

A2	**SWT**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Year**
Observed	**°C**	**5.5**	**4.9**	**5.7**	**7.8**	**11.0**	**14.4**	**16.0**	**16.2**	**14.5**	**11.9**	**9.0**	**6.5**	**10.3**
HadCM3	1961–1990	4.5	4.3	5.0	6.8	9.7	12.8	14.7	15.2	13.9	11.3	8.2	6.2	9.4
	2010–2039	0.1	-0.2	0.0	0.6	1.3	1.3	1.5	1.3	0.8	0.6	0.7	0.0	0.6
	2040–2069	0.7	0.7	0.7	0.8	1.9	1.7	1.9	2.0	1.6	1.3	1.1	0.3	1.2
	2070–2099	1.3	1.4	1.3	2.0	2.3	2.6	3.2	3.2	2.4	1.9	2.3	1.5	2.2
CSIROMk2	1961–1990	4.5	3.8	4.6	6.9	10.7	14.0	16.2	16.4	14.4	11.4	8.6	6.2	9.8
	2010–2039	0.9	0.8	0.7	1.3	0.8	0.6	0.5	0.7	1.0	0.8	0.9	1.3	1.0
	2040–2069	1.6	1.5	1.5	1.7	1.7	1.4	1.3	1.3	1.6	1.5	1.6	1.8	1.6
	2070–2099	2.9	2.7	2.5	3.1	2.7	2.1	2.1	2.2	2.5	2.2	2.2	2.7	2.5
CGCM	1961–1990	4.4	3.8	4.6	7.0	10.5	14.3	16.1	16.4	14.4	11.4	8.5	6.0	9.8
	2010–2039	0.9	0.6	0.7	0.9	1.0	0.5	0.8	0.8	1.0	0.9	0.4	0.7	0.8
	2040–2069	1.6	1.4	1.5	1.4	1.7	1.1	1.7	1.8	1.9	1.6	1.5	1.7	1.5
	2070–2099	1.8	1.5	1.9	1.9	1.7	1.6	2.2	2.2	2.4	2.1	2.0	2.0	1.9
B2	**SWT**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Year**
Observed	**°C**	**5.5**	**4.9**	**5.7**	**7.8**	**11.0**	**14.4**	**16.0**	**16.2**	**14.5**	**11.9**	**9.0**	**6.5**	**10.4**
HadCM3	1961–1990	5.1	4.2	4.9	7.2	10.5	14.3	16.3	16.1	14.2	11.6	8.8	6.7	10.1
	2010–2039	-0.5	0.2	0.3	0.5	0.6	0.2	0.2	0.7	0.9	0.3	0.4	-0.3	0.2
	2040–2069	0.4	0.7	0.5	0.6	0.7	0.5	0.3	1.0	1.1	0.6	0.8	0.2	0.6
	2070–2099	0.3	0.6	0.7	0.8	1.4	0.9	0.9	1.5	1.4	1.3	1.0	0.6	0.8
CSIRO-MK2	1961–1990	4.5	3.8	4.6	6.9	10.7	14.0	16.2	16.4	14.4	11.4	8.6	6.2	9.8
	2010–2039	1.1	1.3	1.1	1.1	0.8	0.9	0.8	0.9	1.4	1.2	1.0	1.1	1.1
	2040–2069	2.0	1.8	1.6	1.8	1.7	1.6	1.3	1.5	1.7	1.6	2.0	1.9	1.7
	2070–2099	2.2	2.1	2.3	2.3	2.3	1.7	1.7	1.7	2.1	2.0	1.9	2.4	2.1
CGCM	1961–1990	4.4	3.9	4.5	7.0	10.6	14.4	16.1	16.5	14.4	11.3	8.4	6.0	9.8
	2010–2039	0.8	0.9	1.0	1.0	0.8	0.3	0.9	0.8	0.9	0.9	0.7	0.8	0.8
	2040–2069	1.2	1.1	1.2	1.1	1.1	0.9	1.3	1.3	1.6	1.4	1.1	1.2	1.3
	2070–2099	1.4	1.2	1.6	1.6	1.6	1.3	1.6	1.7	1.9	1.9	1.7	1.5	1.6

Table 26: Overall A2 scenario: lake surface water temperature (SWT) (0.5 m) and deep water temperature (DWT) (40 m) in °C for the observed period and for the 1961–1990 period for the combined GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods for the A2 scenario.

		J	F	M	A	M	J	J	A	S	O	N	D	Year
SWT observed	**°C**	**5.5**	**4.9**	**5.7**	**7.8**	**11.0**	**14.4**	**16.0**	**16.2**	**14.5**	**11.9**	**9.0**	**6.5**	**10.3**
A2	1961–1990	4.4	3.8	4.6	6.9	10.6	14.2	16.2	16.4	14.3	11.4	8.5	6.1	9.8
	2010–2039	0.7	0.6	0.5	0.9	0.7	0.4	0.5	0.7	0.9	0.7	0.6	0.6	0.6
	2040–2069	1.4	1.4	1.4	1.3	1.4	0.9	1.2	1.4	1.6	1.3	1.3	1.4	1.5
	2070–2099	2.0	2.0	2.0	2.1	2.0	1.8	2.2	2.3	2.3	2.0	2.2	2.0	2.1
DWT observed	**°C**	**5.5**	**4.9**	**5.7**	**7.1**	**8.2**	**9.2**	**9.6**	**9.7**	**9.8**	**10.9**	**8.7**	**6.5**	**8.0**
A2	1961–1990	4.5	3.9	4.6	5.8	7.0	8.1	8.6	8.8	8.7	9.5	8.3	6.1	7.0
	2010–2039	0.7	0.7	0.4	0.5	0.5	0.2	0.1	0.2	0.3	-0.1	0.4	0.5	0.4
	2040–2069	1.4	1.4	1.2	0.8	0.8	0.4	0.3	0.2	0.4	0.4	1.3	1.2	0.8
	2070–2099	1.9	2.0	1.8	1.6	1.6	1.0	0.9	0.8	0.9	0.5	1.8	2.0	1.4

Table 27: Overall B2 scenario: lake surface water temperature (SWT) (0.5 m) and deep water temperature (DWT) (40 m) in °C for the observed period and for the 1961–1990 period for the combined GCM models together with the absolute change from this period for the 2010–2039, 2040–2069 and 2070–2099 periods for the B2 scenario.

		J	F	M	A	M	J	J	A	S	O	N	D	Year
SWT observed	**°C**	**5.5**	**4.9**	**5.7**	**7.8**	**11.0**	**14.4**	**16.0**	**16.2**	**14.5**	**11.9**	**9.0**	**6.5**	**10.3**
B2	1961–1990	4.6	4.0	4.6	7.0	10.6	14.2	16.2	16.4	14.3	11.4	8.6	6.1	9.8
	2010–2039	0.7	0.9	0.9	0.9	0.7	0.6	0.7	0.8	1.0	0.9	0.7	0.8	0.8
	2040–2069	1.4	1.1	1.2	1.1	1.1	1.1	1.1	1.4	1.5	1.2	1.2	1.2	1.3
	2070–2099	1.4	1.3	1.5	1.6	1.6	1.4	1.5	1.7	1.8	1.7	1.6	1.5	1.5
DWT observed	**°C**	**5.5**	**4.9**	**5.7**	**7.1**	**8.2**	**9.2**	**9.6**	**9.7**	**9.8**	**10.9**	**8.7**	**6.5**	**8.0**
B2	1961–1990	4.7	4.0	4.6	5.9	7.2	8.4	8.8	8.8	8.8	9.2	8.3	6.1	7.1
	2010–2039	0.6	0.9	0.7	0.5	0.3	0.0	0.1	0.2	0.0	0.3	0.6	0.7	0.4
	2040–2069	1.3	1.2	1.0	0.9	0.8	0.4	0.4	0.3	0.3	0.4	1.1	1.1	0.7
	2070–2099	1.3	1.4	1.2	1.1	1.1	0.5	0.4	0.4	0.3	0.4	1.5	1.5	0.9

Similar increases were apparent in the monthly mean values. There was a tendency for greater increases in the autumn and winter months than in summer for the simulations based on the CSIRO-MK2 and CGCM GCMs (Table 25). In contrast, higher increases were indicated in summer for the HadCM3 model. The projected increases for combined simulations based on the A2 scenario for the more immediate future (2010–2039) ranged from 0.4°C in June to 0.9°C in April and September (Table 26). The changes for the B2 scenario ranged from 0.7°C (January, May, June and November) to +1.0°C in September (Table 27). For the period 2040–2069, the changes based on the A2 scenario ranged from 0.9°C in June to 1.6°C in September. The lowest monthly increases for the A2 scenario for 2070–2099 were again in June (1.8°C) while the highest were in August and September (2.3°C).

The most striking difference between the projections for DWT and SWT were related to differences during summer months when the model lake was stratified (Table 26 and Table 27; Figure 35 and Figure 36). Simulated DWT were always similar to SWT in those months during which the lake was fully mixed between October and April. In contrast, and as would be expected, there was a substantial difference in surface and deep water temperature when the lake was stratified. In simulations based on observed data and in the simulations for the reference period 1961–1990, SWT and DWT differed by up to 6.5°C during the period of stratification. In contrast to SWT, there was no significant increase in DWTs during the months between May and October (Figure 35 and Figure 36). This lack of any increase in DWT replicated the buffering of the water column below the thermoclime from the influence of changes in local weather during summer months.

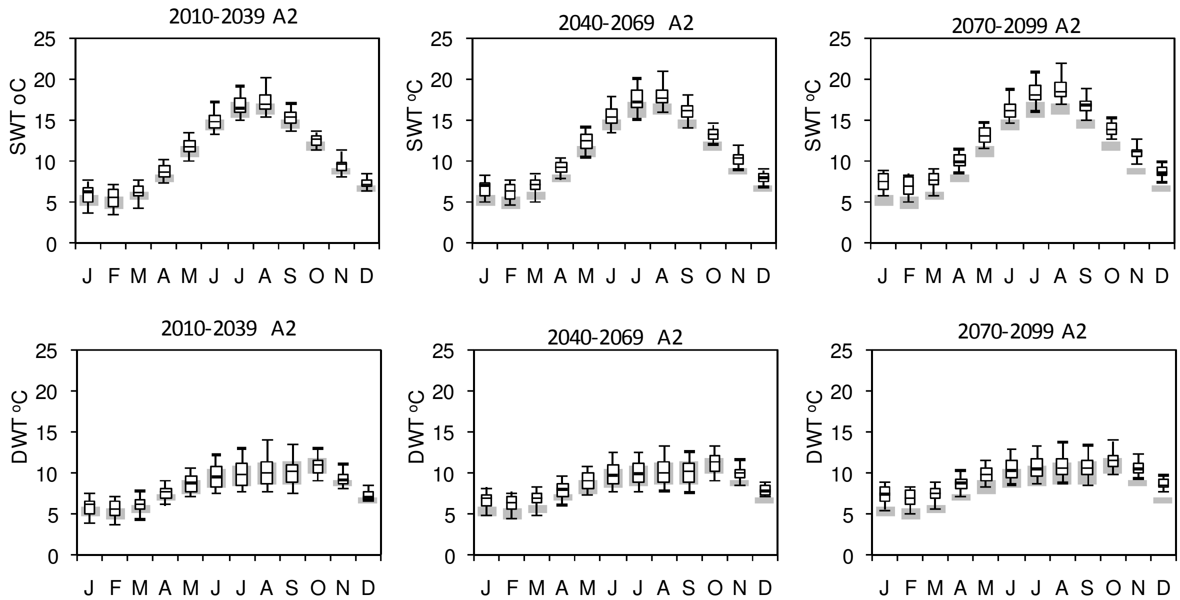


Figure 35: Boxplots of lake surface (SWT) and deep water temperature (DWT) in °C based on the A2 scenario for the three GCM models for three future periods: 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using resampled historical meteorological data and are used to represent observed variability.

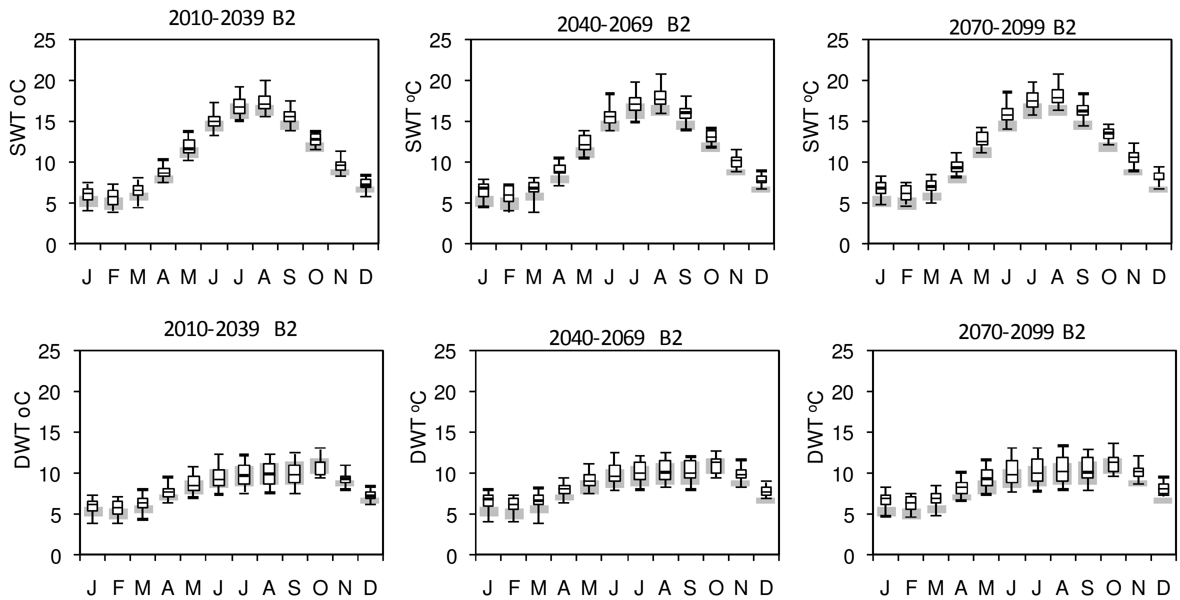


Figure 36: Boxplots of lake surface (SWT) and deep water temperature (DWT) in °C based on the B2 scenario for the combined models for 2010–2039, 2040–2069 and 2070–2099. Shaded areas are the 25 percentile to 75 percentile range for model runs using resampled historical meteorological data and are used to represent observed variability.

