Climate change and future flooding in the UK

Geoffrey John Caedmon Darch

PhD Thesis

University of East Anglia

Climatic Research Unit

and Tyndall Centre for Climate Change Research,

School of Environmental Sciences

September 2010

Abstract

A series of recent flood events in the UK has highlighted the tensions between flooding and the human use of floodplains. With increasing, competing pressures for resources, coupled with a changing climate, assessing future risks requires an inter-disciplinary approach. Although such studies exist, few have taken a catchment approach based on storyline-driven scenarios.

This research sets out a framework for the integrated assessment of floodplain futures, which seeks to downscale socio-economic and climate scenarios for use in catchment models. Further research is required to parameterise socio-economic drivers in appropriate models. Therefore this thesis focuses on climate scenarios and hydrological–hydraulic models used in flood risk management decisions. Downscaled climate model output, from UKCIP02 and ENSEMBLES, is applied using a change factor method to a continuous model of the lowland Bedford Ouse catchment, and to a discrete event model of the upland Eden catchment. The Bedford Ouse model is formed of 21 rainfall–runoff models and the Eden 26 rainfall–runoff models, with hydraulic models used in both catchments to route flow downstream.

For the Bedford Ouse, flows in the 2080s are generally higher in winter and significantly lower in summer. Three patterns of runoff changes have been identified and related to catchment characteristics, although results from three of the five ENSEMBLES scenarios were more influenced by the climate change factors. The proportion of catchments that returned enhanced runoff for high flow events depends strongly on the scenario, with the same three scenarios leading to enhanced runoff for nearly all of the 21 catchments at the Q1 and Q0.1 baseline flow thresholds. Changes in runoff related to extreme historical events also depend on the scenario as well as the timing of the event. The influence of PET on runoff appears to be significant, for both average and high flows. Maximum peak water levels and flows in the downstream catchment did not exceed those of the baseline, but could do based on alternative timing of events in future. The 20% national indicative sensitivity range was generally found to be precautionary, but this varied with receptor, event and scenario.

For the Eden, peak 2080s runoff increased for virtually all the combinations of baseline events and scenarios examined. The size varied depending on the scenario, timing of the event and catchment response type, with the monthly precipitation change factor the single largest determinant of the change in peak flow. Therefore, for the perturbation of the January 1999 event, the median catchment response exceeded 20% for four of the six scenarios. Peak water levels and flows increased at all downstream receptors examined, but with large differences between receptors, events and scenarios. For example, some receptors appear less sensitive to climate change than others.

There are several limitations with the methodologies applied in the research. A proportional change factor does not allow for a change in variance, and for the Bedford Ouse a daily rainfall timestep was used along with a temperature-based PET formula; these factors could lead to an underestimation of future flood risk. In contrast assumptions were made in the models, for example fixed retention level rules, which could be varied in order to manage flood risk. More broadly, the results are an outcome of the particular scenarios modelled, which only capture part of the known climate-related uncertainties.

Scenarios provide a number of benefits particularly with continuous simulation, including a better understanding of geography, uncertainty and the role of PET and antecedence effects. However, the volume of data and the nature of the models present challenges. Nonetheless, the continued use of a single national sensitivity range is questionable; a wide range of catchment-specific or regionally specific sensitivity factors may prove more robust.

Key words: climate change, future flooding, United Kingdom, Eden, Bedford Ouse.

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List of acronyms

Acronym	Explanation
AAD	Annual Average Damage
AAR	Annual Average Rainfall
ABI	Association of British Insurers
ACCELERATES	Assessing Climate Change Effects on Land use and Ecosystems from Regional Analysis to The European Scale project
AGCM	Atmosphere General Circulation Model
APE	Annual Probability Event
API5	Antecedent Precipitation over 5 days, parameter in FEH
AOD	Above Ordnance Datum
AOGCM	Atmosphere Ocean General Circulation Model
BAU	Business As Usual
BESEECH	Building Economic and Social Information for Examining the Effects of Climate cHange project
BETWIXT	Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes
BF	Base Flow, parameter in FEH
BFI	Base Flow Index
BP	Before Present
CCS	Climate change scenario
CEH	Centre for Ecology and Hydrology
CF	Change Factor
CFMP	Catchment Flood Management Plan
CLASSIC	Climate and LAnd use Scenarios Simulation In Catchments, CEH continuous flow simulation model
CLG	Department for Communities and Local Government
COW	Critical Ordinary Watercourse
CRANIUM	Climate change Risk Assessment New Impact and Uncertainty Methods project
CRU	Climatic Research Unit, University of East Anglia
CWI	Catchment Wetness Index
DDF	Depth-Duration-Frequency
Defra	Department for Environment, Food and Rural Affairs
DHI	Danish Hydraulic Institute
DJF	December, January and February (climatologically the winter season in the northern hemisphere)
DMI	Danish Meteorological Institute
DP-S-I-R	Driving Pressures-State-Impact-Response (Turner, 2005)
DTLR	Former Department for Transport, Local Government and the Regions
EA	Environment Agency (of England and Wales)
EARWIG	Environment Agency Rainfall and Weather Impacts Generator (Kilsby, 2006)
ENSEMBLES	Ensembles project
ETH	Used in the modelling sections of this thesis as an abbreviation for ETHZ
ETHZ	Swiss Federal Institute of Technology Zurich
FAO	Food and Agriculture Organization of the United Nations
FEH	Flood Estimation Handbook (IH, 1999)
FM	Fluvial modelling
FRA	Flood Risk Assessment
FSR	Flood Studies Report, succeeded by FEH
GCM	General Circulation Model
GDP	Gross Domestic Product

Acronym	Explanation
GHG	Greenhouse Gas
GIS	Geographical Information System
GLM	Generalised Linear Model
GVA	Gross Value Added
HLT	High Level Target
HOST	Hydrology of Soil Types
IDB	Internal Drainage Board
IPCC	Intergovernmental Panel on Climate Change
IRMA-SPONGE	INTERREG Rhine Meuse Action Scientific Programme ON GEnerating sustainable flood control project
JJA	June, July and August (climatologically the summer season in the northern hemisphere)
KNMI	Royal Netherlands Meteorological Institute
LA	Local Authority
LDD	Local Development Document
LPA	Local Planning Authority
LTA	Long Term Average
MAM	March, April and May (climatologically the spring season in the northern hemisphere)
MDSF	Modelling and Decision Support Framework (designed to support production of CFMPs)
METO-HC	Met Office Hadley Centre
MORECS	Met Office Rainfall and Evaporation Calculation System (Hough *et al.*, 1997)
MOSES	Met Office Surface Exchange Scheme (Cox *et al.*, 1999; Essery *et al.*, 2001)
MPI	Max-Planck-Institut für Meteorologie
NAM	Nedbør-Afstrømnings-Model, Danish for precipitation-runoff-model (DHI MIKE11 rainfall–runoff model)
NGO	Non-Governmental Organisation
NRFA	National River Flow Archive
OGCM	Ocean General Circulation Model
OST	Office of Science and Technology
pdf	Probability distribution function
PET	Potential evapotranspiration
POT	Peaks-over-threshold, method of flood frequency analysis
PPG25	Planning Policy Guidance Note 25 *Development and Flood Risk* (DTLR, 2001a); superseded by PPS25.
PPS	Planning Policy Statement
PPS25	Planning Policy Statement 25 *Development and Flood Risk* (CLG, 2006); preceded by PPG25.
PR	Percentage Runoff, parameter in FEH
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects project
RASP	Risk Assessment for flood and coastal defence for Strategic Planning (HR Wallingford and University of Bristol, 2004)
RCM	Regional Climate Model
RFRA	Regional Flood Risk Assessment
RMSE	Root Mean Square Error
RSPB	Royal Society for the Protection of Birds
RSS	Regional Spatial Strategy
SAAR	Standard Average Annual Rainfall, parameter in FEH
SAC	European Special Area of Conservation
SBAB	Stable-Bed Aggrading Bank model (Brown and Keough, 1992)
SEPA	Scottish Environment Protection Agency

Acronym	Explanation
SES	Socio-economic Scenario
SFRA	Strategic Flood Risk Assessment
SFVI	Social Flood Vulnerability Index (Tapsell *et al.*, 2002)
SIRCH	Social and Institutional Responses to Climate Change and Climatic Hazards: Drought and Floods project
SMD	Soil Moisture Deficit, including a parameter in FEH
SMHI	Swedish Meteorological and Hydrological Institute
SOIL	(Inverse) measure of the winter rainfall acceptance potential WRAP used in determining PR based on the contribution of each SOIL type
SON	September, October and November (climatologically the autumn season in the northern hemisphere)
SPA	European Special Protection Area
S-P-R	Source-Pathway-Receptor
SPR	Standard Percentage Runoff, parameter in FEH
SRES	Special Report on Emissions Scenarios (IPCC, 2000)
SSSI	Site of Special Scientific Interest
STARDEX	STAtistical and Regional dynamic Downscaling of Extremes for European regions project
SWURVE	Sustainable Water: Uncertainties, Risk and Vulnerability in Europe project
Tasmax	Maximum temperature
Tasmin	Minimum temperature
TBR	Tipping Bucket Rainfall
TCR	Transient Climate Response
TIDSIM	Tidal Prediction Program developed by George Mitchell, Atkins
TMAX	Maximum temperature
TMIN	Minimum temperature
Tp	Time to Peak, parameter in FEH
UK02	Used in the modelling sections of this thesis as an abbreviation for UKCIP02
UKCIP	UK Climate Impacts Programme
UKCIP02	UKCIP scenarios published in 2002 (Hulme *et al.*, 2002)
UKCP09	UK Climate Projections 2009
UKMO	UK Meteorological Office
UKWIR	UK Water Industry Research
URBEXT	Urban extent, parameter in FEH

Acknowledgements

Although this PhD is my own work, there are numerous people who have helped in a range of ways (apologies if I have not remembered everyone).

For excellent their supervision, I thank Professors Richard Hey, Kerry Turner and especially Phil Jones. Richard was my primary supervisor until his retirement from UEA in 2006 and helped ensure that the work to come on future flooding was grounded in a good understanding of fluvial geomorphology. Kerry advised me on the socio-economic aspects and his conceptual work in assessing environmental pressures and futures underpins the future flooding framework. Phil was my primary supervisor from 2006 and has guided the use of climate change scenarios and the weather generator and their application; hosting me at CRU for a few weeks over the past few years was very beneficial in writing the thesis. Thanks also to colleagues at CRU including Mike Salmon for IT access, Dr Claire Goodess for discussions, Dr David Viner (now with the British Council) for his paper on the uncertainty cascade, and particularly David Lister for advice on and extraction of ENSEMBLES data.

Thanks to my examiners Professor Rob Wilby (Loughborough University) and Professor Declan Conway (UEA) for comments in particular regarding the implications and abstract, which have helped improved the presentation and I hope the usefulness of the thesis.

The PhD was sponsored by my employer, Atkins, and I am very grateful to my managers for agreeing to this, supporting me through the years and for allowing me time off at the end to help write up. Thanks to Dr Nathan Richardson, Phil Sutherland and Dr Brian Arkell. In particular, thanks to Mark Blackmore, for helping me to balance my time and for always challenging my thinking. Also at Atkins, I want to especially recognise Tom Rouse, Paul Morgalla and Dr Kevin Sene. Tom helped hugely with the research on the Bedford Ouse, guiding my understanding and use of the model and interpretation the baseline results and always willing to answer my questions. Paul helped with all aspects of GIS, but especially with the UKMO rainfall dataset and the interpolation of climate model outputs. Kevin facilitated much of the work on the Eden and provided helpful comments on drafts of Chapters 6 to 10. Thanks also to Tracey Ashworth for running the Eden hydraulic model, Dr Yiping Chen (formerly Atkins) who wrote the Eden flood forecasting model, Chris Scott who produced the earlier Eden models, Dominic Bradley for information regarding Carlisle, Marc Huband (now at Aberystwyth University) for advice, Pamela White (formerly Atkins) for discussions on River Ely pilot CFMP, Sarah Marsh for a guided tour of the St Ives and Hemingfords Flood Alleviation Scheme and for photos of the area, Dr Helen Gavin for information on PET and MORECS including a copy of the update to Hydrological Memorandum 45 (Hough *et al.*, 1997), George Mitchell who wrote the TIDSIM software, and Carmela Carrino for binding the draft thesis.