6.6. Key Results

- Projected changes in climate are likely to affect a range of water quality parameters, including water temperature, water DO concentrations and DOC concentrations, which may impact on fish growth and survival.
- The projected increases in mean annual RWT for both the A2 and B2 scenarios for 2010–2039 were 0.6°C, 1.1°C and 0.8°C for the HadCM3, CSIRO-MK2 and CGCM models respectively. The annual increases for the A2 simulations ranged from 0.8°C to 1.6°C for 2040–2069 and 1.9°C to 2.3° C for 2070–2099. The increases for the B2 scenario for the same time periods ranged from 0.8°C to 1.6°C (2040–2069) and from 1.3°C to 1.9°C (2070–2099).
- Increases in DOC concentrations were also projected for all GCM model and emission scenario combinations from the 2010–2039 period onwards. The overall increase from 1961–1990 to 2070–2099 for the A2 scenario was 2.4 mg DOC L^{-1} while that for the B2 scenario was 1.8 mg DOC L^{-1}.
- In spite of the dominant influence of RWT on DO levels, projected changes in temperatures resulted in only an additional 4% to 7% decrease in average daily DO concentrations during summer months.
- The overall increases in lake SWT for the A2 scenario for the three time-horizons 2010–2039, 2040–2069 and 2070–2099 were 0.6°C, 1.5°C and 2.1°C respectively,

while those for the B2 scenario were 0.8°C, 1.3°C and 1.5°C for the same time periods.

- While DWT was projected to increase by a similar range to SWT during months when the lake was fully mixed, there was no significant increase in DWTs during months when the lake was stratified.

7. Impacts of Projected Climate Change on Migratory Fish Species in the Burrishoole

7.1. Introduction

Changing climate is expected to affect fishery resources: it will present a challenge to managers to develop sustainable exploitation and management strategies (Rijnsdorp et al., 2010). With the accumulating evidence for changing climate linked to increasing concentrations of GHGs (IPCC, 2007), there is a general concern about the impact on productivity and distribution of many commercially exploited marine stocks and also the effect on the sustainability of fisheries (reviewed by Rijnsdorp et al., 2010; Graham and Harrod, 2009). Fish have complicated life cycles, and each life-history stage (eggs, larvae, juveniles and adults) may have varying habitat and dietary requirements (Rijnsdorp et al., 2010). Diadromous species complicate this picture further by migrating between the sea and freshwater in order to complete their life cycle, requiring transformations in physiology often in conjunction with the maturation process. The assessment of possible impacts is complicated by the fact that diadromous species may migrate through several climatic regions. As a result, for a full understanding of the possible effects of climate change on these species, it is important to adopt an integrated approach that includes the full life cycle and the various habitats and environments.

Worldwide, there are estimated to be roughly 250 species of diadromous fish (Nolan et al., 2009). Diadromous fish in Ireland are composed of a limited number of species because of factors such as recent glaciations and the island's northerly location. They include Atlantic salmon (*Salmo salar*), sea trout (*S. trutta*), eel (*Anguilla anguilla*), twaite and allis shad (*Alosa fallax* and *Alosa alosa*), smelt (*Osmerus eperlanus*), sea and river lamprey (*Petromyzon marinus* and *Lampetra fluviatilis*), along with flounder (*Platichtys flesus*), stickleback (*Gasterosteus aculeatus*) and some mullet species (*Family Mugilidae*). These species can be further divided into anadromous species that spend most of their lives in the sea and migrate to freshwater to breed (e.g. Atlantic salmon, sea trout and shad) and catadromous species that conversely migrate from freshwaters to the sea to breed (e.g. European eel and flounder).

Given their high sensitivity to environmental conditions and the large distances that some of these fish can cover during their migration, diadromous species are particularly vulnerable to changes associated with climate, both in freshwater and in the marine environment (Lassalle et al., 2008). The key eco-physiological processes of the various life stages of diadromous fish in freshwater – such as hatching and survival in anadromous fish and smoltification and migration in salmonids – are controlled by a range of environmental variables, including temperature, sunlight, day length and rainfall. Other variables, such as water colour, oxygen levels, pH and water flow may also impact on these key processes by, for example, reducing light penetration or increasing drought- or flood-induced mortality.

Projected changes in rainfall and temperature associated with climate change are likely to have significant impacts on the ecology of fresh and transitional waters in Ireland. Ocean climate changes are already known to have an impact on salmon at sea, largely through the close interaction between growth and survival (Peyronnet et al., 2007). Diminishing eel populations may also be the result of changes in the ocean in conjunction with human-induced pressures (ICES, 2008). It is also expected that climate change will drive the distribution of many diadromous fish species northwards as various species respond largely to temperature- and precipitation-related variables (Lassalle and Rochard, 2009). While such responses are likely to be species and catchment specific, it is largely unknown whether the observed or predicted distributional shifts are caused by the relocation of spawning and feeding grounds, a change in the local survival of fish or immigration into new habitats. These species are, however, subject to a range of other pressures in addition to climatic drivers. Many of these pressures, such as exploitation, eutrophication, habitat change, fluctuating population densities and genetics (e.g. caused by stocking non-native or cultured fish) have been changing over the last few decades in parallel with the observed changes in climate. Untangling these various drivers is part of the challenge of assessing the impacts of climate to date and of making projections for the future impact of changing climate.

7.2. Trends in Diadromous Fish in Burrishoole

Mill Race fish trap, Burrishole, Co. Mayo

The Burrishoole catchment, situated in Newport, Co. Mayo on the west coast of Ireland, has full fish-trapping facilities for counting fish migrating between the sea and freshwater. The Marine Institute's facility in Burrishoole is an international index site for some diadromous species. Present in the Burrishoole catchment are salmon, trout, char, eels and stickleback. Intensively monitored fish-trapping operations in Burrishoole have the unique advantage of being able to monitor all movements of salmon, sea trout and eels to and from freshwater. The data collected over the last 50+ years are used nationally to model population dynamics of the local stock and by the International Council for the Exploration of the Sea (ICES) to help gauge the overall status of the Irish stocks of salmon, sea trout and eel on an annual basis. In line with the fish-stock monitoring, a comprehensive monitoring network of instrumentation, including the Met Éireann Weather Station in Furnace, has been established, leading to a considerable dataset of environmental variables (Whelan et al., 1998). It is this environmental dataset (described and analysed in the current project), along with those from strategically selected catchments around the country, that will form the basis for assessing the future impact of changing climate on riverine and lacustrine habitats and species.

Salmon, sea trout and eel populations have been monitored in Burrishoole since 1958, with a full census of upstream and downstream migrating fish since 1970. An experimental captive breeding and smolt release (ranching) programme was also established in Burrishoole between 1960 and 1964 using the native grilse; this has been continued to date in parallel to the wild census progamme. There have been a number of observed changes to the stock structure and numbers of fish migrating over this time period for all three species but probably for different reasons. In many cases, the changes may have been caused or influenced by ocean- or climate-related factors overlaid with human-induced impacts.

7.2.1. Atlantic salmon

The numbers of Atlantic salmon recorded in the upstream traps since full trapping commenced in the 1970s have fluctuated from a high of 1,777 in 1973 to a low of 252 in 1990 (Figure 37). Annual escapement to freshwater is known to have been influenced by both the level of exploitation in the coastal drift net fishery and fluctuation marine survival to the coast. Following the cessation of this fishery in 2007, a marked increase in the numbers of fish returning to the catchment was recorded in that year. However, this increase occurred only in 2007, with numbers in 2008 and 2009 falling to levels similar to those recorded prior to the cessation of drift netting. This fall in numbers would indicate a probable decrease in marine survival in line with the reported downward trend in pre-fishery abundance for the Irish stock (Peyronnet et al., 2007).

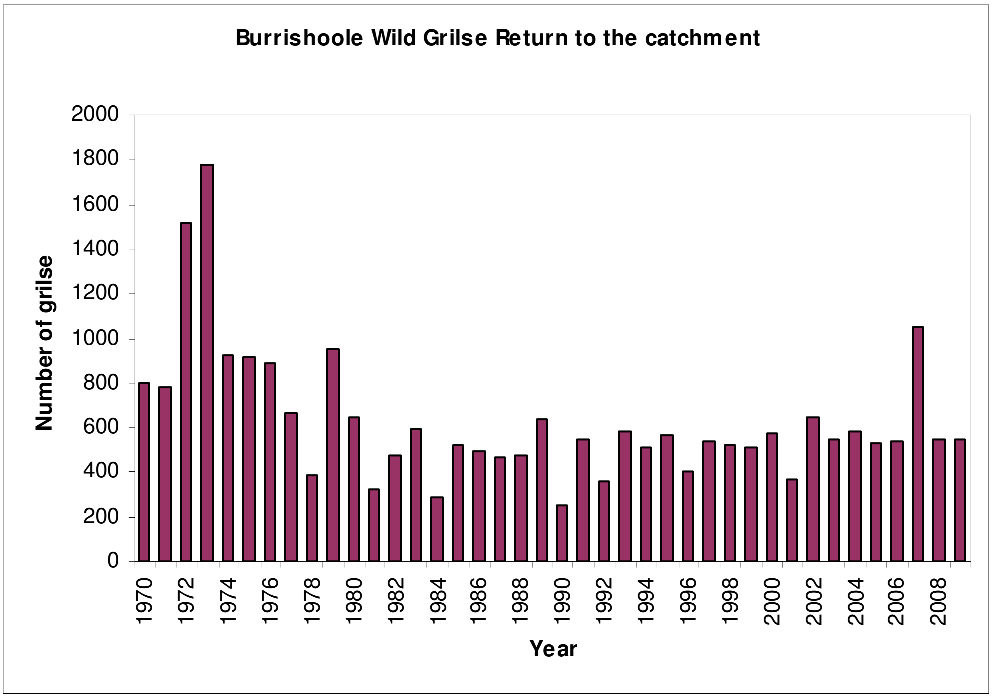


Figure 37: Number of returns of wild adult salmon to Burrishoole catchment (trap and fishery), 1970–2009.

The numbers of smolts recorded in the downstream traps have varied from a maximum of 16,136 in 1976 to a minimum of 3,794 in 1991. It is difficult to determine an overall trend during the time-series because factors – such as ranched fish components released into the spawning stock or habitat availability and quality – have varied during the period.

7.2.2. Sea trout

In the Burrishoole catchment, there has been a considerable annual variation in the numbers of returning finnock (0+ sea-age adult sea trout), with returns historically varying between 11.4% and 32.4% of the smolt output, indicating that marine survival is probably affected by a number of factors (Poole et al., 2006). The stocks of returning sea trout collapsed during the period 1989–1990, with a sudden strong reduction in marine survival to a finnock return of only 1.5% in 1989 (Figure 38). A regime shift in marine survival of 0+ sea-age trout (finnock), which began in 1987 has been detected in the Burrishoole data using Rodionov's (2005) sequential regime shift detection. This corresponded with several factors being negatively related to marine survival of the trout: the development of salmon farming in Clew Bay; warm winter and spring temperatures; and higher rates of sea lice on wild sea trout in Clew Bay (Tully, 1992; Gargan et al., 2003). Sea trout and salmon go through a physiologically stressful transition from freshwater to sea water and this, in conjunction with a new lice burden, can cause additional stress to the fish (Poole et al., 2000). In addition to the pressures caused by salmon farming, 1987/1988 was the year in which a significant step change was noted in air and water temperatures in Europe (e.g. Fealy and Sweeney, 2005; Hari et al., 2006) and in Ireland (Donnelly et al., 2009). This step change was associated both with an increase in disease in trout in Switzerland (Hari et al., 2006) and increased sea lice production in western Ireland in 1987 to 1989 (Tully, 1992) – underlining the problems of untangling impacts where multiple drivers are involved.

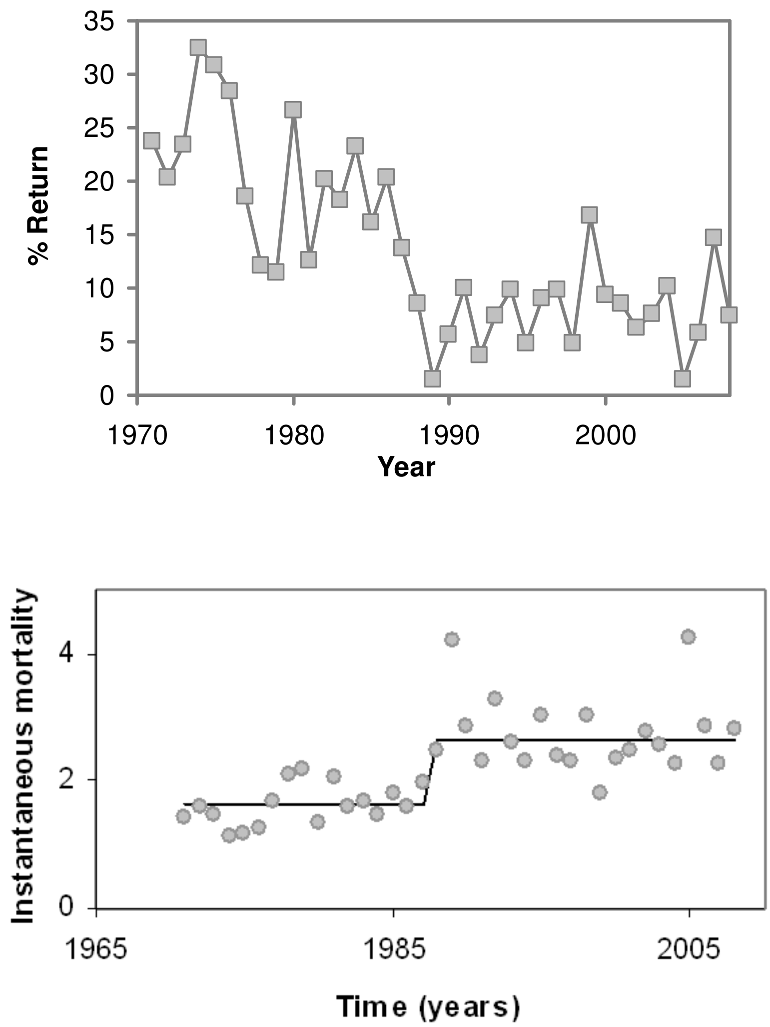


Figure 38: (a) Annual percentage return of sea trout smolts returning as finnock (0+ sea age) to the Burrishoole traps (updated from Poole et al., 2006) (top). (b) Instantaneous mortality rates for finnock (circles) showing regime shift (weighted mean of regimes [black line]) before and after the 1987 step change (bottom).

7.2.3. Trends in smolt run timing in Burrishoole

The timing of the salmon smolt run in Burrishoole has shown a general advancement in the start date of the run. A severe drought in the Burrishoole catchment in 1980 caused an exceptional delay in smolt migration. If the data from 1980 are included, a significant trend in the data (*$p<0.01$*) can be seen, with the salmon run starting on average 11 days (9 days excluding 1980) earlier in recent years when compared to data from the 1970s and 1980s (Figure 39). Although the date when 50% and 95% of smolts had migrated did not show a significant trend, they were 6 and 2 days earlier, respectively, in recent years.

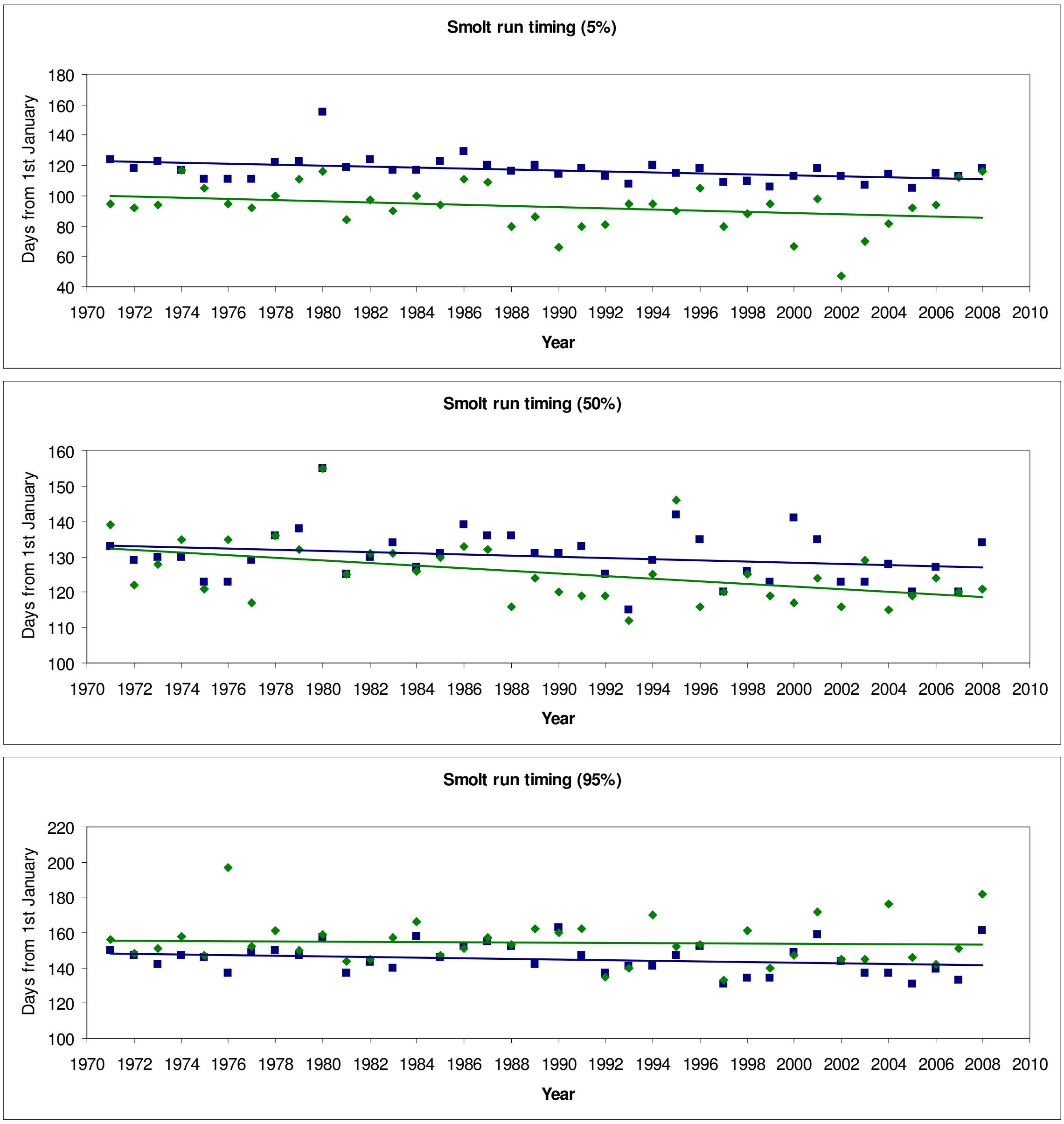


Figure 39: Number of days from 1 January each year for 5% (top), 50% (middle) and 95% (bottom) for the salmon (blue) and sea trout (green) smolt runs to be achieved in the Burrishoole catchment, Co. Mayo, 1971–2008 (provided by Lee Hancox).

For the sea trout smolt migration, the midpoint of the run was significantly earlier with the 50% point occurring 14 days earlier in recent years (*$p<0.004$*). The 5% point of the run also appears to be occurring approximately 14 days earlier, but this change was not significant (*p = 0.08*).

The general trend for both species is for a longer smolt run that starts earlier. The earlier start time of the run is likely to be linked to warmer water temperatures during the preceding winter, although some years also see a delay in the later part of the smolt run because of droughts. Jonsson and Jonsson (2009) also observed that smolt migrations started earlier and took place over shorter time periods in mild years. There is, however, an interaction between the earlier timing due to rising temperature and the delay due to drought. The outlying point for 1980, and evidence from a similar event in 2010 when the salmon smolts migrated in a 4-day period in June, could be an indicator of what may happen if such droughts become more frequent in the future as suggested in Section 5. Repeated higher frequency of droughts could have serious impacts on the survival of subsequent generations of salmon.

7.2.4. Eel

There are no local data for the recruitment of glass eel into the Burrishoole. Anecdotal information indicates that recruitment into the catchment has fallen drastically since the early 1980s in line with other areas in Ireland and around Europe (ICES, 2009), where all glass eel recruitment series demonstrated a clear decline since the early 1980s. For the different areas (Baltic, North Sea, Atlantic, Mediterranean, Britain and Ireland), levels have dropped to between 1 and 9% of 1970s' levels (ICES, 2009). Such a large-scale decrease over the large number of recruitment indices across Europe suggests that a broader meteorological or climatic change might be a contributory factor. Such a change could also affect both the larval survival in the ocean and adult growth in freshwater by altering the conditions needed by the species to grow and migrate.

The silver eel migrations in Burrishoole have been studied since 1959 (Piggins, 1985; Poole et al., 1990) using the total downstream trapping facilities. Numbers of eels in the annual migrations have decreased over the time period (Figure 40). The total weight of the silver eels has not been affected by the drop in numbers, which has been compensated for by a change in sex ratio from 63% males in the 1970s to 32% in the 2000s; this has also been accompanied by a rise in the average size of female eels. A decline in elver recruitment and increasing catchment productivity may be contributory factors in causing these changes (Poole et al., 1990).

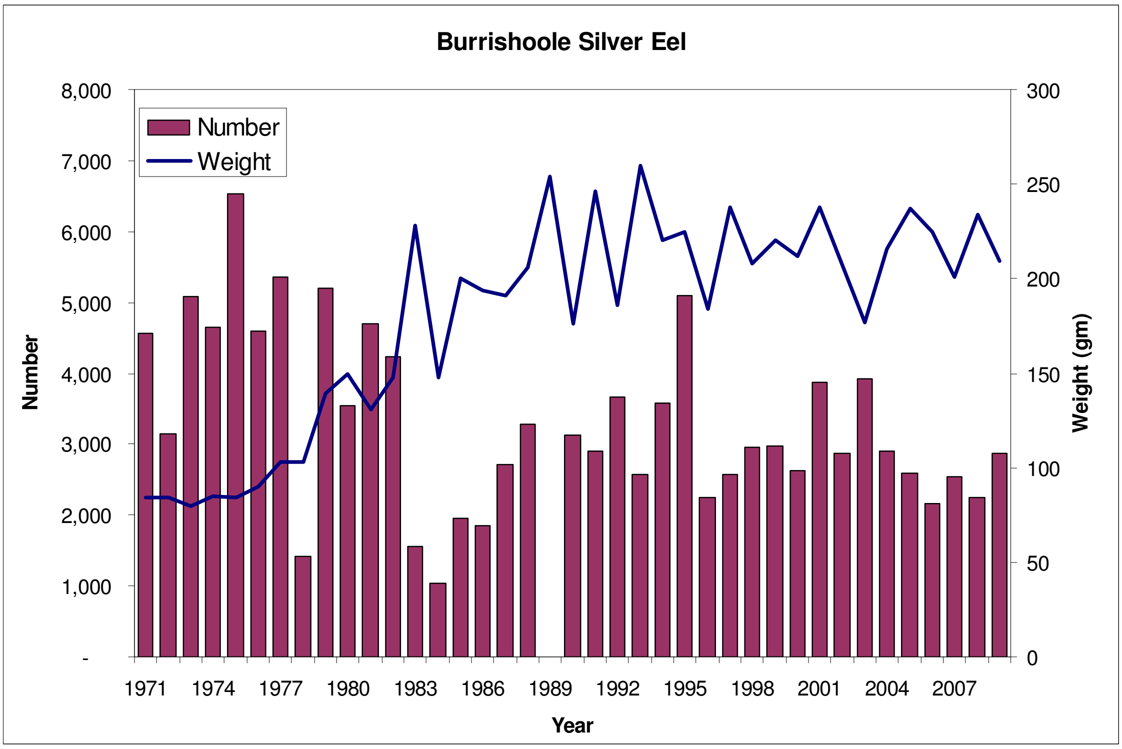


Figure 40: Number and average weight of migrating silver eels from Burrishoole, 1971–2009.

7.3. Studies on Fish Growth in Burrishoole

7.3.1. Salmon

Temperature affects metabolic processes and growth in fishes. It also influences the timing and duration of most life-history stages – from the emergence of fry from spawning gravels, to the size of parr in freshwater to the emigration of smolt to the sea (Connor et al., 2002). Fish are sensitive to temperature changes both through heat exchange in the gills and by heat transfer through the body wall (Elliott, 1981). Because of the allometric relationship between the volume and the surface area of a fish, small fish are more susceptible to fluctuations in water temperature than larger ones (Elliott, 1994).

Age at smolting is influenced by parr growth and size. Fast growers tend to smolt at an earlier age and at a smaller size than more slow-growing individuals from the same populations (Strothotte et al., 2005). The effects of water temperature on smolt age and size are mediated through variations in growth rate, although smolt size may be more directly associated with water temperature (Jonsson and Jonsson, 2009). Salmon smolts growing in rivers which empty into relatively warm sea water are generally smaller than those smolts entering colder sea water. This is thought to be partly due to the fact that ionic regulation in cold sea water is easier for larger than for smaller fish (Jonsson and Jonsson, 2009). Even though growth rate is temperature dependent, there may be some confounding factors such as fish density and feeding opportunities (Jonsson and Jonsson, 2009).

An analysis was carried out on the average percentages for each age class for salmon smolts in Burrishoole for the years 1968–1984 inclusive and 2003–2008 inclusive. Smolt age showed a significant shift in the percentage make-up of the age classes over time, mainly demonstrated by the increase in the proportion of the 1+ age class in recent years from <11% to >11% compared to the 2-year-old smolts (2 and 2+ age) (Chi-squared value = 10.75, DF = 2, p = <0.001).

Smolt length was also assessed. Significant differences in length were found between 1968 and all other years sampled, with fish from 1968 being significantly smaller. After this, fish from 1977, 1982, 1984 and 2007 were significantly larger than fish from 2004 and 2008, and fish from 2004 and 2006 were significantly smaller than fish from 2007 (ANOVA, $p<0.001$). However, there was no significant trend in terms of either increasing or decreasing fish length over time.

In addition to the analysis on smolt age, the growth rate of juvenile salmon in Burrishoole was determined using back-calculation of increments from their scales (Figure 41). Scales preserve the growth history of the fish through different widths of circuli laid down, similar to annual rings used to age trees. While clear changes in growth rates were not apparent in this study there was, however, an increase in recent years in the growth rate during the second year of growth (both periods – 'summer' vs 'winter') for 2+ smolts, the dominant age class in Burrishoole. It was also clearly apparent that the winter growth in both 1-year-old and 2-year-old parr in 2008 was the fastest observed in any of the years studied.

Other studies have also observed increases in juvenile growth rate and a reduction in smolt age. Aprahamian et al. (2008) found an increase in growth rate in juvenile salmon and a concomitant decline in smolt age for salmon from the River Dee (UK) for the time period 1937–2005. On the River Dee, the increase in freshwater growth rate is likely to explain the decline in mean smolt age as the faster growing parr migrate to sea earlier (Metcalfe et al., 1989; Økland et al., 1993). This change would appear to have started in the 1980s. The study suggested that this increase in growth rate may have been related to a reduction in density-dependent processes – that is, the density of fish (i.e. less fish leads to less competition for food and faster growth) in the catchment habitat (Gibson, 1993; Jenkins et al., 1999; Imre and Boisclair, 2005; Lobón-Cervia and Mortensen, 2005). However, other studies have found no such relationship (Egglishaw and Shackley, 1977; Elliott, 1994). Temperature is known to affect the timing and the size of alevins at emergence and their subsequent growth and survival (Brett, 1979; Elliott et al., 2000). However, although the mean temperature in the Dee has increased by 0.2°C a year since the 1960s, it was considered unlikely that a change in emergence time alone could account for the increase in length at age (Aprahamian et al., 2008).

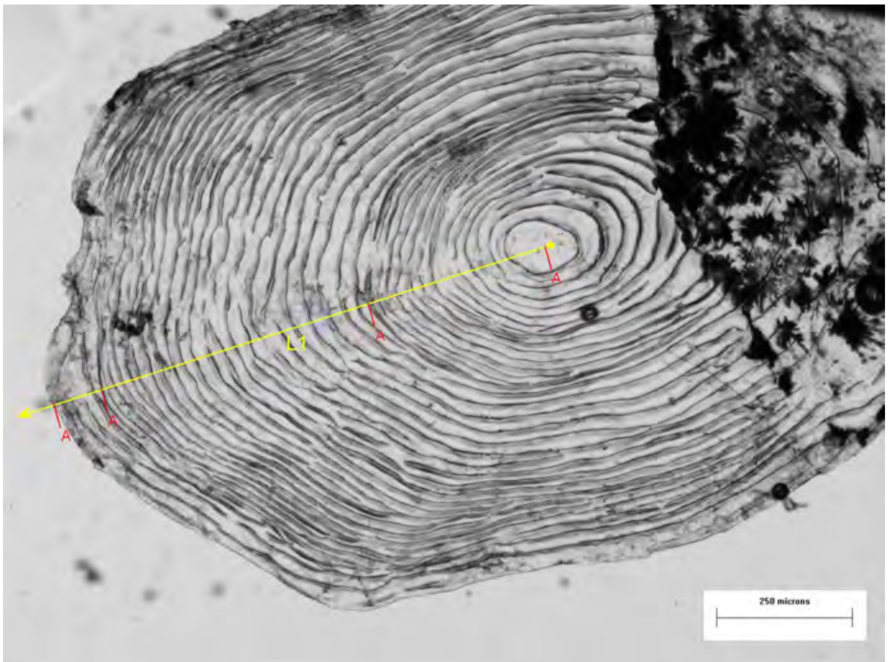


Figure 41: Salmon smolt scale with annual markings. Yellow line is the axis used to calculate growth and red markers are points identified as the central focus, the end of years 1 and 2 and the outer 'plus growth'.