The hydrological–hydraulic models used in the PhD are owned by the Environment Agency, and as well as granting licences to use these and associated data (details below), several staff members were of assistance. Thanks to David Murphy for initial discussions, Jon Lampard for the Bedford Ouse rainfall data, Robin Poole for the Bedford Ouse model, Ben Lukey for the Eden model and discussion of the modelling approach, Peter Spencer for the final Eden model, Nigel Worthington for the final Eden CFMP, Lucy Harper and Neil Pope for the scoping and final Bedford Ouse CFMP respectively, and Dr Mark Grout for permission to quote Entec (2007).

Thanks to Dr Jean-Philippe Vidal (formerly HR Wallingford) and Dr Steven Wade (HR Wallingford) for general discussions on data preparation for rainfall–runoff modelling. Thanks also to Dr Katy Appleton (UEA) for discussions on visualisation.

Thanks to Dr Richard Chandler (University College London) for offering use of the GLM and to Aidan Burton (Newcastle University) for use of RainSim. These are both potential developments of the work presented here.

Since May 2004, I have been affiliated to the Tyndall Centre for Climate Change Research. I must thank Laura Middleton for suggesting this, Professor Richard Hey for nominating me and Professor Mike Hulme for confirming my affiliated status as part of the adaptation research theme. In particular I have benefited from attendance at the Tyndall PhD Workshops and Tyndall Assemblies, where I have been exposed to ideas and challenges to my research from a truly inter-disciplinary group. Thanks also to Professor Jim Hall for sponsoring my Tyndall Mobility Grant that enabled me to visit Newcastle University in February 2008 and to Drs Hayley Fowler, Claire Walsh and Lucy Manning for the resulting discussions. Thanks also to colleagues Dr Suraje Dessai for discussions and Dr Ruth Wood for papers and discussions regarding socio-scenarios and participatory responses.

Thanks to colleagues at the Chartered Institution of Water and Environmental Management and the European Water Association, in particular Paul Horton, for discussions and opportunities to represent these professional bodies at various events.

Finally, thanks to my wonderful family and friends. Thanks to my parents for supporting me to do my MSc in Climate Change (at UEA), which set the direction of my career and this thesis. Thanks to my wife, and now our two children, for your patience, love and for ensuring lots of life alongside the work! Thanks to my wife's parents and sister for hosting us in Norwich for various weeks spent at UEA. Thanks to my brother for professionally proof reading the final draft; I hope I've captured the nuances of en-dashes and hyphens! And thanks also to all my family and friends who have encouraged me and listened to the latest developments with interest!

Data providers

The UKMO data were provided under licence from the UK Met Office to UEA. Thanks also to the Met Office for permission to quote Climate Memorandum 24 and to Graham Bartlett in the Met Office library for a copy of Hough and Hood (2003)

EARWIG v2.1 was provided by Professor Chris Kilsby and Dr Hayley Fowler at Newcastle University, who are thanked along with Professor Rob Wilby (then at the Environment Agency) for permission. Thanks also to Dr Colin Harpham (CRU, UEA) for earlier versions.

© Crown Copyright 2002. The UKCIP02 Climate Scenario data have been made available by the Department for Environment, Food and Rural Affairs (DEFRA). DEFRA accepts no responsibility for any inaccuracies or omissions in the data nor for any loss or damage directly or indirectly caused to any person or body by reason of, or arising out of any use of, this data. Thanks to Jacqui Yeates (formerly UKCIP) for arranging the licence, Stephanie Ferguson for arranging access and to Dr Richard Westaway (formerly UKCIP) for information on the future 5 km by 5 km gridded output.

PRUDENCE project Data have been provided through the PRUDENCE data archive, funded by the EU through contract EVK2-CT2001-00132.

The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged.

The Bedford Ouse model and associated data was provided under licence from the Environment Agency by Robin Poole. Rainfall data was provided under licence by Jon Lampard.

The Eden model and associated data was provided under licence from the Environment Agency by Ben Lukey and Peter Spencer.

BESEECH data was provided thanks to Dr Roger Salmons (Policy Studies Institute).

Maps were created using the data described above, along with Ordnance Survey OpenData.

1. Introduction

1.1 Floodplains

Floodplains are of central importance to fluvial catchments. Their primary function of extending the channel in flood, holding and passing waters downstream, belies a more complex role. Floodplains are also sinks and sources of sediment and provide habitats for a diverse range of flora and fauna. The sedimentary and ecological deposits stored in floodplains provide a valuable record of previous environments at the catchment scale (Hudson, 2003). Humans have long been attracted to rivers and associated floodplains for water supply, fertile soil, navigation, and flat terrain suitable for building and transport (Alexander and Marriott, 1999). In the UK many floodplain wetlands have been drained to support agriculture and for flood defence purposes (Purseglove, 1989; Cook and Williamson, 1999b) and the processes of development and urbanisation are perhaps the most important observed on floodplains today (Penning-Rowsell and Tunstall, 1996).

Floodplains are worth studying for a number of reasons and from several disciplinary perspectives. For geomorphologists, although floodplain forms may be unimpressive, the insights into fluvial processes and environmental history within the catchment are unique and hold great potential for examining landscape response to future climate and land-use change (Hudson, 2003). For ecologists, floodplains are important ecosystems that form transitions between aquatic and terrestrial environments (Thoms, 2003). For hydrologists and hydraulic engineers, floodplains represent a complex zone over which flood waters move and where flood waters represent a hazard to humans and infrastructure. For planners and developers, floodplains have traditionally been ideal locations for the construction of railways, roads, homes and businesses, and still continue to be, despite the challenges this presents for managing flood risk.

Floodplain evolution, particularly in temperate regions such as the UK, has been strongly influenced by climate and changes in climate, directly through precipitation and indirectly through the effect on vegetation. However, in the latter part of the Holocene, human influences within the catchment, and directly on the floodplain and in river channels, have begun to dominate floodplain evolution, particularly in the lowlands of southern and eastern UK.

In many countries floodplains now contain extensive urban areas, as well as large expanses of agricultural land and important transport routes. In recent years some countries have experienced serious flooding, for example in the UK in 1998, 2000 and 2007 and in central Europe in 1997, 2002 and 2005. Floods themselves are an intrinsic part of life on floodplains and, in the absence of an increase in the trend of floods in the UK (Robson *et al.*, 1998; Robson, 2002; Wilby *et al.*, 2008), or Europe (Mudelsee *et al.*, 2003), the greater vulnerability and losses can largely be attributed to the increase in population and capital located on the floodplain as well as modifications to hydrological systems (Mitchell, 2003).

1.2 Climate change

The rise in greenhouse gas emissions, over the last 150 years in particular, along with changes in land use has led to global warming, which for the late twentieth century is most likely attributed to anthropogenic causes (Hegerl *et al.*, 2007). The effects on global, hemispheric and regional climate are well documented (see Solomon *et al.*, 2007) and advances in atmospheric research and computer power have facilitated the development of General Circulation Models (GCMs), which attempt to predict future attributes of climate based on levels of atmospheric greenhouse gas emissions. These show that global climate is likely to warm significantly in the twenty-first century, particularly if atmospheric greenhouse gas concentrations are not stabilised.

There now exists a large body of research describing the impacts of climate change on the environment, economy and society of different locations and regions (see Parry *et al.*, 2007). This research is currently biased towards particular sectors, for example water, and certain countries, particularly in north-west Europe and North America. For example, there are numerous UK studies describing potential hydrological impacts, with a particular focus on the change in flood frequency and understanding uncertainty. Although there is no detectable change in river flow records yet nor likely in the near future (Wilby, 2006), these studies indicate that climate change will have a significant effect on runoff. Impacts vary considerably based on scenarios, method and catchments, but in general there is a greater seasonality of flows and an increase in the magnitude and frequency of (winter) high flows.

Despite the increasing quantity of research into the impact of climate change on flooding, there are few inter-disciplinary, end-to-end studies of the impact of climate change on floodplains at the catchment scale. Consideration of the nature of the potential impacts (e.g. an increase in flooding) and the changes in historical floodplains in response to climate change (e.g. aggradation or downcutting) suggests that the impacts may be significant, although the past may no longer be a reliable guide to the future. Critically though, these impacts are also occurring at a time when floodplains are experiencing major non-climatic pressures, as described above.

1.3 Floodplain futures

The management of floodplains is inherently complex, and predicting their future is highly uncertain. In this context, exploratory scenarios offer a potential approach to assess the interaction of both climatic and socio-economic changes over the twenty-first century. The landmark Foresight Future Flooding study (Evans *et al.*, 2004a; Evans *et al.*, 2004b) adopted this approach on a national scale using gridded datasets and the scaling of flood risk drivers and responses. Ideally, national socio-economic scenarios, along with climate scenarios, would be downscaled for use in catchment models to define specific *floodplain futures*. However, such a framework can only be conceptual at present, limited by the ability to physically model socio-economic changes and assess their impacts at the catchment scale. Instead, Catchment Flood Management Plans adopt a sensitivity approach based on land use change, urban growth and climate change. The use of climate change scenarios is particularly pertinent. Academic scenarios have become increasingly sophisticated in their use of climate model output in hydrological models. However, the treatment of climate change in the models used in decision-making, for example those used for the design of flood defences, remains rudimentary. The current Defra guidance stipulates an indicative sensitivity range of 20% for peak river flow, which although initially based on research on the Severn and Thames catchments, has been applied in a variety of ways to numerous catchments. Recent research suggests that the UK indicative sensitivity range may not be sufficient and that a national indicative sensitivity range may not be appropriate (Reynard *et al.*, 2009). Therefore, the use of downscaled climate model data in catchment models should be considered.

1.4 Research objectives

The objectives of the research are to:

- **Review the evolution and management of floodplains, assess the implications of climate change for future management and to identify research gaps**. It is not the intention of this research to address all identified research gaps. For example, although it is possible that climate change may initiate or enhance channel instability in active rivers, it is assumed that such change would be managed where problematic, and as such this research gap was not explored further.
- **Produce a framework for the assessment of catchment-specific floodplain futures that integrates climate and socio-economic change**. As described above, such a framework can only be conceptual at present and so not all of the phases of the framework are implemented in this thesis. In particular, the quantification and parameterisation of socio-economic scenarios proved problematic for several of the socio-economic driving pressures, especially those relating to land

use and management and river channels. There also remains a high level of uncertainty regarding the impact of land use on flood flows, especially where the changes are minor and where catchments are large.

- **Use climate model information directly in design models, assess the implications for future flooding and examine the associated methodological benefits and drawbacks**. This addresses the impasse between academic studies, which have generally used catchment-specific scenarios, and information being used in decisions, based on the national indicative sensitivity range.

1.5 Thesis outline

Chapter 2 ***Review of floodplain definition, evolution, function and management*** reviews the definition of floodplains, and then provides an overview of the evolution of floodplains from channel initiation to floodplain formation. This is followed by a review of current floodplain functions and their management.

Chapter 3 ***Review of climate change, implications for floodplain management and identification of research gaps*** begins with a review of climate models and scenarios of climate change for the UK, before examining the implications for floodplain management. Research gaps are then identified.

Chapter 4 ***A framework for integrated assessment and research methodology*** introduces a comprehensive framework for the integrated assessment of floodplain futures, covering scoping, modelling, consultation, reporting and evaluation phases. The aims of the following research are then presented, which focus on climate change and future flooding, in particular to use climate model information directly in design models (as described above). A methodology for the development of socio-economic scenarios under the framework is presented in **Appendix 1**.

Chapter 5 ***Case study catchments and flood risk driving pressures*** introduces the two case study catchments, the Bedford Ouse and the Eden, and then identifies the driving pressures for flood risk, along with significant exemplar receptors.

Chapter 6 ***Baseline climate*** describes the baseline climatology for each catchment.

Chapter 7 ***Climate change scenarios*** details the methods used for producing the climate change scenarios, including their application to the hydrological models.

Chapter 8 ***Future flooding: the Bedford Ouse*** assesses the changes in flooding in the Bedford Ouse catchment that result from the climate change scenarios, focused on the exemplar receptors. **Appendix 2** presents work undertaken to identify potential relationships for selecting likely periods of flood-producing rainfall from the stochastic weather generator. **Appendix 3** presents further graphical outputs from the Bedford Ouse modelling.

Chapter 9 ***Future flooding: the Eden*** assesses the changes in flooding in the Eden catchment that result from the climate change scenarios, focused on the exemplar receptors. **Appendix 4** presents further graphical outputs.