Lower mean smolt ages have been also been seen in other British (Davidson and Hazelwood, 2005; J. Maclean, unpublished data) and French populations of salmon (Baglinière et al., 2005). Davidson and Hazelwood (2005) reported an overall decline in the mean smolt age of both 1SW and 2SW salmon on the Severn (England) and Wye (Wales) since the 1960s. The onset of this decline also appeared in the 1980s but was less marked on the Severn. This decline in smolt age may affect reproductive success as egg size is smaller for S1 as opposed to S2 smolts of the same sea age while early survival (egg to swim-up) may also be lower (Moffett et al., 2006). Increased marine mortality may be related to the fact that salmon smolts are migrating at a younger age and thus smaller size (Økland et al., 1993) resulting in a lower survival rate when compared to their larger conspecifics (Chadwick, 1985; Lundqvist et al., 1994).

7.3.2. Trout

In Burrishoole, trout are a partially migratory species, with both resident and migratory individuals present. The migrants move to the sea to feed, while the residents remain in freshwater. Resident individuals usually become mature at the parr stage, while the migratory individuals mature later after undergoing smoltification and a growth period in the sea. Parr maturity is linked to growth rate, and therefore indirectly related to temperature (Jonsson and Jonsson, 2009). Anadromy in trout populations also increases with increasing latitude, possibly because of improved feeding opportunities in the marine environment. This is a situation which could be influenced by future climate change (Jonsson and Jonsson, 2009).

There has been a dramatic change in the numbers of sea trout smolts migrating from the Burrishoole catchment. Smolt output has fallen from 4000+ pre-1985 to an average of ~700 in the last decade (Poole et al., 2006). This decline would have resulted in a concurrent change in density in the freshwater environment which could influence trout growth rate and smolt age. This makes a comparison between years and with other environmental factors difficult.

Comparison of smolts and resident trout from Lough Feeagh in Burrishoole showed smolts to be consistently larger at each age class (Poole et al., 1995; Current study). This would appear to contradict the hypothesis that smolts are largely derived from slower-growing parr unable to maintain territories and therefore undergo density-dependent downstream migration. Four-year-old smolts were the only group that seemed to exhibit slower or equal growth to their resident counterparts. Bohlin et al. (1994) also showed smolts to be longer and heavier than either mature male parr or immature parr 1 year in advance of smoltification. Elliott (1994) also concluded that it is the larger, faster-growing fish in each cohort that actively migrate downstream as smolts.

The mechanisms determining the size and age at which salmonids smoltify and migrate to sea remain unresolved. For Atlantic salmon, Elson (1957) claimed that parr must attain a minimum length of 10 cm by autumn in order to smoltify the following spring. Physiological studies (Wright et al., 1990; Skilbrei, 1991) provide supporting evidence that the 'decision' to smoltify is taken the previous autumn. Jonsson (1985) found growth rate, rather than absolute size, to be more effective in determining smolt age. An examination of the Burrishoole smolt data would also point towards growth rate rather than absolute size as a key factor in triggering smoltification.

Elliott (1994) recorded a slight decrease in the mean smolt age of trout from Black Brows Beck (UK). Similar trends in some Irish and Scottish populations have been attributed to increased growth due to milder winter conditions and a prolonged feeding period, and to increased abundance of prey through agricultural enrichment (Fahy, 1978; Pratten and Shearer, 1983). While the current Burrishoole study has not shown any significant increases in growth rate in trout smolts, there is an indication that smolt age may be reducing, with a higher percentage of 2/2+ smolts in the 2008 sample together with an absence of 4/4+ smolts, although this is highly variable between years (Poole et al., 2006).

7.3.3. Eel

Burrishoole eels mature at a smaller size and an older age than most of the studied European eel populations, and are most similar to those of Lough Neagh and the Rivers Bann and Erne (Matthews et al., 2003), although the ages in Burrishoole are considerably older. In fact, female eels as old as 57 years were recorded in the silver eel migration in 1987 and 1988 (Poole and Reynolds, 1996). This is typical of the more northern latitudes in the eels' range and of nutrient-poor catchments.

The effect of temperature on eel growth is well known in aquaculture where eels are reared at optimal temperatures for growth of between of 23 and 25°C (Ciccotti and Fontenelle, 2001; Dosoretz and Degani, 1987; Holmgren, 1996). The water temperatures observed in Burrishoole are generally well below the optimum for eel growth.

Simulations of future changes in RWT in the Burrishoole catchment for 2010–2099 indicate that temperatures will increase throughout the year (Section 6). Generally, the relative increases in summer (June to August) are expected to be of a smaller magnitude than the annual increase. In contrast, the increases in late autumn to early spring (November to March) are higher. Eels are unlikely to be negatively affected by the projected changes in RWT in Burrishoole over the next century and are more likely to benefit. The results from the current study in Burrishoole (Current study), using back-calculation of growth rates from otoliths (Figure 42), indicated that there had been an increase in the growth rate of eels in their first 5 years in freshwater based on data from 1990 onwards. It would be expected that the predicted future increases in RWT would result in a further increase. Higher winter RWT especially could have positive knock-on effects for food supply and the length of the growing season.

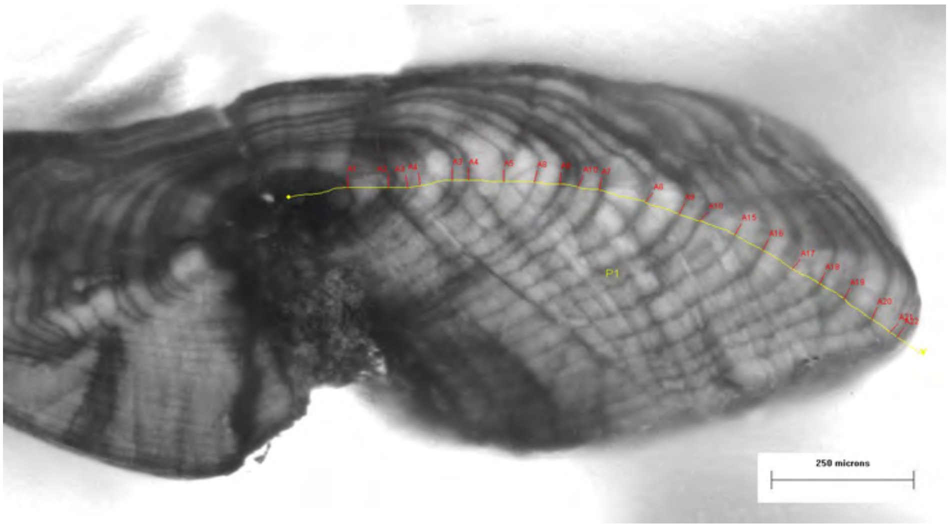


Figure 42: Eel otolith prepared by cutting and burning with annual age markings overlaid as indicated by red markers.

An increase in growth rate is likely to have several impacts on factors – such as age and size at maturation and on the sex ratio within the catchment. Faster growth will result in eels reaching a larger size at a younger age and migrating out to sea to spawn at an earlier age than that currently observed in Burrishoole. A change in the sex ratio of eels has already been observed in the Burrishoole catchment, with the percentage of males changing from 63% in the 1970s to 32% in more recent years. One theory to explain this change is that it is linked to increased productivity in the catchment along with reduced recruitment, a situation that is likely to continue with rising water temperatures.

While there are many factors affecting the survival of European eels in freshwater, it is possible that increasing water temperatures in Northern Europe will have a positive impact on the species, possibly aiding in a future recovery of the stock.

7.4. Potential Impacts of Climate Change on Fish Populations

The projected changes in climate and water-quality parameters described in this report which could directly affect fish growth and survival include increases in RWT and lake SWT, and changes in river flow related to changing rainfall patterns, decreases in DO and DOC concentrations and river flow related to changing rainfall patterns.

7.4.1. Impacts of projected temperatures on salmonids

Increases in water temperature may have both potential positive and negative consequences for salmonid populations and ecosystem functioning in the Burrishoole catchment. Direct temperature impacts would include changes in the number of times when threshold values are exceeded and to the impacts of upward trends in mean temperatures on physiology and phenology. The projected monthly mean RWTs and lake SWTs in Burrishoole remained within the ideal range for salmonid fish habitats (7°C to 20°C). However, the number of days when RWT exceeded 22°C – for example, the threshold when salmon parr cease feeding and seek refuge (Elliot, 1991; Cunjak et al., 1993) – increased in all four time-horizons for both scenarios (Figure 43; Table 28). There was also a slight increase in the number of days when RWT exceeded 26°C (the ultimate lethal threshold for trout parr) in the two later time-horizons: 2040–2069 and 2070–2099. It is notable, however, that the number of days when lake SWT was projected to exceed the 22°C threshold was much lower than that indicated for RWT, and was confined to simulations based on the HadCM3 model (Figure 43a and b; Table 28).

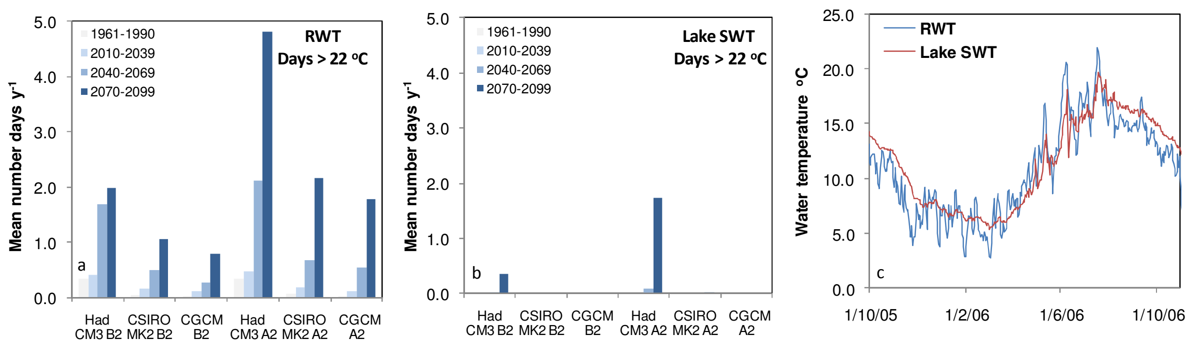


Figure 43: Number of days over 22ºC (upper threshold for *S. salar* parr to cease feeding and to seek refuge) for a (left) RWT, b (centre) SWT and c (right) RWT and lake SWT.

This difference in the occurrence of extreme temperatures between the lake and catchment rivers reflects the more buffered nature of lake SWT, as illustrated using measured data from Lough Feeagh and one of the catchment RWT monitoring sites for 2005/2006 (Figure 43c). The lower projected increase in deeper waters in the lake during summer months also highlights the potential for these deep lake waters below the thermocline to provide a refuge for fish species if surface waters should exceed critical thresholds (Tanaka et al., 2000; Mathes et al., 2010).

Table 28: Average number of days/year when projected river water temperature was above critical temperature thresholds for A2 and B2 scenarios.

°C	Threshold	Period	A2	B2
22	Seek refugia (salmon parr) Upper range feeding (salmon parr)	1961–1990	0.15	0.13
		2010–2039	0.26	0.23
		2040–2069	1.11	0.82
		2070–2099	2.91	1.27
26	Ultimate lethal level (trout parr)	1961–1990	0.00	0.00
		2010–2039	0.00	0.00
		2040–2069	0.01	0.02
		2070–2099	0.05	0.02
30	Ultimate lethal level (salmon parr)	1961–1990	0.00	0.00
		2010–2039	0.00	0.00
		2040–2069	0.00	0.00
		2070–2099	0.02	0.00

The temperature thresholds presented in Table 28 are all at the extreme high end of the temperature range and more likely to occur in summer. However, the season with the greatest projected increase in both RWT and lake SWT in Burrishoole was winter. A recent study based on data from the Burrishoole system has shown that higher water temperatures during the first and second winters, when salmonid eggs were incubating in gravel beds and when fish were in the parr life stage, respectively, have had negative impacts on salmon freshwater survival (McGinnity et al., 2009). A dearth of such long time-series datasets for key taxonomic groups, including fish, and a shortage of studies on ecological responses to combined pressures, were identified as major knowledge gaps in research supporting the EU Water Framework Directive (Directive 2000/60/EC) by Heiskanen and Solimini (2005). Adult Atlantic salmon in the Burrishoole river system typically spawn in late November, December and early January. Historical estimates of egg deposition in the catchment included eggs from both wild salmon and those from adults from an experimental captive breeding and smolt release (ranching) programme established between 1960 and 1964. Returning ranched adults, surplus to the requirements of the breeding programme, were allowed to ascend the river system until 1997 and could therefore interbreed with wild fish (Thompson et al., 1998). The numbers of ranched fish entering the river has since been curtailed to prevent such interbreeding.

Analyses of these data indicated that 76% of the variability in freshwater survival was explained by five climate-related factors and the proportion of eggs contributed by ranched fish. The proportion of eggs from ranched fish had a negative impact on survival (McGinnity et al., 2009).

Higher water temperatures in the first winter when eggs were incubating in gravel beds and during the second winter when fish were in the parr stage also had negative impacts on survival. The impact of higher winter water temperatures was, however, significantly greater when there was a larger cohort of ranched fish in the total population, suggesting that the progeny of ranched fish are more sensitive to projected temperature increases. Poor survival during the first winter was attributed to the fact that warmer water surrounding incubating eggs may lead to earlier hatching, before sufficient food supplies are available. A locally adapted population of salmon may be expected to match the energy demands of a typical winter by producing eggs with sufficient energy reserves while egg size in captive-bred populations evolves in a benign hatchery environment where there is no penalty for producing small eggs (Heath et al., 2003). Similarly, in the case of parr, elevated temperatures are known to increase fish metabolism, so juvenile fish may deplete their energy reserves before an adequate spring food supply becomes available (Metcalfe et al., 1992). The study also found, however, that high spring temperature just before smolts migrated to sea had a positive impact on survival (McGinnity et al., 2009).