Chapter 10 ***Conclusions, implications for policy and practice, and recommendations for research*** summarises the findings of the research, critically reviews the methodology, and presents recommendations for further research.

2. Review of floodplain definition, evolution, function and management

This chapter reviews relevant literature concerning floodplain definition, evolution, function and management, and is split into the following sections:

1. **Floodplain definition** reviews the variety of ways in which floodplains are defined.
2. **Floodplain evolution** considers channel initiation, stream discharge and flooding, floodplain formation and evolution, and floodplain classification. The evolution of UK floodplains over the Quaternary is then described and a summary of driving factors is presented.
3. **Floodplain function and management** provides an overview of current floodplain function and use before describing the policy and practice of contemporary floodplain management. The chapter concludes with a summary of current drivers and future challenges in floodplain management.

2.1 Floodplain definition

There are a variety of definitions of floodplain, which relate to particular disciplines, functions or the way in which they are managed. Expressed simply, a floodplain is:

> the strip of land that borders a stream channel, and that is normally inundated during seasonal floods.
>
> (Bridge, 2003: 260)

The relationship between the channel and floodplain is fundamental and connects the floodplain with the catchment. This is reinforced in Schmudde's (1968 in Alexander and Marriott, 1999: 2) definition:

> …as a topographic category, it is quite flat and lies adjacent to a stream; geomorphologically, it is a landform composed primarily of unconsolidated depositional material derived from sediment being transported by the related stream; hydrologically, it is perhaps best-defined as a landform subject to periodic flooding by the parent stream.

Floodplains are almost always defined in relation to a stream channel and do not generally relate to any area inundated by pluvial flooding or groundwater flooding, unless a channel is involved (Alexander and Marriott, 1999). Therefore there are areas outside floodplains (e.g. around spring heads, or urban areas) that are subject to flooding and which may experience more severe flooding under climate change than at present. However, such areas are not considered further in this thesis.

As described subsequently in this chapter, floodplains evolve in response to changing climate and fluvial regimes and consequently floodplain landforms exist which have no relationship to contemporary fluvial or floodplain processes. In some valleys such relic landforms can be recognised as river terraces which can be found at the edge of the modern floodplain. Nanson and Croke (1992) describe the overall landform as a *polyphase floodplain*. Some floodplains reflect the controls of former regimes, whereas others are dominantly formed or reformed by contemporary processes (ibid.). Nanson and Croke (1992: 460) term the latter a *genetic floodplain* and define it as:

> the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the *present flow-regime*. (Emphasis added.)

This definition provides links to regime theory, dominant discharge and environmental change, which are discussed in the following section. However, as Alexander and Marriot (1999) suggest, this definition should be broadened to include other processes of sediment accumulation such as in-situ organic growth. More fundamentally, the definition is focused, quite deliberately, on geomorphic history and excludes modern-day flood extent. This is discussed further below.

In contrast to Nanson and Croke's geomorphologically focused *genetic floodplain*, other definitions relate purely to the flooding process, particularly flood extent. Wolman and Leopold (1957) found that a diverse range of floodplains are subject to flooding about once per year, but while rivers may come out of bank at about this frequency, the floodplain is generally considered to encompass the flood extent of much larger and more infrequent floods, and therefore can cover a much greater area. Hydrologists and engineers normally consider the floodplain to be the area covered by the 1 in X year flood or *design flood*. Nanson and Croke (1992) term this the *hydraulic floodplain*. The hydraulic floodplain is defined through empirical models of runoff and flow or with knowledge of historical flood extents and associated discharge frequency (Alexander and Marriott, 1999).

The Environment Agency's original *Indicative Floodplain* map was based on the 1 in 100 year return period (excluding the effect of defences), or the highest known flood. Their revised map[1] includes the 1 in 1000 year ("extreme") flood outline (excluding the effect of defences), as well as zoning areas according to their likelihood of flooding[2] (including the effect of defences). The zoning approach has also been adopted in Strategic Flood Risk Assessments produced by local planning authorities (Williams and Worth, 2003).

[1] The flood map was published on 7 October 2004 and is available on the internet at: www.environment-agency.gov.uk. It shows both the 1 in 100 year and 1 in 1000 year flood extents, which provide the divisions between Zones 1 and 2, and 2 and 3, respectively, of PPS25.
[2] Likelihood of flooding is split into three categories: significant (greater than 1 in 75 chance of flooding in any year), moderate (1 in 75 or less, but greater than 1 in 200) and low (1 in 200 or less).

Planning Policy Guidance Note 25: *Development and Flood Risk* (PPG25) (DTLR, 2001a) defined the *functional floodplain* as the floodplain on the riverward (undefended) side of flood defences:

> Floodplains are generally flat-lying areas adjacent to a watercourse … where water flows in times of flood or would flow but for the presence of flood defences where they exist. Functional floodplains are the unobstructed or active areas where water regularly flows in time of flood.
>
> (PPG25, paragraph 25)

In reality, the functional floodplain is delineated by man-made structures other than flood defences, for example railway and road embankments. In the replacement *Planning Policy Statement 25* (PPS25), the simple definition of *Zone 3b The Functional Floodplain* is: “this zone comprises land where water has to flow or be stored in times of flood” (CLG, 2006: 24). The Environment Agency’s flood map will, in time, include the position of all riverine flood defences which protect against the 1 in 100 year flood, with the defended floodplain delineated. Therefore the functional floodplain will effectively be defined by the flood defences, where they exist at a given standard. PPS25 also provides flood zones, defined by design floods, which have been related to appropriate planning responses (CLG, 2006). For river floodplains these zones are (1) low probability (less than a 0.1% annual probability of flooding), (2) medium probability (0.1% to 1.0% probability), (3a) high probability (greater than 1.0% probability) and (3b) the functional floodplain.

The hydraulic floodplain is influenced by a number of factors. The factors include processes both internal and external to the catchment (Alexander and Marriott, 1999). Internal processes include, for example, change in runoff and flood discharge due to upstream land use change, and construction of flood defences that reduce the floodplain area. External factors include climate change, which can alter the quantity, intensity and timing of precipitation. Some factors, such as the construction of a road embankment or flood defence, can have an immediate impact on the hydraulic floodplain, not just locally but on the wider catchment (mainly downstream, but also a little upstream due to ‘backing-up’).

The hydraulic definition of a floodplain does not relate to processes that formed the landform beneath the floodplain surface (Alexander and Marriott, 1999). Physically, a genetic floodplain is the landform that spatially lies beneath the hydraulic floodplain surface and adjacent to the channel. Under a changing flow regime (for example under climate change), the hydraulic floodplain will alter more quickly, with the genetic floodplain taking significantly more time to re-form (particularly in temperate, vegetated catchments with cohesive soils). This lag between process and form poses a challenge when considering environmental change. Part of this problem is related to the timescale of enquiry, but the problem becomes more acute as the rate of climate change accelerates (Brown and Quine, 1999).

The definitions of floodplains discussed above have all been related to floodplain width, rather than the upstream and downstream limits to floodplains which are also debatable (Alexander and Marriott, 1999). Upstream, there is no well-defined point at which a stream gains a floodplain, although a floodplain cannot exist where the stream bed is the same width as a steep-sided valley floor, even if flooding and sedimentation can occur (ibid.). Downstream, the floodplain limit will generally coincide with the tidal limit, although this does not preclude tidal flooding of a fluvial floodplain (and vice versa) in extreme circumstances (ibid.). In tidal areas coastal or tidal floodplains may be defined, but this thesis only considers fluvial or river floodplains.

Administratively, the Environment Agency's *Indicative Floodplain* was only applied to Main Rivers[3], although the new flood map extends further upstream and includes some Ordinary Watercourses. Downstream, a distinction is made between fluvial floodplain and tidal floodplain, which on Main Rivers occurs at the tidal limit.

2.2 Floodplain evolution

2.2.1 Channel initiation

Fluvial floodplains, by definition, are only formed in relation to a channel; therefore, to understand how floodplains form, it is necessary to first consider the role and formation of channels. Channel initiation can result from storm runoff or from subsurface or groundwater flow.

Initial research focused on storm runoff, following Horton's 1933 theory of *infiltration-excess overland flow*. In this theory, which seemed to provide a scientific explanation for Sherman's 1932 unit hydrograph, the process of infiltration divides precipitation into overland flow (quickflow in a stream) and infiltrated water (which, if not evaporated or taken up by plants, percolates into groundwater and forms baseflow) (Jones, 1997). According to the theory and later work by Horton, the depth of overland flow would increase downslope (as the contributing area increased) and at a critical distance non-erosive laminar flow would be replaced by turbulent flow, which would initiate rills, gullies and eventually stream channels (ibid.). In reality rill initiation is promoted by inhomogeneities on slopes, which disrupt laminar flow, and depends on the nature of the slope material itself. Horton's theory is most applicable to arid and semi-arid areas of thin soils, low infiltration capacities and sparse vegetation (ibid.).

[3] Rivers in England and Wales are classified as Main Rivers or Ordinary Watercourses. Main Rivers are all waters shown as such on statutory main river maps and for flood defence purposes are controlled by the Environment Agency. Ordinary Watercourses are the responsibility of local authorities for flooding and drainage purposes, except Critical Ordinary Watercourses (COWs) which the Environment Agency is now responsible for.

Research in humid and temperate vegetated areas has provided new theories of runoff generation and methods of channel initiation. The concept of *return flow* has been particularly important. Return flow is subsurface water that emerges onto the surface and then flows overland. It was recognised that the areas of the catchment contributing this *saturation overland flow* varied and were dynamic: expanding and contracting based on the seepage from upslope (Jones, 1997). In such environments channel initiation is less dependent on a critical flow distance; more important is the location of surface and subsurface flow convergence, such as slope concavities or existing drainage lines (Summerfield, 1991).

In formerly glaciated areas, channels were formed beneath glaciers and by proglacial outwash. Nye or N-channels formed beneath glaciers and were incised into the substratum by the consistent flow of water along the same route (Benn and Evans, 1998). Downstream of glaciers, proglacial fluvial systems developed. These have distinctive morphologies characterised by highly variable discharges and, in particular, high sediment loads (ibid.). Glacial activity has left a legacy in many river systems, firstly by carving new valleys into bedrock or into glaciers' own till deposits and secondly through the deposition of outwash. The alternating aggradation of outwash sands and gravels, and incision, as the climate and flow regimes changed, has produced sequences of terraces in many river valleys (Lowe and Walker, 1997). It is in this context that many contemporary UK floodplains have formed.

2.2.2 Stream discharge, flooding and floodplain flows

Once a channel has been initiated and established, its floodplain can be defined, at least in a hydrological context, as the "landform subject to periodic flooding by the parent stream" (Schmudde, 1968 in Alexander and Marriott, 1999: 2). The definition of a flood varies, but in general implies an overbank flow (Wolman and Leopold, 1957). An overbank flow occurs when the stream discharge exceeds the conveyance capacity of a channel, where the conveyance capacity depends on the cross-sectional shape, longitudinal bed slope and resistance to flow (Knight and Shiono, 1996).

Discharge at a point is described in a hydrograph. The hydrograph summarises the key processes, namely rainfall (at least the peak) and the resulting discharge over time, with the time to (discharge) peak reflecting the time taken for water to move over and through the catchment surface. Discharge is made up of baseflow (slower flow through the ground) and quick or storm flow (overland or rapid shallow subsurface flow) (Bridge, 2003). Hydrographs therefore reflect the temporal and spatial distribution of precipitation, the type of flow, as determined by antecedent conditions and catchment characteristics, and drainage system geometry (ibid.). The unit hydrograph and its derivatives provide a standard hydrograph based on the average pattern of runoff resulting from a specific amount of rainfall (usually one centimetre) falling on the whole catchment (Jones, 1997). However, the assumption of uniformity means that this approach is only suitable for small catchments. The synthetic unit hydrograph can be used where no data exists, with parameters based on equations constructed from empirical data, as in the Flood Estimation Handbook. As well as being useful in considering the events of an individual storm, over longer periods of time hydrographs are useful in assessing other influences on rainfall and runoff (Bridge, 2003), which may be internal to the catchment, for example land-use change, or external, for example a change in precipitation.

Discharge can be predicted by using rainfall–runoff models. Beven (2001) describes the rainfall–runoff modelling process beginning with a perceptual model (the modeller's perception of how the catchment responds to rainfall), which is followed by a conceptual model (the mathematical description of the processes), the procedural model (where, for more complicated conceptual models, an additional stage of approximation is required to compute the equations), model calibration (definition or fitting of model parameters i.e. inputs and state variables) and finally model validation (evaluation of model performance). A large variety of conceptual models have been developed to describe and predict the rainfall–runoff process. Beven (2001) makes a distinction between lumped and distributed models and between deterministic and stochastic models: lumped models treat the catchment as a single unit with catchment average parameters, whilst distributed models break the catchment down into smaller units; deterministic models provide one output from one set of inputs and parameters, whilst stochastic models output a range based on uncertainty in input values or parameters. Rainfall–runoff models are classified as hydrological or hydraulic models, the former concerned with runoff production and the latter with runoff routing. Rainfall–runoff models can be used to model single events or provide a continuous simulation, although models are generally designed for a particular application.

The relationship between stream discharge and water level (stage) is very important in understanding the extent and depth of floodplain inundation. Stage-discharge relationships (described using rating curves) have been established at gauging stations and are used to calibrate hydraulic models, although the relationship becomes hard to quantify once the stream is in flood.

The initiation of overbank flooding is not well studied, but during the rising flow stage water moves onto the floodplain via low points on stream banks or in levees and by overland flow (Bridge, 2003), which can no longer enter the stream. Water level in streams can be higher at this time leading to accelerating, erosive flows from the channel onto the floodplain (ibid.).

During peak flow, flood water moves downstream as an extension of the channel, albeit with a significantly different cross-sectional shape and potentially a new flow path, particularly where the stream is meandering (Knight and Shiono, 1996). The floodplain offers more resistance than the main channel and consequently the flow on floodplains is slower. Naef *et al.* (2000) distinguish two types of retention: standing retention, where floodplains act as detention basins, and flowing retention, where water flows parallel to the main channel, albeit at a slower rate. Floodplain flows depend on the local topography and are likely to be faster in channels or in areas of flow convergence (Bridge, 2003). Analysis of floodplain flows is therefore complex, particularly at the intersection of flows with those in the main channel where shear stress leads to the development of vortices and the exchange of water between the channel and floodplain (Knight and Shiono, 1996; Bridge, 2003). This complexity means that the one-dimensional models suitable for flow routing in channels are generally too simple and instead two- or three-dimensional models are required (Knight and Shiono, 1996). Current models generally treat flow as two-dimensional (depth averaged); three-dimensional models need to improve their representation of processes such as turbulence and require better data for calibration (Bridge, 2003).

During the falling stage of a flood, water flows back into the main channel, directly via channels or through infiltration and groundwater (Bridge, 2003).

Finally, it is worth considering the frequency of flooding on floodplains. Clearly, areas proximal to the channel flood the most often, whereas those distal areas on the valley edge, or which are elevated, flood less frequently. As discussed, Wolman and Leopold (1957) found that the floodplains of many streams of different sizes flowing in diverse physiographical and climatic regions are subject to flooding at a frequency of just over once per year. Subsequent research in the USA and UK has arrived at an average recurrence interval of 1.5 years (Hey, 1993). However there is considerable variation around this value in some cases, which reflects the difficulty in defining bankfull, measurement problems, and real differences in the return period and possibly therefore in flow regime (ibid.). Therefore the 1 to 2 year return period of bankfull discharge is now seen as an over-simplification (Werritty, 1997a). Other difficulties relate to the method of calculating the return period (annual maximum or partial duration), which can produce different values. Furthermore, return period calculations are based on instantaneous flood peaks and therefore ignore the duration of flood events (Hey, 1993). Exceedence duration of bankfull flow is rarely determined, although the limited data available suggest considerable variation between sites (Hey, 1997).

2.2.3 Floodplain formation and evolution

The flooding of the area adjacent to the channel may define the floodplain hydrologically, but geomorphologically a floodplain "is a landform composed primarily of unconsolidated depositional material derived from sediment being transported by the related stream" (Schmudde, 1968 in Alexander and Marriott, 1999: 2). Therefore, the formation of a genetic floodplain requires the contemporary stream to deposit its own floodplain.

Before discussing the sources and processes of deposition, it is first necessary to describe the relationship between the stream flow, its sediment load and channel stability. When there is no net change in the discharge capacity or morphology of a channel over a number of years, the channel is said to be in *regime* (Hey, 1993). This does not preclude change, or even channel shift, as long as the average condition is restored by other events. Channels in regime are generally self-formed in alluvial material and flow within their own floodplain (ibid.). At equilibrium, channel morphology is controlled by discharge (Q) and sediment load (Q_s) from upstream, the calibre of bed (D) and bank (B) material, valley slope (S_v) and bank vegetation. In stable channels with vegetated banks and where there is no change in valley slope, the only controls on channel morphology are discharge and sediment load, and change in either of these will therefore lead to instability and adjustment (ibid.).

A stream in regime has adjusted its morphology to transport sediment from upstream so that over a period of years there is no net erosion or deposition (Hey, 1993). This adjustment is based on the range of flows and loads that may be experienced by a channel. However, Blench (1951, cited in Wolman and Miller, 1960: 65) suggested that there may be a dominant discharge, a "steady discharge that would produce the same result as the actual varying discharge". Wolman and Miller (1960), in a seminal paper on magnitude and frequency in geomorphic processes, examined the theoretical relationship between the rate of transport, applied stress and the frequency with which the stress is applied. The theory demonstrates that, although events of larger stress can cause a greater rate of transport, such events are infrequent and therefore the maximum transport actually occurs at a moderate, more frequent stress. Applied to streams, Wolman and Miller (1960) suggested that moderate discharges transport most sediment and therefore are likely to represent the dominant discharge within a channel. They supported their theoretical work with observations from a variety of rivers across the USA and concluded that "significant alluvial land forms are formed by frequently recurring events of moderate intensity and not by rare floods of unusual magnitude" (Wolman and Miller, 1960: 67). This conclusion was the same argument that supported the uniformitarian paradigm, which was the accepted view of nearly all earth scientists for much of the nineteenth and twentieth centuries (Werritty, 1997a).

The effective, or channel-forming, discharge of a stream is generally defined as the flow that transports most sediment (the modal flow), although Marlette and Walker (1968) defined it as the flow above which half the sediment is transported (the median flow) (Hey, 1993). Early work by Schaffernak (1922) only considered bedload, but subsequent studies have also included suspended and total loads, the latter being preferable (Hey, 1993).

Based on the recurrence interval of bankfull discharge, Wolman and Miller also concluded that "the floodplain and shape and pattern of the river channel are related to the discharges approximating the bankfull stage" (Wolman and Miller, 1960: 65). This has been supported by further studies and although some concluded that a single effective discharge could not be determined (e.g. Biedenharn et al., 1987 and de Vries, 1993, cited in Hey, 1993), while others noted the difficulties in the morphological definition of bankfull discharge (e.g. Williams, 1978 cited in Werritty, 1997a), the relationship between effective and bankfull discharge is generally accepted, albeit with some qualification (Hey, 1993; Werritty, 1997b). However, as the emergence of neo-catastrophism has highlighted, it is important to consider the geomorphic potential of major floods on channel morphology and stability, and on the wider landscape (Werritty, 1997a). Related to this, it is also necessary to assess the relaxation time of streams and floodplains i.e. the time it takes to recover from a major flood and for the pre-flood situation to be restored. In temperate climates, rivers with fine-grained beds and vegetated banks and floodplains, typical of lowland England, the relaxation time is likely to be short and the geomorphic effectiveness of major floods may be limited.

As discussed, the formation of a genetic floodplain requires the contemporary stream to deposit its own floodplain. The literature distinguishes two ways in which this occurs: firstly by overbank flows of finer material in suspension, often called vertical accretion, and secondly, within the channel, bars, including point bars, form from the deposition of coarser bedload material, a process termed lateral accretion (Marriott, 1998). The terms vertical and lateral applied in this way are rather confusing because both vertical and lateral processes occur in the evolution of channels and floodplains (Bridge, 2003).

Early research suggested that overbank accretion was only a minor contributor to floodplain deposits. Wolman and Leopold (1957) concluded that just 10% to 20% of deposits on a normal floodplain resulted from overbank flows, based on the observed dominance of lateral deposits, particularly related to point bars. Wolman and Leopold (1957) suggested that a lack of overbank deposition could be explained by lower concentrations of suspended sediment in peak or out-of-bank flows, and high enough flow velocities over the floodplain to obviate deposition. They also noted that floodplain height could be restricted by lateral erosion. The observations fitted well with the apparent constant frequency of flooding from channels in regime. However, under conditions of net aggradation, both the floodplain and the channel bed are likely to be aggrading and therefore flood frequency would remain the same (Bridge, 2003). More recent studies have questioned the dominance of lateral accretion in every floodplain environment and have found that point bars are not always the primary sedimentary landform in lateral deposits (Nanson and Croke, 1992). Further research has found that suspended sediment concentrations do not always precede peak discharge and overbank deposits have been found to dominate the formation of some floodplains (Marriott, 1998). This is particularly relevant in streams with cohesive banks and relatively low stream power, or where rivers have been channelised or trained, which limits or prevents channel migration (Marriott, 1998; Walling *et al.*, 1996). This is the case in some lowland UK floodplains, although the most active vertical accretion occurs in high-energy channels with sandy floodplains (Nanson and Croke, 1992).

Overbank deposits are varied and include levees, crevasse splays, channel fills and exceptional sheet-flood deposits (Nanson and Croke, 1992; Bridge, 2003). Levees are small landforms that line the banks of some rivers, separating the channel from the floodplain. They are deposited by flows which decelerate as they move from the channel onto the floodplain and therefore contain coarse sediments. Sediment deposited close to the bank may also have been moved by traction as bedload (Marriott, 1998). Crevasse splays are landforms rapidly deposited following the breach of a levee and are made up of relatively coarse sediments carried by flows accelerating through the breach, or crevasse (Summerfield, 1991). Channel fills are deposited throughout the floodplain in abandoned main channels, crevasse channels and tributary channels (Bridge, 2003). Initially filled with coarser bedload sediment, the abandoned channels eventually become lakes and receive finer suspended-sediment deposits (ibid.). Sheet deposits that cover the floodplain were not considered by Wolman and Leopold (1957) to be a significant process in floodplain building. Although the rates of such sedimentation are small, they can form a large proportion of the total sediment accumulation over the floodplain and such deposition represents an important sink for suspended sediment (Walling *et al.*, 1996). Exceptional floods may also deposit thick sheets of sediment over large parts of the floodplain (Bridge, 2003).

Zwolinski (1992) has constructed a six-phase descriptive model of geomorphic events during flooding, related to the floodplains of lowland meandering rivers in the temperate climatic zone. The model, summarised in Table 2-1, links the processes of flood inundation with the processes of sediment erosion, transport and deposition on the floodplain. Erosion, then transport, initially dominate, whilst deposition is the key process following the flood peak, at which point there is a moment of dynamic equilibrium between erosion, transport and deposition (Zwolinski, 1992). Quantitative, deductive models of overbank deposition have also been developed and are reviewed in Marriot (1996; 1998).

Table 2-1 A model of overbank deposition on the floodplains of lowland meandering rivers

Phase	Geomorphic process	
1: Rising water stage; bank modification	Erosion of floodplain edges (banks) Counterpoint deposits form (in-channel) towards end of phase	
2: Floodplain inundation; initial deposition	Erosion in breaches, crevasses, chutes Re-deposition of older terrace sediments Counterpoint development continues Natural levees built up, especially on vegetated banks Meander sand covers deposited	
3a: Adjustments of overbank flow to floodplain; transport and deposition dominant	Accretion and deposition of many facies e.g. levees, crevasse splays, counterpoint bars, sand covers and shadows, meander scroll ridges, slack water deposits	
3b: Flood peak; widespread transport and deposition	Erosion almost ceases Deposition in farthest parts of floodplain Accretion and deposition of facies as in Phase 3a	
4: Falling water stage; high intensity deposition	Material from river channel reduces Maximum deposition Overbank returns leave traverse or oblique structures in top sets Erosion practically ceases	
5: Cessation of overbank flow; final deposition	Accumulation strongly dependent on waning transport Unloaded outflowing water modifies new deposits	
6:Post-flood transformation of overbank forms and deposits	Decantation of fines and formation of micro-cliffs due to wave-like motion of stagnant waters in depressions	Sub-aerial processes, such as desiccation, disturbance due to animals and humans and vegetation growth

Adapted from Zwolinski (1992).