Future changes in water temperature were simulated for Lough Feeagh in that study using output for two time-horizons: a control period of 1961–1990 and the late 21st century, 2071–2100. Future egg-to-smolt survival was then estimated with low and high populations of ranched fish. The results indicated no reduction in survival when the proportion of eggs from ranched fish was low. Poor outcomes and considerably lower survival were predicted when the proportion of eggs from ranched fish was high. During the current project, McGinnity et al.'s (2009) model was used to assess egg-to-smolt survival using the lake SWT data presented in Section 6. Projected survival rates were produced for the four time-horizons with both low and high populations of ranched fish. These new projections gave information on projected changes over the intermediate time-horizons (2010–2039 and 2040–2069) in addition to the control period (1961–1990) and the late 21st century (2070–2099). Estimates of survival were also produced using historical data, again for populations with low and high numbers of ranched fish. These historical estimates (grey boxes in Figure 44) indicated a potential 29% reduction in survival when numbers of ranched fish were consistently high. The addition of future climate data resulted in further projected reductions in survival, but only for the population with a high proportion of ranched fish. For the A2 scenario median survival rates for the population with high levels of ranched fish decreased by 7%, 30% and 44% for the 2020s, 2050s and 2080s respectively (Table 29). The reductions for the B2 scenario were 18%, 32% and 26%.

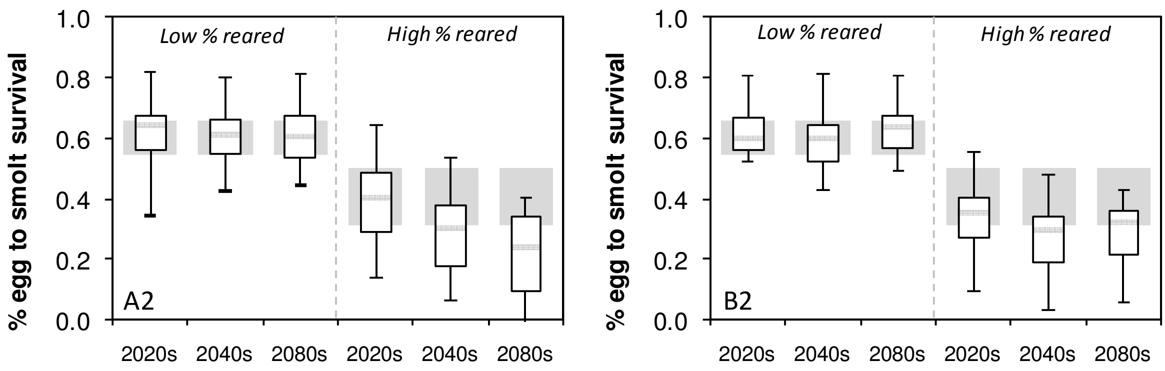


Figure 44: Boxplots of projected impacts of changes in water temperature and precipitation on salmon egg to smolt survival in the Burrishoole catchment for populations with low and high proportions of ranched fish. The grey boxes are estimates of egg-to-smolt survival produced using historical data (25th and 75th percentiles).

Many fish species have shown the ability to adapt to changing temperatures when exposed gradually to increases (Graham and Harrod, 2009). These results presented here support the conclusions of McGinnity et al. (2009) that wild salmon populations may be able to adapt to projected increases in temperatures. However, it also supports the suggestion that cultured fish capable of breeding in the wild should not be deliberately introduced into natural salmon rivers, and that measures must also be found to reduce the numbers of escaped farm salmon in nature, if wild salmon populations are to adapt successfully to climate change. Further development of fish growth models will help to clarify responses for species and populations and inform catchment management strategies.

Table 29: Projected salmon egg to smolt survival for the observed period (1961–1990) together with the absolute % change from this period for the 2010–2039, 2040–2069 and 2070–2099 for both the A2 scenario and the B2 scenario.

	Low	% change	High	% change
Observed	0.61		0.43	
2010–2039 A2	0.03	6	-0.03	-7
2010–2039 B2	-0.01	-2	-0.08	-18
2040–2069 A2	0.00	1	-0.13	-30
2040–2069 B2	-0.01	-1	-0.14	-32
2070–2099 A2	0.00	0	-0.19	-44
2070–2099 B2	0.03	5	-0.11	-26

7.4.2. Impacts of climate-related change in flow rates on fish populations

Migration, particularly in freshwater fish, has often been regarded as an adaptive strategy to increase growth and survival which may contribute to increased abundance (Northcote, 1978). Salmonids migrate downstream to sea as smolts in springtime. Adult salmon return to freshwater to spawn as early as December/January as multi-sea winter salmon and right through the summer months and into the autumn as one sea winter grilse. The projected changes in hydrology for the Burrishoole catchment include higher winter flows and lower summer flows (Section 5). Droughts leading to low water levels can result in delayed downstream migration of smolts and also present difficulty for adults to return to freshwater from the sea. Low summer flows in combination with high temperatures can be serious and lead to mortality, particularly where adult salmonids returning from the sea get delayed for extended periods and are unable to migrate upstream into freshwater (e.g. Solomon and Sambrook, 2004; Graham and Harrod, 2009). It is likely that the impact of the projected changes in water flow will be more profound in the smaller spatey catchments than in the larger catchments, although prolonged droughts experienced in recent years can result in significant delays to both downstream smolt migrations and upstream returns of adults.

7.4.3. Water-level changes and juvenile fish

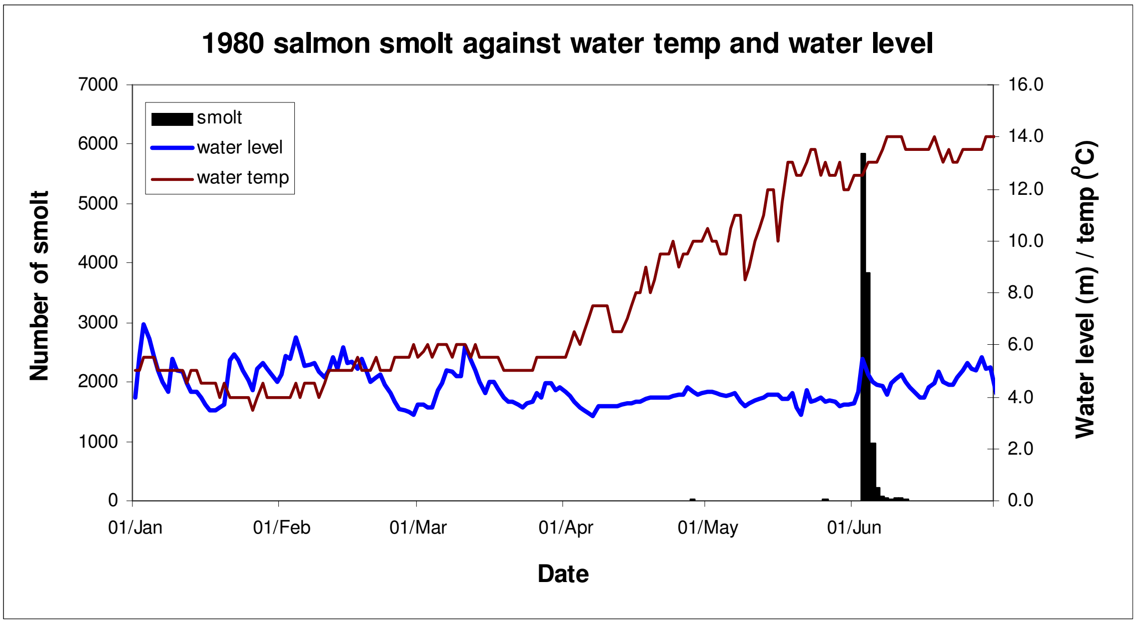
Droughts that lead to unusually low water levels can have impacts on different life stages of fish at different times of the year. Winter droughts may have an impact on accessibility to spawning beds for adult salmonids and after spawning can lead to isolation and the drying of redds and nursery habitat, leading to higher mortalities of eggs and fry. Summer droughts can also lead to mortalities because parts of the stream beds are left dry. These droughts often affect only one life stage and do not usually feed through to have a marked impact on the overall population. Extreme and repeated drought may, however, affect the population density of future spawning adults. Elliott (1994) demonstrated the effect of summer drought on trout survival in a stream in the UK and concluded that higher mortality was most probably due to a marked reduction in the wetted area of stream available to trout and subsequent retarded growth of fish. Where significant pool area and/or lakes exist in a catchment, the impact of summer drought on juveniles might be lower.

The impact of high flows in winter is less clear. Extreme high flows during winter can have a devastating impact on salmonids' survival with the scouring of spawning beds and the possible mortality of adults, eggs and fry. The increase in the frequency and volume of winter floods that is projected under the climate change scenarios therefore could have serious consequences for the viability of some stocks. High autumn and winter precipitation can, in contrast, also have a positive impact on survival of fry (Jonsson et al., 2005; Crozier et al., 2008; McGinnity et al., 2009). Jonsson et al. (2005) attributed this effect to an enlargement of the aquatic habitat in streams and an improvement in the production of food organisms for emerging fry. High autumn flows have also been found to be strongly positively correlated with juvenile survival in Chinook salmon but only in populations in cooler, narrower streams (Crozier et al., 2008).

7.4.4. Combined impacts of temperature and water level on smolts

In Irish waters, salmon are obligate migrators; if they smoltify but are not able to migrate they die; trout appear more flexible. There is a short window of opportunity for downstream migration of smolts – mostly in April and May – which is dependent on environmental factors, such as water temperature and water level (Byrne et al., 2003; Byrne et al., 2004). Trout are not believed to be obligate migrators. Trout populations can be made up of anadromous and resident cohorts and it is believed that if a sea trout smolt does not get to migrate, it can revert and migrate as an older fish. The term smoltification describes two different phenomena: transformation and migration. Light and temperature are both involved in the process of smoltification: the increase in day-length in the spring (photoperiod) acts as the synchroniser of an endogenous rhythm, the environmental factor that most influences the onset of parr-to-smolt transformation (Byrne et al., 2004, Jonsson and Jonsson, 2009). Temperature can affect both the transformation and the migration of smolts. A number of studies have shown that salmonids do not commence migration until a threshold temperature has been reached (Fried et al., 1978; Solomon, 1978), but it has been shown that temperatures above a certain threshold tend to cause a premature decrease in euryhalinity, or a detransformation in salmonids (Zaugg, 1982). There is a lack of published information in this regard relating to sea trout.

Rainfall tends to have an indirect impact on the migration process through changes in water levels; low water levels tend to inhibit or at least deter smolt migration, simply by impeding the successful passage of smolts to the sea. The effect of a spring drought in 1980 on the descent of smolts in the Burrishoole fishery is a case in point (Cross and Piggins, 1982). In that year, a prolonged dry period with low water levels from early April delayed the whole smolt run into June (Figure 45 [top]). This resulted in delayed migrations of both salmon and sea trout smolts, in a depleted sea trout smolt run, and in poor marine survival of the delayed salmon smolts. In contrast, 1984 was a more typical year with plentiful water flow (Figure 45 [bottom]). The projected changes in flow rates for Burrishoole include an increase in the incidence of extreme low flows during summer and spring, with this trend becoming more pronounced through the latter part of the century (Section 5). Such an increase is likely to have negative consequences for salmonids in Burrishoole similar to those reported for 1980.



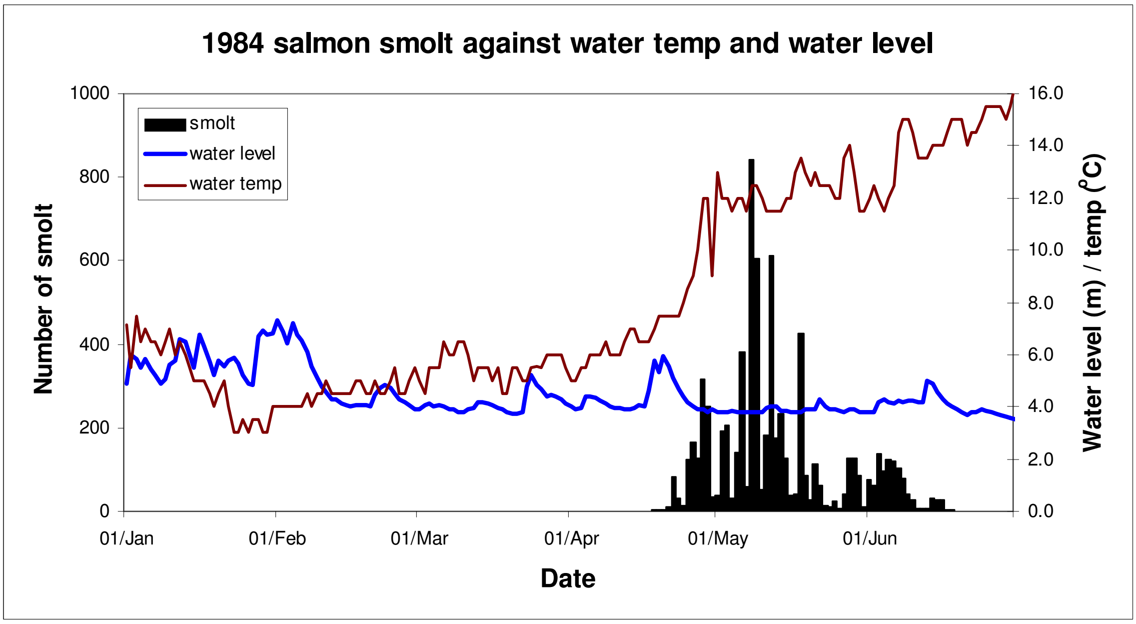


Figure 45: Examples of salmon smolt migration timing plotted along with water temperature (°C) and water level (m) for 1980 (delayed by drought – top) and 1984 (not delayed – bottom) (provided by Lee Hancox). (*Note different Y-axis).

Previous work carried out in the Burrishoole catchment looked at cumulative sea trout smolt migrations in the system from 1975 to 1990 (Whelan et al., 1993). These were compared with the corresponding freshwater temperatures and rainfall levels. Sea temperatures for the past 15 years were also plotted and their patterns noted. The sea trout smolt migration did not usually commence until freshwater temperature reached a threshold level of 9°C. Rainfall levels affected the timing of the downstream migration indirectly, through its impact on water levels. Recruitment was adversely affected by the occurrence of temperatures of 13°C or higher before sea trout smolt migration had taken place. No evidence was found to suggest that warm springs resulted in higher recruitment of sea trout smolts in the Burrishoole catchment.