The second type of accretion contributing to the deposition of floodplains is the development of in-channel structures that subsequently become incorporated into the floodplain. In regime rivers the incorporation of channel deposits, such as point bars, into the floodplain will coincide with erosion of the opposite bank. Thus channel migration effectively recycles the floodplain, although the sediment itself is passed downstream over time. Wolman and Leopold (1957) concluded that 80% to 90% of a normal floodplain may be composed of lateral accretion deposits. Assuming only a small amount of net overbank deposition, this suggests that considerable lateral migration occurs across a normal floodplain. Although difficult to measure and to extrapolate, evidence presented by Wolman and Leopold (1957), from a variety of rivers, shows that even the slower rates of migration would over time:

> … permit the river to move readily from one side of its valley to the other. The very existence of the broad valley indicates that it has done so in the past.
>
> (Wolman and Leopold, 1957: 96)

Lateral point-bar accretion occurs on the convex bank of meandering channels. Sediment is deposited at this location because of flow divergence and a complex pattern of shear stress related to the main flow and secondary currents (Nanson and Croke, 1992). Point-bar deposits are typically composed of relatively coarse sediment, but, as the bar becomes more established and flooded less frequently, comprise increasingly finer particles (Wolman and Leopold, 1957; Bridge, 2003). Although important, point-bar accretion is no longer synonymous with lateral accretion and other forms of lateral accretion that contribute to floodplain development have been recognised. These include counterpoint accretion and abandoned-channel accretion. Counterpoint accretion occurs in the slack-water area downstream of point bars and includes a high proportion of suspended sediment and organics (Nanson and Croke, 1992). Abandoned channel accretion deposits grade from sands and gravels upwards to fine-grained swampy or lacustrine sediments (ibid.).

Sediment accounting for floodplain formation is transported by the stream from a variety of sources. Following channel initiation, the deposits in which the channel becomes established may provide the major source of sediment. For example, in areas covered by glacial sand and gravels, these would have been the initial source, whilst over time soils and other organic matter developed, along with the products of weathering. Material is delivered to the channel directly, for example by overland flow or through landslides from the valley sides, or by the erosion of tributary and main channel bed and banks. Studies examining floodplain deposits elucidate the changing nature of sedimentation over time and provide information on sediment provenance, as well as clues to the processes by which sediment was eroded and transported (see for example Brown, 1996; Walling and He, 1999). Sediments have also been examined to assess the relative impact of land use and climate change on floodplain deposition and this is discussed further in the following sections.

In order to transport sediment the stream must entrain the sediment; the ability to move particles of a particular size depends on the competence of the flow, or the critical shear stress. The sediment transport regime of catchments can be determined by the amount of sediment supplied to the drainage network, by the capability and efficiency of this network in transporting the material, and by the amount of deposition along the river and its floodplain (Asselman *et al.*, 2003). The proportion of sediment eroded on the hillslopes to that received at the catchment outlet provides a sediment delivery ratio, which can also be calculated for different parts of the system, including the channel (Asselman *et al.*, 2003). The proportion of the material supplied to the channel that reaches the catchment outlet provides a useful measure of conveyance loss and deposition, either within the channel, or on the floodplain. For example, Lambert and Walling (1987) examined suspended sediment loads upstream and downstream of an 11 km reach of the lower River Culm in Devon and estimated that approximately 28% of the annual load was deposited on the floodplain, which was subject to regular inundation.

The rate of sedimentation determines the speed at which a floodplain forms and evolves. It is controlled by sediment availability as well as the efficiency of the sediment transport regime from source to sink. Rates of lateral channel migration, and of floodplain building or recycling, vary considerably. Channels in bedrock, and some alluvial channels, migrate slowly or not at all, even over long time periods (Summerfield, 1991). Howard (1996) noted that meandering alluvial channels that do not migrate share a number of characteristics including: a low supply of bedload; a low and wide floodplain; cohesive, strongly vegetated banks and floodplain surface; and a low valley gradient. Howard proposed that such channels were barely competent to induce bank erosion and that erosion rates fell before meander cut-offs occurred, with more recent accretion occurring via overbank flows. In complete contrast, channels on humid alluvial fans migrate continuously and the exceptional Kosi River on the southern flank of the Himalayas has migrated more than 100 km over the past 250 years (Summerfield, 1991). Most alluvial channels migrate at more modest rates – in the UK at 0.1% to 5.5% of channel width, with maximum recorded steady rates of up to 2.8 m per year (Newson *et al.*, 1997).

Rates of overbank floodplain sedimentation are also highly variable, in time and space. Some floodplains experience little overbank deposition but, as discussed above, it can be the main source of sediment where channel migration is limited. Overbank sedimentation occurs infrequently, but flooding provides the opportunity for the deposition of a significant proportion of the suspended sediment load (Walling *et al.*, 1996). Marriot's post-flood sampling of sediment deposited by the River Severn flood of January to February 1990, revealed sandy material up to 150 mm deep close to the river bank (Marriott, 1996). Further from the channel a film of fine-grained material covered the floodplain, while thicker (5 mm) deposits of fine sediment had formed in areas where water had ponded (Marriott, 1996). Long-term rates of deposition have been calculated for some rivers: for example 1.4 mm per year over the past 10,000 years on the River Severn floodplain, and 5 mm per year over the past 3,000 years on the River Avon floodplain in Warwickshire (based on Brown, 1987 and Shotton, 1978, cited in Walling and He, 1999). These rates are similar to those gained from studies of contemporary sedimentation based on both sedimentation traps and radiocaesium measurement (Walling and He, 1999). Changing rates of overbank floodplain sedimentation, coupled with an understanding of sediment provenance, have provided an understanding of the impact of land use and climatic changes within catchments. This is discussed in the context of the UK in Section 2.2.5.

2.2.4 Floodplain classification

Floodplains can be classified according to various criteria, including stream power and sediment characteristics (Nanson and Croke, 1992), sediment texture patterns (Bravard and Peiry, 1999), soil geography (Avetov and Balabko, 1995), geomorphological river styles (Brierley and Fryirs, 2000) and flood risk (CLG, 2006). Floodplains are primarily classified for the purposes of furthering scientific understanding, but classifications can also support river-related management activities, for example by delineating agricultural land use (Avetov and Balabko, 1995), targeting conservation and rehabilitation efforts (Brierley and Fryirs, 2000; Thomson *et al.*, 2004) and managing flood risk (CLG, 2006). In the following, the most relevant classification schemes for floodplain management are reviewed.

Nanson and Croke (1992) identified three types of floodplain classifications which have been used in historical studies: morphological, specific and genetic. Morphological classification involves the description of discrete floodplain landforms and river patterns, but does not closely link form and process. Specific classifications have been undertaken in support of river management activities, but with no dominant or unifying variable they can be limited to a data inventory. Genetic classifications link river processes with floodplain form, with previous studies using up to four geomorphic parameters as criteria: channel pattern, lateral stability, morphological landform description, and sedimentary characteristics. The multivariate and interactive nature of process and form means that simple genetic classifications are difficult to formulate, but provide the best geomorphological classification (Nanson and Croke, 1992).

Nanson and Croke (1992) developed a comprehensive energy based classification of genetic floodplains. It is based on the interrelation between a stream's ability to do work (estimated using specific stream power) and the erosional resistance of the floodplain (estimated using sediment size). Three primary classes result:

1. **High-energy non-cohesive floodplains**. Typically these are disequilibrium floodplains which erode in response to infrequent extreme events. Floodplains are largely composed of coarse vertical accretion deposits.
2. **Medium-energy non-cohesive floodplains**. These are in dynamic equilibrium with the annual to decadal flow regime. Floodplain formation occurs preferentially through lateral point-bar or braid-channel accretion.
3. **Low-energy cohesive floodplains**. These are usually associated with single or anastomosing channels of high bank resistance. Floodplain formation is predominantly by vertical accretion of fine overbank deposits.

Beneath these three classes floodplain orders and suborders are recognised based on nine geomorphic factors, which are mainly fluvial processes such as accretion mechanisms.

Nanson and Croke (1992) recognise that environmental change affecting the channel will lead inevitably to a shift from one floodplain type to another, albeit with some time lag. A set of reversible floodplain transformations are proposed, which relate changes in variables with various transformations in floodplain orders and suborders, including changes between floodplain classes. For example, a decline in stream power and associated sediment calibre and load can lead to a transformation from a braided river floodplain to a wandering gravel-bed river floodplain and then a meandering river, lateral-migration floodplain. A further reduction in energy would then lead to a low-energy cohesive floodplain with a laterally stable, single-channel or anastomosing river floodplain (Nanson and Croke, 1992).

The CM pattern, a technique for describing textural patterns and depositional processes, can be used to classify floodplains (Bravard and Peiry, 1999). The CM pattern technique separates deposits on the basis of the type of sediment movement that led to deposition, for example particles rolling along the bed, graded suspension and uniform suspension. This distinction is made by analysis of the log-log graph produced by plotting the coarsest percentile grain size (C) from a sample deposit against the median (M). The shape of the CM pattern across a valley indicates the energy available and provides an assessment of the cohesiveness of floodplain deposits. Comparison of patterns along a valley axis demonstrates the progressive loss of stream power, fining of sediment texture and better sorting resulting in more uniform suspension and deposition of silt-rich, cohesive floodplains downstream (Bravard and Peiry, 1999). The CM pattern technique does not provide a comprehensive classification system; however, as Bravard and Peiry note, it does complement the classification of Nanson and Croke (1992).

Floodplains are also classified in relation to contemporary land use and management, especially with respect to flood risk. For example, Planning Policy Statement 25 (CLG, 2006) classifies areas of the floodplain according to flood frequency (see Section 2.1). Floodplain function and management are considered further in Section 2.3.

2.2.5 Quaternary (and Holocene) floodplain evolution in the UK

The evolution of UK floodplains during the Quaternary, and in particular during the Holocene, has been well researched and provides the physical context for the study of present-day floodplains. Much of the UK was covered in glaciers at least once during the Quaternary, with the Anglian glaciation (0.43 to 0.48 million years BP; marine oxygen isotope stage 12; Table 2-2) being the most extensive, reaching as far south as the present-day Bristol Channel and Thames Estuary. The most recent glaciation, the Devensian (glacial maximum around 21,000 BP; marine oxygen isotope stage 2–4d), covered Wales, Scotland, parts of northern England and extended down the North Sea, including the coastal parts of Yorkshire, Lincolnshire and north-west Norfolk (Lowe and Walker, 1997). Evidence for the intervening Wolstonian glaciation is disputed. Sand and gravel deposits in the Waveney Valley, along the Suffolk–Norfolk border, show signs of cold conditions, but no evidence of ice proximity (Coxon, 1984, 1993). The glaciations resulted in considerable changes in the landscape through the erosive action of ice sheets and meltwater, and the deposition of sediment beneath and beyond glaciers. For example, during the Anglian glaciation the Thames was diverted to its present position, the area now occupied by the Wash and fens was scoured and the radial drainage pattern of the rivers of East Anglia was established.

Table 2-2 Simplified Quaternary stratigraphy of the UK since the Anglian

Timescale (million years BP)	Marine oxygen isotope stage(s)	Glacial / interglacial	Cold / temperate
0 – 0.01	1	Flandrian (Holocene)	Temperate
0.01 – 0.08	2–4d	Devensian	Cold
0.08 – 0.13	5e	Ipswichian (Eemian)	Temperate
0.13 – 0.30	6–8	Wolstonian	Cold
0.30 – 0.43	9–11	Hoxnian	Temperate
0.43 – 0.48	12	Anglian	Cold

Adapted from Lowe and Walker (1997).

Areas of the UK not covered by glaciers were also heavily influenced by the change in climate. In catchments downstream of glaciers the hydrology and geomorphology was dominated by the supply of water and sediment by the glaciers, which varied on a daily and seasonal basis, while catchment surfaces would be frozen, at least during winter, and support limited vegetation. Proglacial channels typically deposited large quantities of sands and gravels, the source of extensive aggregate extraction today. In areas beyond the influence of glaciers, periglacial processes were dominant; fluvial activity would be highly seasonal, with large spring discharges and significant associated erosion and transport of material.