Anadromous salmonids smolt and migrate to sea during spring. Byrne et al. (2003; 2004) divided factors controlling the smolt run into regulating and controlling factors. Regulating factors operate before (affecting the physiological smoltification process) and controlling factors operate during the smolt run (such as those controlling speed of downstream migration). The primary regulating factors of the smolt run are photoperiod and temperature. Day length is a timer, and increasing and decreasing photoperiods are major predictive, proximate factors which indicate the season (Wootton, 1998). Temperature affects the rate of development, and low-water temperature can limit the response of salmon parr to increased day length (McCormick et al., 2002).

Water temperature is largely responsible for annual variation. To smolt successfully, fish require a certain amount of heat, which can be measured in degree days (number of days x mean temperature [°C]). Zydlewski et al. (2005) showed that the temperature experienced over time determines the behavioural and physiological changes associated with the smoltification process as well as the onset and ending of the smolt run in salmon. The main controlling factors of smolt migrations are water temperature, water flow and changes to both these factors. Some studies indicate a pervasive effect of temperature and temperature increases for the initiation of a seaward migration in salmonids (Jonsson and Ruud-Hansen, 1985, Jutila et al., 2005). Smolt migration seems not to be triggered by either a specific water temperature or a specific number of degree days but is controlled by a combination of the actual temperature and temperature increase in the water during spring (Byrne et al., 2004). The positive impacts of higher spring temperatures on freshwater survival were also noted in a study of salmon in the Burrishoole system (McGinnity et al., 2009).

7.4.5. Impacts of climate-related change in dissolved oxygen and dissolved organic carbon on fish populations

Despite the dominant influence of RWT on DO levels, projected increases in RWT resulted in only a 4% to 7% decrease in average daily DO concentrations. However, these increases in water temperature will also influence rates of organic matter decomposition by bacteria and possibly rates of in-stream primary productivity. The projected changes in the concentration of DOC in streams could also impact on rates of decomposition rates and therefore oxygen consumption during summer. Increases in DOC concentrations were projected for all GCM model and emission scenarios from the 2010–2039 period onwards. However, the greatest increases in DOC levels occurred during autumn, a period when catchment streams are generally well oxygenated. The projected increases would, however, have consequences for the ecology of Lough Feeagh and other lakes in peaty catchments. Many highly coloured lakes like Feeagh exhibit net heterotrophy due to the central role of catchment DOC in fuelling the upper trophic levels via the bacterioplankton-protozoan link (e.g. Tranvik, 1992; Kankaala et al., 1996). The projected increases in DOC may, therefore, alter the food-web dynamics in the lake. Reduced light intensity also lowers the reactive distance of fish and their ability for size-selective predation (Wissel et al., 2003). The hypolimnion can also easily become anoxic during periods of intense stratification as DOC is decomposed (Salonen et al., 1984). This oxygen-depleted zone can then provide a refuge for prey species less sensitive to oxygen availability than fish (Wissel et al., 2003). In addition to these local impacts, the projected increases in DOC concentration may have implications for water treatment in peat catchments (Jennings et al., 2006; Naden et al., 2010) and on the global carbon cycle should they have an impact on a regional scale. A positive feedback mechanism between decomposition in organic soils and climate change has been suggested, with changes in climate driving increases in the export of DOC which in turn would increase atmospheric CO_2 concentrations and contribute to further global warming (Knorr et al., 2005; Davidson and Janssens, 2006).

High DOC concentrations can also affect stream pH levels as many DOC compounds are organic acids (Clark et al., 2005; Evans et al., 2005). The processes contributing to in-stream pH levels are complex however and include processes occurring in catchment soils and surface waters, together with impacts of regional-scale pollution and local land-use changes (Eshleman et al., 1992; Foster et al., 2001; Cox, 2003; Clark et al., 2005; Evans et al., 2005). The assessment of in-stream pH levels in the Burrishoole system in Section 3 highlighted both the rapid temporal changes which can occur in pH levels during high-flow events and the potential influence of regional pollution sources.

7.5. Key Results

- A number of marked changes in the migratory fish stocks in Burrishoole have been observed over the period 1970–2009.
- Marine survival of sea trout collapsed in the late 1980s leading to a collapse in the spawning stock and a subsequent significant reduction in smolt recruitment.
- Changes have been observed in the numbers, sex ratio and size of adult silver eels migrating from the catchment.

- The changes observed in these stocks of migratory fish are thought to be due to a number of complex and sometimes interrelated factors, of which weather patterns and climate change may play an important role.
- The changes to fish populations in the catchment already observed and the possible responses to climate change, while specific to Burrishoole, may be taken as indicative to many similar peaty spate river systems. Fish populations in lowland systems with slower water-level changes and different water chemistry may respond differently to those in more upland catchments.
- Projected changes to rainfall patterns will impact on water flow regimes in rivers, which will affect the timing of migrations into and out of freshwater and may reduce the survival of various life history stages of salmonids.
- Projected changes in lake water temperature may also affect survival rates, particularly where inshore areas of lakes provide nursery habitat for older age classes.
- Increases in water temperature are likely to affect eels positively through higher growth rates, survival and younger age at migration.
- Thermal stratification, where warmer upper lake waters are separated from cooler deeper waters by a thermocline, may provide a refuge for salmonids during periods of high water temperature. The lack of any projected increase in DWTs in the lake in summer months also highlights the potential for waters below the thermocline to provide a refuge for fish species if surface water temperatures should exceed critical thresholds.
- Monthly mean projected RWTs and lake SWTs remained within the ideal range for salmonid fish habitats (7°C to 20°C). However, the number of days when RWT exceeded 22ºC, for example, the threshold when salmon parr cease feeding and seek refuge, increased in all four time periods for both scenarios.
- The season with the greatest increase in RWT and lake SWT was winter. Higher water temperatures during the first and second winters when eggs were incubating in gravel beds and when fish were in the parr life-stage, respectively, has previously been found to have negative impacts on survival for Atlantic salmon at Burrishoole. This impact was greater when the population had a high proportion of ranched (cultured origin) fish.
- Estimates of future survival were produced based on this model for the three future time-horizons. There were reductions in survival for all three time periods, but only for the population with a high proportion of ranched fish, suggesting that the wild population will be able to adapt to increasing winter temperatures.

8. Challenges and Responses

8.1. Introduction

Salmonid fish, in particular the Atlantic salmon, have an intrinsic cultural significance in Ireland. They also possess a high conservation value. However, migratory fish, and in particular diadromous fish species, are sensitive indicators of environmental changes, both in the marine and in the freshwater environment. This sensitivity to environmental conditions means that they are particularly vulnerable to changes in the climate system, which is likely to have an impact on all life cycle stages of salmonids. Due to their sensitivity, monitoring these species is of particular importance in providing an early warning to changes in the climate system. The continued long-term monitoring of these species, at sites such as the Burrishoole, is essential for providing an indicator of, and a measure of, global and regional environmental change.

Reflecting its status as an important freshwater site for the conservation of Atlantic salmon, the catchment is designated a Special Area of Conservation (SAC) under the EU Directive on the Conservation of Habitats, Flora and Fauna (Directive 92/43/EEC). While the European eel and trout are not protected under this directive, eel is listed in the Convention on International Trade in Endangered Species (CITIES) and the International Union for Conservation of Nature (IUCN) as critically endangered and trout in the IUCN as a low-risk species.

In addition to their cultural and conservational status, salmonid fish also possess a high economic value to the state. In a survey of water-based tourism in Ireland that assessed the economic contribution of water-based leisure activities to the Irish economy in 2003, the Marine Institute (2004) found that freshwater angling for game fish (Atlantic salmon, sea trout and brown trout) accounted for a total of €22.1 million in annual national expenditure, or 5.1% of total water-based leisure tourism, having increased from €16.6 million (3.4%) in 1996. Of this total national expenditure, a significant proportion was attributed to the Borders, Midlands and West region (Marine Institute, 2004). In terms of both direct and indirect employment arising from this activity, the Marine Institute (2004) estimated that it contributed over 330 jobs in 2003. However, such figures do not include an economic value associated with maintaining Irish river catchments and water quality to a high ecological status, and the resultant provision of essential ecosystems services.

8.2. The Burrishoole Catchment: A Sentinel Climate and Environment Research Facility

The Burrishoole catchment is an internationally important index site for monitoring anadromous fish species, including the Atlantic salmon, brown trout, and catadromous species, such as eels. In addition to fish-trapping operations that monitor all movements of fish to and from the freshwater environment, the catchment is highly instrumented and intensively monitored. Datasets available for the catchment include long-term data such as air temperature, precipitation (recorded at Furnace meteorological station jointly operated by Met Éireann and the Marine Institute), and water temperature, which have been measured since the late 1950s. These are supplemented with more recent high-resolution monitoring – for example, meteorological data, pH, DO and lake temperature profiles. The research facility, which combines biological, environmental and climatological datasets, provides a unique and essential baseline for research that can further understanding of the long-term interactions between climate (including natural variability and anthropogenic climate change) and sensitive ecosystems, habitats and species.

In recognition of its importance as a sentinel environment and climate research site, the research facility has participated in a number of large-scale national (e.g. EPA ILLUMINATE – *Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in two contrasting instrumented catchments in Ireland*; EPA IN-SIGHT– *Identification of Reference-Status for Irish Lake Typologies Using Palaeolimnological Methods and Techniques*) and international research programmes (e.g. EU CLIME – *Climate and Lake Impacts in Europe*; EU SALIMPACT – *Impact of aquaculture on the immune response genes of natural salmonid populations: Spatial and temporal genetic signatures and potential fitness consequences*; EU REFLECT– *Response of European Lakes to Environmental and Climate Change*). The facility also participates in a number of international alliances, including the International Council for the Exploration of the Sea (ICES), the International Atlantic Salmon Research Board (IASRB/NASCO) and the Global Lake Ecological Observatory Network (GLEON).

The Marine Institute's research facility at Burrishoole has been at the forefront of both the national and international research effort in assessing the impact of long-term climate and environmental change on riverine and lacustrine ecosystems and habitats. Because of the long-term, environmental and climatological monitoring undertaken within the catchment and its importance internationally as an index site for diadromous and catadromous fish species, the long-term strategic aims for the catchment need to ensure the continuity of monitoring and data-collection activities to maintain the catchment as a 'living laboratory' for climate- and environment-related research.

Such long-term data are vital for developing strategic research programmes that seek to contribute to scientific understanding of climate-change impacts at the catchment and ecosystem scale. While the focus of the current research was centred on assessing the impacts of climate change on the Burrishoole catchment, because of the ecological importance of the catchment and availability of long-term data, the derived methods and findings are of significant relevance to similar type catchments located along the west coast of Ireland.

The report has outlined a novel method, and provides a template, for undertaking climate-change impact assessments at the catchment scale. Its findings are of value nationally to highlight the need for effective mitigation and adaptation strategies and regionally to inform decision makers about the likely impacts of climate change at scales appropriate to managing catchments along the west coast. Finally, the current research will provide stakeholders in the Burrishoole catchment with the necessary information to integrate climate-change considerations into the strategic management of the catchment.

8.3. Sensitivity and Resilience: Challenges for the Catchment

Observational evidence suggests that Irish populations of both Atlantic salmon and sea trout are already in decline (Stefansson et al., 2003; Peyronnet et al., 2007). Such findings are consistent with long-term fish census data from the Burrishoole, and other Irish and European catchments. Returning Atlantic salmon numbers, which originally started to decline in the 1970s, have continued to remain low since the 1980s, while stocks of returning sea trout collapsed in the late 1980s and have yet to recover to their pre-1980 levels. The collapse in numbers of sea trout returning to the Burrishoole catchment, which began in 1987, corresponds with the development of fish farming in Clew Bay, warm winter and spring temperatures and higher rates of sea lice in the wild population of sea trout. Similar declines are evident in glass eel recruitment levels with consequent changes in the annual silver eel migrations. These declines have continued in spite of both national and international efforts to reduce pressures from fishing and against the backdrop of measures introduced to protect critical habitats (Friedland et al., 2009) (e.g. Habitats Directive, Angling bag limits, drift net restrictions, drift net ban).

As noted above, such diadromous or migratory fish species are considered sensitive indicators (indicator species or 'climate canaries') of environmental changes (Lassalle and Rochard, 2009), and the timing and widespread geographical distribution evident in the decline in marine survival rates of these species would indicate a large-scale environmental change, such as in the ocean or climate system. This is supported by the findings of Beaugrand et al. (2002) who identified a biogeographical shift, of more than 10° latitude in the North Atlantic, in the abundance of both warm and cold water copepod assemblages consistent with an increasing trend evident in the North Atlantic Oscillation and northern hemisphere temperatures, also reflected in sea surface temperatures, over the period since 1960 (e.g. Fealy and Sweeney, 2005; Friedland et al., 2009). While our understanding of the exact nature of marine environmental effects on survival rates is limited, and these effects are likely to be complex and multifactored (Davidson and Hazelwood, 2005), a close interaction between marine survival rates and marine growth, particularly during the post-smolt year (Friedland et al., 2009), has been identified for Atlantic salmon (Peyronnet et al., 2007). However, Friedland et al. (2009) suggest that while changes in the marine environment may be a factor in controlling stock-complex productivity, freshwater conditions may be a more important factor in controlling species distribution and viability.

Observed changes in the terrestrial climate system, particularly evident since the middle of the 20th century, are likely to influence the freshwater survival and development of juvenile fish populations (Nolan et al., 2009). Temperature is a significant factor in controlling the key chemical and biological processes in water; therefore, changes in temperature will have both a direct effect, driving phonological changes (Walther et al., 2002), and an indirect effect, through impacting water quality (Harley et al., 2006), on aquatic ecosystems. Consequently, water temperature is a major determinant of habitat in rivers and streams (e.g. Elliott, 1984; Eaton and Scheller, 1996). Riverine ecosystems are also susceptible to alterations in precipitation patterns, which, in the case of prolonged droughts, may exacerbate extreme RWTs (Graham and Harrod, 2009). Changes in the magnitude and seasonality of precipitation are also expected to have significant effects on streamflow (e.g. low flows, high flows and water velocity) and water quality (Jennings et al., 2010; Naden et al., 2010; Whitehead et al., 2009).