Knowledge regarding floodplain evolution during previous interglacials is limited. Relatively few deposits from previous interglacials have been studied, as they have been eroded or buried in subsequent, geomorphologically more active glacial periods. However, it seems likely that the floodplain environments of previous interglacials were very similar to those of the Holocene. At Hoxne in Suffolk – the type-site for the Hoxnian period in the UK – and associated sites nearby, sedimentary and palaeobotanical records indicate lacustrine infilling of depressions in the underlying till deposited in the Anglian (Coxon, 1993; Gladfelter *et al.*, 1993). An Ipswichian site at Wortwell in Norfolk contained preserved sediments deposited in quiet, low-energy, backwater environments, close to the edge of the Waveney floodplain (Coxon, 1984), while in the Wensum Valley at Swanton Morley, Norfolk, sediments indicate a meandering river with abandoned channels (Coxon *et al.*, 1980). The general lack of persistence in the deposits of previous interglacials illustrates their limited importance in long-term floodplain evolution.

The fluctuations in climate, resulting in alternating glacial and interglacial periods, has had a profound effect on UK floodplain evolution. In particular, the processes associated with glacial periods have led to extensive deposition. However, not all the sediment deposited by glaciers and, in particular, by proglacial channels remains and it is clear that periods of extensive erosion have also occurred. The timing of this downcutting is subject to debate (see Bridgland and Allen, 1996), but it seems most conceivable that it mainly occurred during glacial periods, when there is no equilibrium between the climate and vegetation cover, which produces a high discharge to sediment yield ratio and an excess of energy for erosion (Bridgland, 1994; Bridgland and Allen, 1996). Downcutting has produced terraces in many valleys, preserved on the edge of valleys, as older floodplain surfaces are abandoned due to incision. It was traditionally thought that the highest terraces represented the oldest river levels, with lower terraces reflecting successively younger stages; while this generally holds, terrace sequences are often more complicated (Lowe and Walker, 1997). One of the problems in understanding this pattern is that climate change and its effect on sea level and hydrology cannot fully explain why successive downcutting phases reach progressively lower base levels (Bridgland and Allen, 1996). Successive downcutting is fundamental to the formation of terraces and Bridgland and Allen (1996) suggest it may be the result of long-term isostatic adjustment between areas of net erosion and net deposition.

Bridgland (1994) proposed a climatic model for terrace formation, based on the post-Anglian terrace sequence of the River Thames (Table 2-3). This suggests that during interglacials there is an initial period of aggradation followed by downcutting and then another period of aggradation, the principal aggradation phase in the Thames sequence. The temperate phase had more limited aggradation and floodplains developed through in-channel and overbank accretion.

Table 2-3 Bridgland's 1994 modified climatic model for terrace formation

Phase	Process	Description
1 (mid cold episode)	Downcutting	High discharge leads to erosion, controlled by base level.
2 (late cold episode)	Aggradation	High energy levels, but sedimentation (sands and gravels) exceeds erosion and new floodplain is formed.
3 (temperate)	Limited aggradation	Limited deposition through in-channel and overbank deposits; estuarine sedimentation in the lower valley.
4 (early cold episode)	Aggradation	Climatic deterioration results in increases in discharge and enhanced sediment supplies. This leads to removal and/or reworking of existing floodplain and renewed aggradation of sand and gravel.

Adapted from Bridgland (1994) and Bridgland and Allen (1996).

Floodplains have continued to evolve during the most recent interglacial, the Holocene, which extends to the present day. Holocene floodplain evolution in the UK has been dominated by low-magnitude processes, generally resulting in more modest forms when compared with glacial periods. However, floodplains have evolved significantly since late-glacial times, with a wide variety of channel forms responsible for the deposition of new alluvial floodplains throughout the UK (Burrin and Jones, 1991; Brown and Keough, 1992; Macklin *et al.*, 1992; Macklin and Lewin, 1993; Brown *et al.*, 1994; Collins *et al.*, 1996; Taylor and Lewin, 1996; Howard *et al.*, 2000). Macklin and Lewin (1993) drew together the findings from 59 dated sites to establish distinct episodes of regional and country wide alluviation in British catchments (Table 2-4). Evidence of floodplain processes prior to 5000 years before present (y BP) is largely restricted to lowland areas, where accumulating sediments have been more readily preserved (Macklin and Lewin, 1993). Between approximately 8400 and 4800 y BP the lack of dated deposits in upland and lowland Britain has suggested a period of channel stability or erosion (ibid.). At around 4800 y BP sedimentation is recorded for the first time on many valley floors, apparently marking a significant change in fluvial activity (ibid.). Further periods of alluviation occurred in the following millennia, largely in southern Britain, with the most important probably between 2000–1600 and 1200–800 y BP, when widespread valley floor sedimentation also occurred in upland northern and western Britain (ibid.). A number of studies of river systems in northern and western Britain has demonstrated cyclic aggradation and incision during the middle and late Holocene (Howard *et al.*, 2000). In these parts of Britain, which were glaciated during the Devensian, terrace sequences have developed as a result of this cyclicity coupled with isostatic uplift.

Table 2-4 Major known phases of alluviation in British catchments during the Holocene

Time before present	Location in Britain
9600–8400	Lowland
4800–4200	Country wide
2800–3300	Southern
2800–2400	Mainly southern
2000–1600	Country wide
1200–800	Country wide
800–400	Southern
400–0	Upland northern and western

Constructed from data in Macklin and Lewin (1993).

Brown and Keough (1992) have proposed the stable-bed aggrading banks (SBAB) model to explain the mid to late Holocene evolution of lowland rivers such as the Nene, Soar and Severn (Brown and Keough, 1992; Brown *et al.*, 1994). This model explains in particular the metamorphosis of floodplains and river channels, indicated by "accelerated vertical accretion, a reduction in floodplain relative relief, changed floodplain soil conditions, a reduction in channel W/D [width/depth] ratios and a resultant increase in the silty clay proportion of channel perimeter sediments" (Brown and Keough, 1992: 1). The floodplain and channel siltation caused the initial braided-river system to evolve into a predominantly single-channel system, with the reduction in channels compensated by a change in channel type and capacity (Brown *et al.*, 1994). The metamorphosis increased bank resistance and reduced channel migration, providing river systems and channels morphologies that are similar to those found in lowland UK today.

Prior to the early Holocene, floodplain evolution in the UK was driven by climate and environmental change. However, from the mid Holocene human activity began to modify the landscape of catchments and to influence floodplain and fluvial processes. Assessing the relative impact of climate change and human land-use change has and continues to cause significant debate. Based on the synchronicity of alluviation periods in British floodplains (Table 2-4), and their similarity to those identified in the USA and central Europe, Macklin and Lewin (1993) suggested that climatic factors were more important in Holocene floodplain development. However, they also suggested that the expansion and intensification of cultivation in the Neolithic increased sediment supply, explaining the different responses to climate change, with floodplain stability and/or incision in the early Holocene (pre-Neolithic) followed by floodplain aggradation in the middle and late Holocene. Others have attempted to correlate climatic events with evidence of changes in the fluvial record (see review in Brown, 2003). For example, Rumsby and Macklin (1996) examined regional-scale fluvial response to the 'Little Ice Age'. They found that river basins in northern, western and central Europe experienced enhanced fluvial activity at the transitions of this period, particularly during the subsequent warming. The correlation of climatic events and fluvial response is not straightforward. Identifying the temporal and spatial extent of climatic events such as the 'Little Ice Age' is somewhat more complex than traditionally presented (Jones and Mann, 2004) and while regional patterns of fluvial responses exist, these reflect the interaction of intrinsic factors, such as land use, with climate (Brown, 2003). Vandenberghe (2003) suggests that there are different types of climatic influences on fluvial systems: direct forcing (for example peak precipitation); indirect forcing (like permafrost); and partial forcing (such as vegetation, which is highly important in fluvial processes). Other, catchment-based studies have concluded that human impacts have been more significant (Tipping *et al.*, 1999), or at least that climate change has been masked by human activity and secondary climate change impacts such as vegetation control (Burrin and Jones, 1991). In contrast, it is evident that for some catchments, intrinsic geomorphic controls are more significant than either climate or land use, producing very different responses in floodplain evolution, even within the same basin (Taylor and Lewin, 1997; Taylor *et al.*, 2000).

Contemporary geomorphology in the UK is dominated by low-intensity processes operating within an essentially relict landscape (Higgitt, 2001). Nonetheless, over the past 1000 years floodplains have continued to change in response to climate and, increasingly, human activity (Rumsby, 2001). Studies of recent floodplain evolution potentially provide the most relevant context for examining future changes as recent floodplain environments are similar to those of today and catchments have been subject to climatic and land-use change not unlike that expected over the coming century.

Walling and He (1999) found no change in average overbank sedimentation rate over the twentieth century in a variety of floodplains, mainly in the middle and lower reaches of English floodplains. In contrast Owens and Walling (2002) found that average sedimentation rates in the middle reaches of the River Tweed basin were lower in the period since 1963, when compared with the period 1894–95 to 1963. Coupled with changes in sediment sources, Owens and Walling were able to link these with land-use changes including land drainage, afforestation and widespread agricultural land-cover changes. No clear link was established with climate, investigated by considering long-term records of precipitation, weather patterns and river flow, although buffering effects may have masked this (Owens and Walling, 2002). Changes in sediment sources on the River Ouse, Yorkshire, over the past 100 years have also been tentatively linked to land use, rather than climatic change (Owens *et al.*, 1999). Despite the changes in climate and land use, sediment budgets have remained relatively stable in both basins, demonstrating resilience to future environmental change (Walling *et al.*, 2003).

Rumsby and Macklin (1994) have linked river and floodplain response in the River Tyne basin (over the past 300 years) with fluctuations in flood regime that seem to be related to changes in large-scale upper-atmospheric circulation patterns. In cooler, meridional periods (where circumpolar flow is from north to south), there were a greater number of high-magnitude floods resulting in channel incision. In warmer, zonal periods (where circumpolar flows brought more westerly winds) fluvial adjustments were more variable, but included reworking of sediment and aggradation. The role of human activity was to increase the sensitivity to climatically induced changes (Rumsby and Macklin, 1994). A similar study, examining the geomorphic impact of flood-rich and flood-poor periods related to circulation patterns, has been undertaken by Werritty and Leys (2001) in the uplands of Scotland. Although it was found that rates of lateral channel shift are driven by flood incidence, the scale of reworking was less than that of the Tyne and this has been attributed to less mining activity, weaker coupling between active river reaches and valley sides, and relative stability (Werritty and Leys, 2001). It was concluded that future responses to climate change are unlikely to cross extrinsic thresholds and therefore, in terms of floodplain management, major perturbations over the next few decades could probably be discounted (ibid.).

In broad terms both climate change and human activity have influenced floodplain evolution up to the present day. With regards to relative effects:

> On the question of climate or land use as causes of change, it would seem that the answer has to do with different causes at different times, in different places, and of combinations of causations and of feedback. Various research suggests that which cause is dominant depends on the sensitivity of the system, and on the relative magnitudes of the causes and the state of the system.
>
> (Hooke, 2001: 141)

Generally there has been a contrast in UK floodplain and fluvial processes between upland and lowland basins over the past 1000 years (Rumsby, 2001). In lowland areas rivers have exhibited little change, especially over the past century, with channel migration and floodplain sedimentation increasingly restricted by development of natural resistant levees and through human activity (ibid.). In contrast upland catchments have experienced a more direct relationship with climate, with less human activity except in areas of mining (ibid.). Rumsby (2001) relates this dichotomy to the sensitivity of fluvial response to environmental change, as summarised by Brown and Quine (1999). Hyper-sensitive reaches, often found in upland areas, undergo a disproportionately large geomorphic response from a small hydrological change due to abundance of sediment, sparse vegetation cover, unstable beds and un-armoured beds. Under-sensitive reaches, typical of lowland rivers, have a disproportionately small response due to lack of sediment, dense vegetation cover, and resistant beds and banks (Brown and Quine, 1999; Rumsby, 2001). Current evidence suggests this most recent spatial pattern of change is likely to continue into the future (Hooke, 2001).

2.2.6 A summary of the driving factors in UK floodplain evolution

The final part of this section provides an overview of the driving factors of floodplain evolution, with a particular focus on the relative influence of land use and climate in the UK. The key factors identified are: climate (change), isostatic adjustments, discharge, sediment availability, vegetation, soil and geology, and, more recently, human land use and channel modification. These factors are highly inter-connected; for example, climate directly influences discharge and vegetation, while long-term changes in climate have contributed to isostatic adjustments, which have lowered base levels. The importance of each driving factor is hard to determine on a generic basis, particularly because of these inter-connections. There are also processes intrinsic to fluvial systems which mean that floodplains do still evolve while channels remain in regime, for example through lateral accretion. Nonetheless, the factors listed above will control the nature of this evolution.

The importance of the driving factors has varied through time as floodplains have evolved. Major changes in climate and base level during the Quaternary have driven large-scale episodes of floodplain aggradation and erosion and, along with the basement geology, provide the setting for contemporary floodplain environments in the UK. The relationship between sediment availability and discharge, as modified by climate and vegetation, was and remains at the heart of channel and floodplain evolution, at least in a natural setting. Over time, and with relatively low deposition rates (i.e. in warmer periods), soils have developed on alluvial surfaces (Bridge, 2003). These have modified the catchment surface and the processes of infiltration and runoff, have influenced vegetation type and provided a new sediment source. Most recently, human activity has affected floodplain evolution. This has mainly occurred during the last few thousand years of the Holocene and most significantly over the last few hundred years. Human activities affecting floodplain evolution have include deforestation and afforestation, agriculture, urbanisation, mining, sand and gravel extraction, dam building, flow control and abstraction, channelisation and the construction of flood defences. In contrast to the debate on the relative influence of climate and land-use change on floodplain evolution during the Holocene, little attention has been given to the relative influence on contemporary or future floodplain processes. Despite this it is clear that human activity, both incidental and planned, dominates many contemporary floodplain processes (e.g. through flood prevention), especially in lowland areas of the UK. In these areas it could be argued that floodplains are no longer evolving in a geomorphic sense.

The importance of driving factors also varies spatially. Upland catchments have evolved differently to those in the lowlands, largely due to glacial influences, while individual catchments have exhibited major differences in floodplain processes, despite being subject to similar drivers. This illustrates the complexity of floodplain evolution and the importance of considering each catchment individually. Although general, regional responses to climate change have been identified, it is clear that the future evolution and management of floodplains will need to assess all driving factors at the catchment scale.

Examination of the evolution of channel and floodplain systems has provided the context for considering contemporary use and future management of floodplains in the UK. Whilst past changes are not directly relevant to future climate change resulting from increasing greenhouse gas concentrations, they do inform understanding of climate dynamics and of the potential responses of the fluvial system (Arnell, 1996). This understanding, stemming from a naturalistic and historical scientific approach, is an essential balance to the mathematical and predictive approach to modelling the impacts of future climate change (Baker, 1996).

2.3 Floodplain function and management

2.3.1 Floodplain function and use

Today floodplains continue to function hydrologically, geomorphologically and ecologically, but human use of floodplains means that these natural processes are disturbed or managed in many catchments. Indeed, Penning-Rowsell and Tunstall (1996: 493), whilst recognising the importance of such processes in floodplain evolution, argue that "some of the most important processes to be observed on floodplains today – if not the most important processes – are those of development and urbanization".

Historically humans have used floodplains for a variety of purposes. Gregory (2003) identifies eight chronological phases of river channel management, which also informs contemporary floodplain use. Initially, river flows were controlled and diverted for flood control, irrigation and land reclamation. Water mills and then industrial mills and associated infrastructure followed. More recent flood control has led to channelisation, but alternative approaches have recognised the need to work with the river, whilst the most recent phase is concerned with sustainability and a basin-wide approach to managing the river environment.

In the UK, floodplain wetlands have been reclaimed for agricultural purposes since at least Roman-British times (Cook and Williamson, 1999a). The embanking of rivers and increased control of water movement for agricultural, industrial and navigation purposes has generally reduced flood frequency and increased accessibility to lowland floodplains in particular. Many settlements were originally confined to higher and drier land, before industrial and post-industrial urban expansion into floodplains (Gardiner, 1998). Some of this development exploited rivers and canals, while other development benefited from the flatter land. Although historically agriculture has dominated European floodplains, other land uses, including transport infrastructure, flood protection, water supply, nature conservation and recreation, are becoming more important in many places (Mitchell, 2003). This trend is being reinforced in many UK catchments by flood, agricultural and nature conservation policies, and by management practices (see Section 2.3.2), although some argue that floodplains will continue to make a vital contribution to UK agriculture (Bailey, 1998). Development in UK floodplains is being restricted in response to recent flood events, but the construction of urban flood defences and development behind them continues.

Current use of floodplains means that natural functions are disturbed and that human systems, without adequate protection, are vulnerable to natural processes. The functions of floodplains have also been altered by processes extending beyond the floodplain and river system, for example upland farmland practices, deforestation and mining activities.

The ecology of river and floodplain environments has been disturbed by a variety of human activities including land reclamation, urbanisation, dredging, straightening and the construction of various structures such as weirs, sluices and dams. Thoms (2003) modelled the reduction in supply of dissolved organic oxygen from the floodplain to the river due to the effects of floodplain irrigation and levee construction, demonstrating the importance of floodplain and river connectivity for ecosystem health.

The hydrological and hydraulic functions of floodplains and rivers have been altered through floodplain development, flood defences and other structures such as bridges, locks and dams. Although flood defences generally reduce flood risk, at least locally, other developments can exacerbate flooding nearby as well as downstream. Flooding is the most serious natural hazard in the UK, claiming over 1000 lives since 1800 (Lee, 2001). Although many of these deaths were caused by tidal floods and to a lesser extent dam failures, fluvial floods are a real risk. For example, two people were killed in the Carlisle floods of January 2005 (Environment Agency, 2005b). Floods are also very costly: the Environment Agency spends approximately £570 million per year building and maintaining flood defences[4], reducing annual average damages from an estimated £3.5 billion per year if no defences existed to around £0.8 billion per year based on current defences[5] (Halcrow, 2001). Vulnerability to floods is increasing in Europe due to continued development, gentrification of urban areas, an aging population and increased affluence (Mitchell, 2003). These factors are contributing to the increase in economic and financial flood-related losses that have been experienced in recent years (ibid.).

The geomorphological function of floodplains is disrupted by a number of human activities including floodplain development, agriculture, flood defences, channelisation, dredging and in-channel structures. Lowland rivers in particular are more intensively managed, although such rivers are often geomorphologically stable, with low-energy, cohesive floodplains (see Section 2.2.4). Gilvear and Winterbottom (1998) describe how a 38 km section of the River Tay-Tummel System has been altered over the last 250 years from wandering gravel-bed rivers to single embanked channels, with floodplain habitats largely replaced by agriculture. However, historical evidence suggests that these rivers exhibit a degree of natural instability; for example, the Inch of Tullymet Farm is currently of the eastern side of the Tay but was built prior to 1700 on the western side. Despite the embankments, which are still maintained on the Tay, the rivers continue to move. During flood events embankments are regularly breached, topsoil is scoured from unvegetated fields, and sands and gravels are deposited on agricultural land. On the Tay the embankments are repaired and the river is returned to

[4] Environment Agency (England and Wales) expenditure for 2010–11; note there was a further £230 million expenditure planned on non-asset activities including development control, warning, strategies and mapping (Environment Agency, 2009).
[5] Note that the damage figures are based on prices and flood defence standards reported in 2001. Since then spending on flood risk management has increased significantly in real terms and many new defences have been constructed. Figures relate to fluvial, tidal and coastal flooding.

its original course; on the Tummel, where embankments have fallen into disrepair, the river has reverted to a relatively natural planform (Gilvear and Winterbottom, 1998).

2.3.2 Floodplain management in England

Human use of floodplains and their natural functions are highly managed today: “an important policy issue, as well as a significant research focus, is determining why and for what we are managing floodplains, and for whom” (Penning-Rowsell and Tunstall, 1996: 495). The answer is complex: the floodplain is managed to control both resources and risks (Penning-Rowsell and Tunstall, 1996) for a wide range of stakeholders. Balancing resources (e.g. development land, habitat) against risks (e.g. flooding) is a difficult task and one which different stakeholders weigh up according to their own perceptions and preferences.

This section reviews contemporary floodplain management in England. An overview of the institutional arrangement is presented and policies, plans and practices assessed, including those of NGOs and private institutions. Current management has and continues to be informed by a series of recent severe floods and the reviews which followed, including those during Easter 1998 (Box 2-1), autumn 2000 (Box 2-2), in the mid-2000s (Box 2-3) and those of summer 2007 which led to the Pitt Report (Box 2-4).

Box 2-1 Easter 1998 floods, Independent Review and Agricultural Select Committee Report

The flooding followed sustained heavy rain across central England and Wales on Thursday 9 April and Good Friday and was most severe in Warwickshire, Northamptonshire and northern Oxfordshire (Bye, 1998). In many locations the floods were the worst on record, exceeding those of 1947, with return periods of between 75 and 170 years (Bye, 1998). The flooding resulted in five deaths and flooded thousands of properties.

Following the floods, the Environment Agency commissioned an independent review of the flood events and the Environment Agency's performance. Many of the findings of the Bye Report (1998) were in relation to flood warning and operational matters. However, some were relevant to floodplain management and climate change:

- Imprudent development is the fundamental reason for most damage, with the majority of property affected dating from the mid 1900s or earlier.
- The Environment Agency's position in relation to preventing floodplain development should be strengthened.
- Definition of the floodplain through mapping should recognise the uncertainties associated with modelling and climate change.
- Further research should be commissioned to assess the potential magnitude of increases in flood frequency and inundation due to climate change.
- Standards of flood protection should be revised to take into account climate change.

The Environment Agency responded to the independent review, and an internal investigation, by publishing an Action Plan (Environment Agency, 1998), which accepted the recommendations made.

By coincidence, the House of Commons Agricultural Select Committee was undertaking a review of flood and coastal defence in 1998. Their report (HCASC, 1998a) recognises the potential significance of climate change in the opening paragraph, discussing "irrevocable change on patterns of flooding", which combined with other environmental pressures could present "insuperable difficulties" for flood defence authorities. However, the opportunity for securing defence needs whilst enhancing the floodplain environment (e.g. through washlands), within a framework of holistic management, was identified. Better integration of flood defence requirements and the planning system was articulated, with more powers invested in the Environment Agency to determine and object to development. Overall, the report endorsed the 1993 strategy for flood defence (MAFF & WO, 1993), but criticised its implementation at the local level.

In the official response to the report (HCASC, 1998b) the Government rejected the Committee's view of insuperable difficulties, but agreed that a holistic approach was required, including practical action on the ground and the adoption of more environmentally sustainable measures, but only where feasible. The Environment Agency called for clearer and stronger guidance on development, including a planning policy guideline, and for greater standing in the planning appeal process. The Government committed itself to a series of High Level Targets to promote delivery of its national policy.

Box 2-2 Autumn 2000 floods and reviews

The autumn 2000 floods were severe and widespread; they resulted from sustained frontal rainfall in late October and early November, which fell on saturated catchments (CEH and Met Office, 2001). England and Wales experienced the highest total autumn rainfall in a series back to 1766, with a large proportion of the English lowlands receiving twice the long-term average. Locally and regionally more damaging floods have occurred (including Easter 1998) but the 2000 floods were notable for their extent across the country and their duration, with some areas experiencing multiple or highly persistent inundations (ibid.). Ten thousand properties were flooded, with Lewis and Uckfield, as well as parts of Yorkshire and the Severn valley, acutely affected (Howe and White, 2002). Severe groundwater flooding followed in the spring of 2001.

Perhaps for the first time serious questions were raised within the scientific community and the general public about the influence of climate change. *The Guardian* headline of 31 October 2000 stated "Global warming: it's with us now", while Defra commissioned a research report which asked 'To what degree can the October/November 2000 flood events be attributed to climate change?'. The report observed that heavy rainfall and peak river flows of similar duration to those experienced have been increasing in frequency and magnitude over the past 50 years, a pattern consistent with model predictions of anthropogenically driven climate change (CEH and Met Office, 2001). However, the authors concluded that it was not yet possible to attribute such events to climate change, as opposed to natural variability.

Environment Agency reviews were conducted on a regional basis (e.g. Environment Agency, 2001b), while *Lessons Learned* (Environment Agency, 2001a) was collated at national level. The latter review recognised the uncertainty associated with climate change and recommended a revision of investment rules to encourage greater flexibility in flood defence design.