Analysis of mean annual air temperature anomalies at Furnace meteorological station over the 50-year period from 1960 to 2009 indicates that there has been significant warming, with mean annual air temperatures displaying an increase of 1.48°C ($p<0.001$) over the instrumental period of record. When compared to the Irish temperature anomalies over a comparative time period (1961–2004), the mean annual air temperature at Furnace shows a greater increase, of 1.1°C, compared to 0.9°C evident in the Irish anomalies. Seasonal mean temperatures have also increased, with the greatest increase evident in spring (1.8°C), followed by winter (1.7°C), summer (1.5°C) and autumn (1.4°C). Seasonal water temperatures anomalies from the Burrishoole catchment, analysed for the 1960–2009 period, display increases that are consistent with the increases identified in air temperature. An increase in the frequency and intensity of extreme precipitation in winter and annually was also found to have occurred over the period 1960–2009. In winter there was an increase of 3.3 events, while an analysis of the annual precipitation records indicated an increase of 7.5 events. No significant trends were found to have occurred in the observed mean seasonal precipitation.

Projected changes in the climate conditions of the Burrishoole catchment, if realised, will have wide-ranging implications for all aspects of the catchment system, including water temperature and quality, streamflow hydrology, soil processes, and most notably the well-being of its aquatic environment. While the projected changes in climate and their implications, outlined in this report, are specific to the Burrishoole, they are illustrative of likely changes in similar characteristic catchments along the west coast of Ireland. From a catchment-management perspective, the development of catchment specific adaptation strategies will be required as, according to Freidland et al. (2009, after Taylor, 1991), salmon are locally adapted and individual river stocks may need to be viewed, and managed, as a species.

Future management of these catchments will therefore present unique challenges. Reducing the human impact (e.g. removing impoundments and modifications, greater control on pollution, reducing abstractions, modifying land use) is unlikely to play as great a role in mitigating the long-term effects of climate change when compared with other catchments that have been subjected to significant human interference. While McGinnity et al. (2009) suggest that Atlantic salmon may be able to adapt to future changes in water temperature in an ideal situation, additional stressors such as the supplementation of populations with hatchery fish, may cause catastrophic population collapses within 20 generations. As climate change is likely to represent an additional stressor on the catchment, it needs to be considered in combination with other challenges facing the freshwater ecosystem. Such an approach is essential to increasing the resilience of the catchment with the aim of developing robust adaptation strategies. Even if projections of future climate are inherently uncertain, particularly at the regional scale (Fealy, 2010), climate impact assessments that cater for as wide a range of uncertainty as possible provide an invaluable set of tools for stress testing existing or future management options. The development of such strategies, which should remain largely insensitive to uncertainties with regard to future changes in the climate, are more likely to lead to the development of appropriate, cost-effective, adaptation measures that seek to reduce vulnerabilities and increase resilience to any changes in the climate system.

8.3.1. Flow regime and catchment hydrology

Of specific interest in this study are the impacts of a changing flow regime on the catchment's capacity to sustain and nurture indigenous stocks of Atlantic salmon. As hydrological conditions are of fundamental importance to salmonid fish species, anticipated changes in different components of the natural flow regime, including mean and extreme conditions, will have wide-ranging implications for Atlantic salmon populations in the Burrishoole catchment.

In catchments whose hydrological regime is significantly influenced by groundwater flow, increased winter receipts can be beneficial by recharging groundwater stores to a higher level and thus providing sufficient baseflow with which to sustain river/stream water levels during drier periods of the year. Essentially, groundwater-dominated catchments have the capacity to store the additional rainfall received during the winter for release during the drier summer months. The Burrishoole system, however, does not possess the storage properties required to moderate the influence of an increasingly seasonal rainfall regime. The catchment is underlain by relatively unproductive aquifers limiting its overall groundwater storage capacity. This feature of the Burrishoole system leaves it vulnerable to changes in its precipitation regime.

The topography of each catchment, along with the dominance of blanket peat, promotes the rapid transmission of rainfall received over the drainage area to the stream network. This aspect of the Burrishoole's hydrological system impedes groundwater recharge and contributes to the 'flashy' or 'spatey' nature of the flow response to precipitation events. In essence, the Burrishoole system lacks the capacity to buffer or dampen the flood, increasing the potential negative impacts of heavy rainfall events, suggesting it is sensitive to more intense precipitation events.

8.3.2. River water temperature

There is clear observational evidence that changes in water temperature have an impact on salmonid fish species at all life stages through influences on phenology, growth, and metabolism (e.g. Graham and Harrod, 2009). Atlantic salmon and trout exhibit distinct thermal tolerances during each life-cycle stage, with the tolerances for Atlantic salmon being about 3°C higher than the corresponding values for trout (Elliott, 1991). In addition, major phases of fish development, such as egg hatching, parr growth, smoltification, and migration are directly linked with specific ranges in water temperature.

Analysis of long-term trends in midnight water temperature from the catchment, for which consistent records were available, are examined for the period 1960–2009. Midnight water temperature was found to have increased in all seasons, but was most pronounced during winter (1.8°C) and spring (1.8°C). Over the period of record, annual midnight water temperature increased by 1.3°C ($p<0.01$) between 1960 and 2009. Such increases in water temperatures largely reflect the regional influence of surface air temperatures, which were found to have increased at a greater rate then global trends over the same period.

In contrast to the findings of Byrne et al. (2003), analysis of the smolt run data from the catchment, which has been monitored since the 1970s, indicates that there has been a significant trend towards earlier commencement of the salmon smolt run (measured as 5% of the fish migrating), by almost 10 days since records began (Section 7; ICES, 2010), and the middle of the sea trout smolt run by 14 days, coinciding with increased water temperatures over a similar period. A similar trend has been found for the River Bush in Co. Antrim, which is believed to be linked to changes in RWTs (ICES, 2010).

Increasing temperatures also have an indirect effect on aquatic ecosystems, through alteration of the rates of biological and chemical processes that influence water quality, such as DO. Such effects can be further compounded if associated with prolonged periods of drought, which act to reduce the dilution of pollutants. Dissolved oxygen levels in the Burrishoole were found to be strongly dependent on RWT throughout the year and displayed a distinct seasonal pattern. This relationship reflects the negative impact of warmer temperatures on DO solubility (Wetzel, 2001). During the summer months of June, July and August, DO concentrations were also related to rising DOC levels.

While a number of researchers have defined the quality of salmonid habitats according to ranges of DO content, the European Communities (Quality of Salmonid Waters) Regulations, 1988, established thresholds for in-stream DO levels. The Quality of Salmonid Waters Standards (S.I. No. 293 of 1988) state that 50% of DO measurements at a site must be above ≥9 mg L^{-1}, a level considered to be optimum conditions for adult salmonids. Where the DO content falls below 6 mg L^{-1} the local authority must prove that there will be no harmful consequences for the balanced development of the fish population. However, optimum DO ranges vary according to species and life stage (Alabaster and Lloyd, 1982; Crisp, 1996; Louhi et al., 2008) and fish sensitivity to DO levels will be affected by other factors, such as water quality, quantity of suspended sediment (Chapman, 1988; Louhi et al., 2008) and flow parameters (Grieg et al., 2007).

8.3.3. Acidification

Maritime regions of Western Europe, in particular, have been severely affected by acidification associated with increases in sulphur emissions from industrial sources. These emissions increased during the 20th century, but with the introduction of mitigation measures, levels have been declining since the late 1970s. Although concentrations of atmospheric S and N, and hence acid deposition, have been reduced in the last few decades, recovery of surface waters from acidification has been found to be sporadic and inconsistent in terms of pH increase or the reappearance of acid-sensitive taxa (Davies et al., 2005; Monteith et al., 2005; Ormerod and Durance, 2009).

Ireland has few significant sources of atmospheric pollutants. One exception is the large coal-fired power station at Moneypoint in Co. Clare on the west coast (Bowman and McGettigan, 1994), although this is currently undergoing refurbishment to reduce SOx emissions by up to 90% from current level. There is also a potential risk of pollution from more industrialised nations such as the UK and continental Europe (Bowman and McGettigan, 1994; Allott and Brennan, 2000). Deposition from these countries mainly arises when cyclonic weather systems pass to the south of the island of Ireland, generating easterly winds across the country (Allott and Brennan, 2000). While atmospheric deposition of SO_2 and NOx from anthropogenic sources is significant in the eastern part of the country, it is considerably lower in western locations (Bowman and McGettigan, 1994; Aherne and Farrell, 2000). However, the impacts of acid deposition are greatest in naturally occurring acid-sensitive waters which are chiefly located in areas with acid bedrock (Aherne and Farrell, 2000; Allott and Brennan, 2000). These naturally occurring acid-sensitive waters occur principally along the western and north-western coasts, including the Burrishoole catchment, and in the Wicklow Mountains in the east (Bowman, 1991; Aherne and Farrell, 2000).

Acidification of stream water can result in significant impacts such as the loss of species at all trophic levels. Salmonid fish species are particularly vulnerable as they are very sensitive to low pH levels. Depending on their exposure and life stage, low pH levels can result in delayed hatching of eggs (Atlantic Salmon Trust, 1991) to tail deformities in adult fish (Campbell, 1987) and is associated with an increase in mortality at all life stages (McCartney et al., 2003; Finn, 2007; Monette and McCormick, 2008).

Compared to many Irish catchments, the Burrishoole catchment is considered to be relatively free from impact from human activities. Reflecting this, Lough Feeagh was classed by the Environmental Protection Agency in 2003 as a 'Candidate Reference Lake' (Anon, 2005), or a lake whose chemical and ecological status was close to reference conditions, and is regarded as 'probably not at significant risk' (Category 2a). However, analysis of long-term palaeolimnological data, undertaken as part of an EPA/ERTDI-funded project entitled IN-SIGHT (Leira et al., 2006) and the more recent ILLUMINATE project (Dalton et al., 2010) suggests that nutrient enrichment and slight – although not statistically significant – acidification have impacted on the lake over the last *c.* 80 years.

While catchments on the west coast receive generally lower levels of anthropogenically derived acid deposition via atmospheric transfers, inputs of natural organic acids through the oxidation of peat or deposition of marine aerosols (which can act to transfer acidity from the soil to surface waters), all contribute to the acid load on ecosystems (Farrell et al., 1998; Collier and Farrell, 2007). Catchments can also be negatively impacted by the presence of coniferous forestry, where underlying soils tend to be more acid than soils under deciduous vegetation (Ovington, 1957; Federer, 1985). In areas receiving acid deposition, coniferous trees may act as a conduit, and increase the amount of acidifying ions reaching the surface. Both the nature of the vegetation and the growth stage of the trees will influence the scavenging effect: the more mature the vegetation, the greater the effect, with the closed canopies of mature stands of coniferous trees being most effective. There is also evidence that coniferous forests may scavenge pollutants during dry weather, which may be subsequently washed into surface water bodies (Allott and Brennan, 2000). Soil acidification may be further accelerated in soil with low pH thus compounding the problem in areas with naturally acidic soils (Federer, 1985).

Previously it was thought that the chronic acidification of stream water presented the most significant threat to biodiversity, however, the occurrence of episodic acidification can have significant biological impacts (Davis et al., 1992). Such 'acidic episodes' are now considered a possible contributor to Atlantic salmon population decline (Monette and McCormick, 2008) and a cause of slowed recovery from acidification, particularly in the UK and Scandinavia (Kowalik et al., 2007; Laudon, 2008). The occurrence of episodic pH events in upland catchments are linked with the flushing of historical S and N oxides from catchment soils and are associated with heavy or extreme precipitation. High inputs of seasalts during storm events have also been found to induce episodic acidification of surface waters (Farrell et al., 1998). Of the 10 low-pH events analysed for the Glenamong over the 2008–2009 period, 6 occurred as single drops in pH and 4 were composed of multiple decreases in pH over 1- to 2-day periods. All ten episodes were associated with increased precipitation in the Burrishoole catchment and increased flow in the Glenamong River, either in the preceding 7 days or on the event day. More importantly, low pH episodes were associated with anticyclonic conditions in the preceding weeks, suggesting that dry deposition of acidifying compounds during periods of easterly airflow may still be occurring.

8.4. Future Challenges: Climate Change

The climate scenarios developed for the Burrishoole catchment suggest that daily maximum and minimum temperatures are going to increase in all seasons over the course of the present century, with the greatest increases associated with the A2 emissions scenario (which estimates the doubling of equivalent CO_2 concentrations by 2050 and the trebling of concentrations by 2100) for the end of the present century. When all models and emissions scenarios are considered, the greatest warming is projected to occur during the spring (1.8°C) and autumn (2.2°C) seasons by the 2080s. Extreme temperatures (90th and 10th percentile) are also projected to increase.

In contrast to the projected increases in seasonal air temperatures, increases in RWTs and lake SWT are projected to be greatest during the winter months. According to McGinnity et al. (2009), higher winter temperatures during the first and second winters can have negative impacts on salmon freshwater survival, due to an offset in timing between earlier hatching and increased metabolism of parr and availability of an adequate food supply. The impacts of increased temperature on survival were also found to be greater when ranched fish contributed a greater proportion to the cohort (McGinnity et al., 2009). Increases in spring temperatures, just before smolts migrate to sea, had a positive impact on survival (McGinnity et al., 2009). While wild salmon populations are likely to be able to adapt to gradual increases in temperature, the impacts of ranched or hatchery fish being introduced or escaping into the catchment will have detrimental effects on salmon survival (McGinnity et al., 2009). In contrast, fish species with lower thermal tolerances, such as trout (Elliott, 1991), are likely to be negatively impacted by increased water temperatures.

With regard to eels, water temperatures within the catchment are generally at the lower end of the thermal tolerance range for this species and this is reflected in the lower growth rates and older age at maturation of the Burrishoole eel population. However, if the temperature projections outlined are realised, they are likely to have positive impacts on eel species, due to more optimum freshwater temperatures being attained. Such temperature increases are likely to result in faster growth rates and younger age maturation into silver eel. Since 1990, there has been an increase in the growth rate of eels in the catchment and this trend is likely to continue. Such impacts are likely to benefit future stock recovery.

The climate scenarios also project an increasing tendency towards a more distinct seasonal precipitation regime, leading to wetter winters and drier summers – with this trend likely to become more pronounced over the latter part of the century. Evaporative losses, driven by increased solar radiation, are projected to increase during the summer months, which may further diminish streamflow in the catchment during seasons experiencing reductions in precipitation. Due to the projected increase in winter precipitation, average streamflow is likely to increase by up to 25% for the months of January and/or December for all sub-catchments in the Burrishoole over the period 2070–2099. For the month of June, reductions of up to 40% were returned for three of the selected catchments (Glendahurk, Maurmatta and Goulan). Accompanied by this is a suggested decrease in mean flow of between 15 and 40% for the months of September, October and August variously across all catchments.

A reduction in the return period for flooding events is also projected for each sub-catchment, the most extreme of which are associated with the Glendahurk, Altahoney and Goulan with exhibited reductions in the return period of a 50-year event to between 7 and 9 years by the 2080s. Model simulations indicate an increase in extremely low summer flow for each sub-catchment, an outcome which is commensurate with the predicted decreases in summer precipitation. For all sub-catchments, by the 2080s, model simulations suggest an increase in the number of extreme low flows days (≤Q95) of between 13 and 20%. Associated with this is an increase of between 4 and 7 days in the consecutive number of days for which flows are equal to or below the Q95 threshold for all sub-catchments during the summer season. Model simulations suggest that the incidence of summer low flows will increase as the century progresses.

Given the similarity of each of the six selected sub-catchments, in terms of their physiographic features, their response to changing climate conditions is taken to be representative of changes in the hydrology of the Burrishoole system as a whole. Generally, model simulations suggest an increasing tendency towards a more distinct seasonal streamflow regime across the catchment, with higher flows occurring in winter (DJF) and lower flows during the summer (JJA) and autumn (SON). This is commensurate with projected changes in the catchment's precipitation regime. Increased winter flows coupled with the fast response time of the Burrishoole system leave it vulnerable to more intense precipitation events. This manifests itself in a projected decrease in the return period for peak discharge and flooding events. Also suggested is an increase in summer and spring low flows. In general, the results suggest a greater deviation from reference conditions, for both mean and extreme flows, as the century progresses with changes being more acute under the A2 emission scenario when compared to the less carbon-intensive B2 scenario.

Any alterations in the prevailing flow conditions, or 'natural' flow regime, are likely to have significant implications for the Burrishoole catchment's aquatic ecosystem, including its capacity to sustain and nurture Atlantic salmon populations. All aspects of a river system's streamflow regime, including extreme flows, play an important role at each stage in the salmon's life cycle. However, a more extreme flow regime, as is suggested by model projections, has the potential to significantly disrupt the habitat conditions required to sustain salmon populations and prevent them from successfully completing different stages in their life cycle. In this regard, understanding the implications of a climate-induced shift in the flow regime is important when devising future management strategies and making policy decisions for the catchment.

It is known that each component of the natural flow regime (e.g. high, mean and low flows) plays an important role in different aspects of the salmon's life cycle. Spates are required for fish migration while flooding events are beneficial for de-silting spawning gravels and contributing to the overall maintenance of the stream network. Low and medium flows control the amount of available habitat and have a significant influence on fish migration. According to Gilvear et al. (2002), hydrology determines not only the physical habitat in which salmon live but the organisms on which they feed, who themselves are also dependent on flow conditions. This alludes to the multiple direct and indirect relationships that exist between river flow and salmonid populations.

8.4.1. Summary of potential impacts on migratory fish

Climate change will have implications for all life stages of salmonid fish and eel species, both in the freshwater and marine environments (Walsh and Kilsby, 2007; Section 7). Within the freshwater environment of the Burrishoole catchment, these effects, arising from increased river water temperatures, change in flow regime and stream water quality (DO, DOC, pH, turbidity), are likely to have both positive and negative impacts, depending on the particular species and life stage.

Outlined below are some of the potential impacts of climate change in the freshwater environment on salmonid life stage (adapted from Walsh and Kilsby, 2007; Sections 3 - 7).

Spawning and egg deposition

- Higher temperatures during the first winter, when eggs are incubating, have negative impacts on survival, possibly attributed to earlier hatching and an offset in timing in food availability.
- An increase in flash flooding could lead to the wash-out of eggs laid in gravels.
- A sudden decrease in flow levels could leave redds stranded out of water before, or after, fertilisation, preventing the emergence of fry.
- Higher flows may lead to increased sediment loads, which may cause the siltation of redds.
- There may be a reduced availability of spawning habitat caused by decreased or increased flows.

Alevins

- An increase in flow velocity could lead to the displacement of newly emerged fry downstream.
- There may be temperature impacts on the timing and size of alevins at emergence and their subsequent growth and survival.

Parr and juvenile salmon

- Higher temperatures during the second winter, when fish are in the parr stage, have a negative impact on freshwater survival due to an increased metabolism and an offset in adequate spring food supply.
- The number of days when RWTs exceed 22°C may increase – the threshold at which Atlantic salmon cease feeding and seek refuge.
- An increase in the number of days when RWTs exceed 26°C will result in increased mortality of trout.
- Successive reduced flow years may have a detrimental effect on salmonid stocks, taking years to recover.

Smolts, migration and returning adults

- Temperature affects the transformation of smolts, but if temperatures exceed a certain threshold, a detransformation in salmonids can occur.

- Higher spring temperatures, just prior to smolt migration, may have a positive impact on salmon survival.
- Sea trout smolts may be adversely affected by temperatures in excess of 13°C.
- Increased temperatures are likely to result in an earlier commencement of the smolt run. However, periods of drought may result in a prolonged or delayed smolt run.
- Wetter springs may induce earlier migration of smolts to sea, which may reduce survival capacity in the marine environment.
- A reduction in the number of spates may hamper the upstream migration of returning adult fish.
- Rapid reductions in flow may lead to stranding of migratory salmonids.

While Atlantic salmon and trout may be able to adapt to gradual changes in the climate of the catchment (McGinnitty et al., 2009), eel growth may even benefit from increased temperatures although changes in the ocean may continue to impact on eel recruitment. However, climate change represents an additional stressor on fish populations already under pressure. A catchment management approach, based on the *individual river* as the management unit (Collins et al., 2006), and which assesses the contribution of all human-induced pressures (e.g. land use or land-use change, eutrophication, commercial exploitation of stocks, impact of hatchery fish and commercial fish farming) combined with the environmental pressures likely to arise because of climate change may reduce the vulnerability of the catchment ecosystem, and its functioning, to environmental change. Such a locally based approach is necessary at the catchment, and even stream, scale, as some salmonid fish species may be locally adapted and therefore may need to be viewed, and managed, as an individual species (Freidland et al., 2009, after Taylor, 1991). While nationally salmon habitats in Ireland were classified as poor (National Parks and Wildlife Service [NPWS], 2008), the status of individual rivers does not reflect this classification (NASCO, 2009), supporting the need for individual catchment- or stream-based assessments.

8.5. Policy Context

Internationally, the Kyoto Protocol 1997 (United Nations, 1998) established binding targets for reducing global GHG emissions. However, in the national context, no regulatory framework currently exists for achieving the national targets established under the protocol as part of the EU burden-sharing agreement. However, the Framework for Climate Change Bill 2010, published by the Department of Environment, Heritage and Local Government (DoEHLG, 2009), has identified the establishment of legally binding emissions targets as a key priority.

Additionally, the framework seeks to incorporate relevant scientific knowledge relating to climate change into the core national priority of addressing climate change. Such mainstreaming of climate-change information and adaptation options into decision making at the national and regional scale (DoEHLG, 2009) and integrated across all policy areas, such as agriculture, coastal and marine, health, transport, energy, is of critical importance to developing more robust strategies to cope with climate change.

Significantly, two key pieces of EU legislation of relevance to salmonids, the EU Habitats Directive (Directive 92/43/EEC), which seeks to conserve the natural habitats of wild flora and fauna, including the Atlantic salmon, and the EU Water Framework Directive, which seeks to protect high-quality water bodies and restore those of degraded quality to good status by 2015, do not explicitly include the additional pressures arising from climate change into their frameworks for consideration. This is in spite of the fact that climate change, both observed and future projected changes, presents significant, and new, challenges to successfully implementing both directives. Consequently, the cost-effectiveness and conservational aspirations of such statutory instruments may be lessened.

8.6. Conclusion

Statutory obligations under the EU Water Framework Directive require governments to manage all their waters from source to sea (e.g. rivers and lakes, groundwater, estuaries [transitional waters], coastal) and ensure they achieve a good status by 2015. Implementation and management of the directive at the river basin district is achieved through river basin management plans. However, the directive does not explicitly include climate change considerations, in spite of the evidence that observed changes in the climate can have significant impacts on all aspects of the freshwater ecosystem, including water quality. Thus, there is now a requirement to integrate such considerations into catchment management plans. Where the conservation of ecologically important species – such as Atlantic salmon – is of interest, the management unit may need to be at individual stream/river scales, rather than river basin districts as required by the Water Framework Directive.

Climate change will have both direct effects, through altering river water and sea surface temperatures and precipitation patterns, and indirect effects, through impacting on water-quality parameters, such as ocean/freshwater acidity, DO and turbidity, on fish species both in the marine and freshwater environments. There is now significant, and growing, evidence that observed climate and related environmental changes over recent decades are already having an impact on natural and biological systems. Such environmental changes are projected to have increasing significance for habitat and ecosystem functioning over the course of the present century. While both positive and negative impacts are considered likely, the resilience or vulnerability of a particular species to climate and related environmental change may be further affected by additional, non-climate related, stressors.

To ensure that appropriate, cost-effective measures and policies are developed, a more holistic approach that integrates climate-change considerations in combination with other pressures is long overdue. Such measures are essential to developing appropriate adaptation responses, reducing vulnerability and increasing resilience to change. Conservation efforts that ignore the large-scale or external drivers of change (both physical and policy) are likely to be costly and ineffective. For example, in the absence of strict emissions controls internationally, species currently at the southern edge of their biogeographical range are likely to continue to contract or shift northwards due to increasing temperatures, irrespective of the local conservation measures. While climate-change scenarios should not be used as deterministic drivers of policy, such climate information does provide an important decision support tool for developing robust policies – for example, using climate scenarios for assessing the likely future suitability of particular catchments for species – and thus it can play a critical role in informing conservation efforts. Such mainstreaming of climate-change information, including uncertainties, into the decision-making process should lead to more efficient, coherent policy development.

Such an approach is outlined in the Framework for Climate Change Bill 2010 (DoEHLG, 2009). The Framework for Climate Change Bill 2010 proposes to impose statutory requirements on public bodies to assess the impacts of climate and climate change and to ensure they develop appropriate sector-specific adaptation plans on a regular basis. Local authorities may also be obliged to coordinate climate-change adaptation activities.

While the climate scenarios outlined in this report were developed specifically for the Burrishoole catchment, they are likely to be illustrative of changes in similar characteristic catchments along the west coast of Ireland. Thus, the outlined scenarios, and associated uncertainties, may provide useful information as input into a decision-support tool for stress testing existing or future catchment management plans for many similar type catchments located along the western seaboard. The integration of the findings, outlined in this report, into catchment management strategies represents the first step towards developing robust adaptation strategies, as identified in the climate change bill.

8.7. Recommendations

8.7.1. Monitoring and assessment

Significant opportunities exist to develop, test and deploy automated environmental sensor networks within the catchment, leading to real-time data delivery to both catchment managers and the research community. Such a network would provide the basis for expanding the monitoring network into unmeasured catchments.

Long-term monitoring of key biological, climatological and environmental parameters is essential for understanding the complex interactions between climate, ecosystems and species. Sentinel research facilities of international importance, such as the Burrishoole, need to be prioritised for long-term funding, both in terms of human and infrastructural resources, to ensure the continuation of long-term measurements in support of statutory and scientific requirements.

Such monitoring, in addition to providing an indicator of environmental change, is vital to further understand the complex interactions between climate and species. These measurements can provide the basis for:

- assessing interaction between land use and particularly plantation forestry (single and mixed species), and the aquatic environment at the catchment/stream scale
- improving understanding of estuarine-catchment interactions on migratory fish species
- building multidisciplinary capacity in the area of climate-species interactions accounting for the full life cycle (including marine and freshwater components) and associated food webs
- informing decision makers/catchment managers in developing appropriate adaptation responses.

8.7.2. Integration of climate change considerations into catchment management strategies

- The river or stream should form the basis of the management unit for ecologically important species, such as salmonids, which may be locally adapted.
- Awareness of climate and environmental challenges should be raised with all stakeholders.
- Climate change considerations should be mainstreamed into catchment governance/management structures.
- A ‘no regrets’ approach to catchment management, which seeks to enhance the adaptive capacity of the catchment (e.g. assess riparian zone management options)

and its ecosystems (e.g. reduction of non-climate related stressors; prevent mal-adaptation), should be developed.

- Plans should be continuously monitored and evaluated, and revised, as new climate information becomes available.

Acronyms and Annotations

ANNs	Artificial neural networks
ARMS	Automatic river monitoring systems
AWQMS	Automatic water quality monitoring stations
AWS	Automatic weather station
CCGCM2	Canadian Centre for Climate Modelling and Analysis
CO2	Carbon dioxide
CRR	Conceptual rainfall runoff model
CRU	Climate Research Unit
CSIRO-MK2	Commonwealth Science and Industrial Research Organisation
CWR	Centre for Water Research
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DTR	Diurnal temperature range
DWT	Deep water temperature
EEA	European Environment Agency
GCM	Global climate model
GHG	Greenhouse gas
GISS	Goddard Institute for Space Studies
GLEON	Global Lake Ecological Observatory Network
GLM	Generalised linear model
GLUE	Generalised likelihood uncertainty estimation
GWLF	Generalised watershed loading functions
GWP	Global warming potential
HadCM3	Hadley Centre for Climate Prediction and Research
ICES	International Council for the Exploration of the Seas
IPCC	Intergovernmental Panel on Climate Change
LJWT	Lamb-Jenkinson weather types
Mj m-2	Mega joules per metre squared
N	Nitrogen
NO_x	Nitrogen Oxide
PE	Potential evapotranspiration
ppmv	Parts per million volume
RWT	River water temperatures
S	Sulphur

SAC	Special Area of Conservation
SDSM	Statistical downscaling model
SO_x	Sulphur Oxide
SRES	Special Report on Emissions Scenarios
STARDEX	Statistical and Regional dynamical Downscaling of Extremes for European regions
SWT	Surface water temperature

Appendix I – Selected Research Outputs from the Catchment

(From Table 2)

Jennings, E., Allott, N., McGinnity, P., Poole, R., Quirke, B., Twomey, H. and George, D.G. (2000) The North Atlantic Oscillation: implications for freshwater systems in Ireland. Biology and Environment 100B: 149–58. (REFLECT)

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Jennings, E., Allott, N., Arvola, L., Jarvinen, M., Moore, K., Naden, P., Nic Aongusa, C., Noges, T. and Weyhermeyer, G. (2010) Climate impacts on the flux of dissolved organic carbon from catchments. In D.G. George (ed.) The Impact of Climate Change on European Lakes. Springer. 507pp. (CLIME)

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Produced by the Sea Change Management Unit, Strategic Planning and Development Services, Marine Institute

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