The Government commissioned the Institution of Civil Engineers to set up a commission to review approaches to flood defence and make recommendations for future flood risk management. The commission's report *Learning to Live with Rivers* (ICE, 2001) provided a number of relevant conclusions including:

- Scheme design should consider sensitivity related to climatic and land-use changes.
- More innovative methods of flood estimation, including modelling, are required, which move away from pure statistical–empirical approaches.
- Whole-catchment modelling is required to derive the most appropriate solutions.
- Further research is required to determine the effect of climate change on rain duration, multiple-storm sequencing and the frequency and location of stationary heavy rainstorm systems.
- More research is required into the impact of seasonal catchment conditions on flooding, including the effects of climate change.
- Methodologies must use peaks-over-threshold series, rather than the annual maximum series, to include multiple floods.
- Urbanisation may be more significant than countryside change or climate change.
- Design solutions should be less vulnerable to future change.

The Government accepted the findings, in the context of changes already underway, and published a detailed response (Defra, 2002a), which was updated in 2003 (Defra, 2003a).

The National Audit Office review of inland flood defence (National Audit Office, 2001) described the development of strategic plans for river catchments as an action of pressing importance, being fundamental to the consideration of *inter alia* the impacts of climate change.

Box 2-3 Boscastle and Carlisle floods and Environment Committee Report

Flood events occurred at Boscastle in 2004 (reviewed in Environment Agency, 2005a and in a special issue of The Journal of Meteorology, Nov. 2004) and at Carlisle in 2005 (reviewed in Environment Agency, 2005b). These events – summer flash flooding in and around Boscastle, and winter flooding along the River Eden floodplain – are consistent with projections of climate change. Although rare now – Boscastle 1 in 400 year (Environment Agency, 2005a), Carlisle 1 in 200 year (Environment Agency, 2005b) – such events may become more common in future.

The House of Commons Environment Committee report *Climate Change, Water Security and Flooding* (HCEC, 2004) included the following conclusions:

- The approach taken in the Foresight study to examining long-term flood risk was warmly welcomed and it called for a white paper on the implications.
- Planning policy guidance should take account of likely future flood risk as well as present-day flooding risk.
- Planning needs to start now, to determine the way to approach development and flood defence.

Box 2-4 Summer 2007 floods and Pitt Report

The summer 2007 flooding in England followed the wettest May to July period in England and Wales since records began in 1766 (Environment Agency, 2007a). River flooding was particularly severe in Gloucestershire, Oxfordshire and South Yorkshire while Hull experienced major surface water flooding (ibid.). The impacts of the floods were severe: several people were killed, 55,000 properties were flooded, insured losses were around £3 billion, and critical infrastructure, including water supplies and roads, was disrupted (ibid.).

The Government commissioned Sir Michael Pitt to undertake a review of the lessons to be learned from the flooding. The review report (Pitt, 2008) made 92 recommendations, many regarding the resilience of properties and critical infrastructure systems and arrangements for emergency response. Those relevant to floodplain management include:

- The Environment Agency should be given a national overview of all flood risk.
- There should be a presumption against building in high flood risk areas, in accordance with PPS25.
- Local authorities should lead on the management of local flood risk, with the establishment of Oversight and Scrutiny Committees to review work by public-sector bodies in order to manage flooding.
- The Government should commit to a strategic long-term approach to its investment in flood risk management, planning up to 25 years ahead.
- The forthcoming flooding legislation should be a single unifying Act that addresses all sources of flooding, clarifies responsibilities and facilitates flood risk management.

The Government supported changes in response to all the recommendations (Defra, 2008); the Environment Agency published its long-term flood risk management strategy in 2009 (Environment Agency, 2009) whilst the changes in roles were implemented in the Flood and Water Management Act of 2010, although this was not a single unifying Act.

2.3.2.1 Context

The institutional context for floodplain management is underlain by three principles (Penning-Rowsell and Tunstall, 1996: 497):

1. A legal tradition emphasizing common law dominates. The riparian owner has the primary responsibility for managing flooding, but is obligated not to increase flood risk elsewhere.
2. There is a range of policy instruments, including economic (e.g. Defra grant-aid) and regulatory (e.g. development control exercised by local authorities). The private sector also has some influence through insurance provision (and this influence has increased since the floods of 1998 and 2000).
3. The implementation of policy is undertaken by a range of institutions at central Government and local levels. These organisations have permissive powers and no one organisation is in charge (although the Environment Agency now has a strategic overview of flood risk management).

There is no single set of policies covering floodplain management in England. Rather, policy affecting floodplain management is divided up according to the remit of central Government departments. The Department for Environment, Food and Rural Affairs (Defra) is the policy lead for flood defence, while the Department for Communities and Local Government (CLG) leads on spatial planning policy[6]. Legislation is also divided, with responsibilities for (fluvial) flood defence set out in the Land Drainage Act 1991, Water Resources Act 1991 and Environment Act 1995, while planning-related responsibilities are principally established in the Town and Country Planning Act 1990, Planning and Compensation Act 1991 and Planning and Compulsory Purchase Act 2004. Rather than consolidating this legislation, as had been suggested in the Pitt Review (Pitt, 2008), the Flood and Water Management Act 2010 makes a number of amendments to existing water-related legislation, and makes further amendments more straightforward; it also alters the Local Government 2000 Act to allow scrutiny of flood risk management authorities by lead local authorities.

2.3.2.2 Flood risk management

At European level, Directive 2007/60/EC ‘on the assessment and management of flood risks’ requires Member States to assess flood risk, produce flood hazard and flood risk maps and prepare flood risk management plans. England is well prepared for this, with ongoing work on flood hazard mapping and through the production of Catchment Flood Management Plans (CFMPs).

[6] Prior to May 2006, the lead department was the Office of the Deputy Prime Minister (ODPM), prior to May 2002 it was the Department for Transport, Local Government and the Regions (DTLR) and prior to June 2001 it was the Department for Environment, Transport and the Regions (DETR).

Defra published a consultation for a new strategy for flood risk management in England in 2004 called *Making space for water* (Defra, 2004) and a first response to this in 2005 (Defra, 2005a). This replaces the former strategy for flood defence (MAFF & WO, 1993). The proposed new strategy takes a more holistic approach to flood risk management, in line with Defra's overarching statement on water policy, *Directing the flow* (Defra, 2002b). The new strategy seeks to widen the scope of flooding to encompass pluvial, sewer and groundwater flooding. It also intends to improve integration with land-use planning and development, as well as rural land management. Better risk management is advocated, including improvements to the assessment of social and environmental factors, alongside economics. The need to adapt to inevitable climate change over the next few decades is recognised, current design allowances are endorsed and sensitivity testing is advocated, with the promotion of solutions that are less sensitive to future uncertainty. The whole-catchment approach, based around the principles of sustainable development, reflects Gregory's (2003) final chronological phase of river environment management.

The Government response to the consultation exercise on the proposed strategy revealed that the overall reaction to the strategic direction was positive (Defra, 2005a). The revised strategy reiterated the Government's prior commitment to take forward the recommendations of the House of Commons Environment, Food and Rural Affairs Committee Report *Climate Change, Water Security and Flooding* (see Box 2-3). It also stated that Defra and the Environment Agency will provide revised guidance to ensure that climate change becomes an integral part of flood management decision making, with current allowances and recommendations to be reviewed every three years, commencing in 2007 (Defra, 2005a).

The Environment Agency's role in flood risk management is as an operating authority, although it has also been closely involved in the production of policy (HCEC, 2006). The Environment Agency has a general supervisory duty with respect to flood risk management, which was extended in the new Government strategy (Defra, 2005a) and enshrined in law under the Flood and Water Management Act 2010. The Environment Agency has permissive powers to undertake flood defence measures on main rivers and on ordinary watercourses in default of Internal Drainage Boards (IDBs) or on behalf of local authorities. The Environment Agency is responsible for flood warning and public awareness.

The Environment Agency's *Strategy for Flood Risk Management (2003/4–2007/8)* (Environment Agency, 2003) marked a change in approach, from flood *defence* to flood *risk management*, recognising that it will never be technically, economically or environmentally acceptable to prevent flooding. Key targets include the production of CFMPs, reduction in the proportion of properties within the floodplain exposed to a 'high risk' of flooding and prevention of all inappropriate development inside the floodplain. The 'vision' includes accommodation of climate change impacts, whilst reducing flood risk to an agreed level.

The Environment Agency's long-term investment strategy for flood and coastal risk management in England (Environment Agency, 2009), concluded that an investment increase of 80% would be required by 2035 to maintain current standards of protection.

The Environment Agency has also published *Policy and Practice for the Protection of Floodplains* (Environment Agency, 1997). Although many details have now been superseded by more recent strategies and guidance (see above), the key policy statements remain valid and recognise the fundamental role of the floodplain in managing floods.

Production of CFMPs is a key target under the Environment Agency's strategy. CFMPs aim "to identify long-term sustainable policies to manage flood risk throughout the catchment" delivering a "broad brush assessment of risks, opportunities and constraints" (Evans *et al.*, 2002). CFMPs are designed to consider climate change and land-use change (to 2050) in 80 catchments in England and Wales. As such, they represent the highest stage of fluvial risk management (within a catchment), designed to support a progression of planning and implementation to strategy plan level and then to solutions (ibid.). CFMPs are designed to be conducted in a step-by-step process, starting with catchment definition and data collection, before analysing the impact of future changes, appraising policies and residual risk, consulting on the preferred plan and finally disseminating, with a future periodic review. Although each catchment requires a hydrological or hydraulic model (normally the latter for sufficient detail), the analysis is conducted within a specially developed Modelling and Decision Support Framework (MDSF). This is designed to provide an efficient and consistent analysis, allowing planners to concentrate on identifying risks and formulating appropriate policies (ibid.). MDSF includes a Geographical Information System, which takes output from the Flood Estimation Handbook or hydraulic model and, coupled with a Digital Elevation Model, plots flood outlines and depths. A socio-economic impact module computes economic damages and social impacts, while a further module assists in the evaluation of uncertainty (ibid.).

IDBs have permissive powers to undertake flood defence works in Internal Drainage Districts. These districts are generally in low-lying areas, such as the Fens and the Somerset Levels, where a complex system of drains, dykes and pumps ensure land is usable, largely for agricultural purposes.

Lead local authorities are responsible for the management and scrutiny of flood risk in their area with regards to surface water, groundwater and ordinary watercourses. Local authorities have permissive powers to undertake flood defence measures with respect to ordinary watercourses. Local authorities are responsible for emergency planning and emergency response, in liaison with the Environment Agency and emergency services.

2.3.2.3 Development and flood risk

The planning system in England was reformed in 2004 by the Planning and Compulsory Purchase Act. This replaced the production of county structure plans and local development plans with Regional Spatial Strategies (RSSs) and Local Development Documents (LDDs), although the former were abolished shortly after the 2010 general election. Local planning authorities are responsible for LDDs and also control development by determining planning applications. LDDs are statutory plans and set out medium-term proposals for development and land use, along with related economic, environmental and social policies.

Planning policy is informed by national Planning Policy Statements (PPSs). *PPS25: Development and Flood Risk* (CLG, 2006) details how flood risk should be considered in the planning and development process. It states (paragraph 3) that "all forms of flooding and their impact on the natural and built environment are material planning considerations". The impacts of climate change on flood risk are explicitly recognised and are to be taken into account when framing policies for the location of development. A risk-based sequential test is provided to assist Local Planning Authorities (LPAs) in adopting appropriate planning responses to different flood zones (see Section 2.1), with an exception test provided to allow certain development in higher flood risk zones where there are overriding reasons. An amendment was also made to Article 10 of The Town and Country Planning (General Development Procedure) Order 1995 to make the Environment Agency a statutory consultee on application for major development in flood risk areas. This is designed to limit development on the floodplain. In 2004 just under 700 houses were constructed in flood risk areas against the Environment Agency's advice (HCEC, 2006), approximately 11% of new homes were built in flood hazard areas between 2000 and 2005 (HCCLGC, 2006) and around a quarter of properties flooded during summer 2007 were built in the last 25 years (Pitt, 2008). Furthermore, if there is a sustained objection from the Environment Agency on a major development[7], this will be reviewed by the Secretary of State and if necessary called in for determination.

[7] Major development is defined in The Town and Country Planning (Flooding) (England) Direction 2007 as: (a) in respect of residential development, a development where the number of dwellings to be provided is 10 or more, or the site area is 0.5 hectares or more; or (b) in respect of non-residential development, a development where the new floorspace to be provided is 1,000 square metres or more, or the site area is 1 hectare or more (CLG, 2006).

2.3.2.4 Other interests

A number of other parties have an interest and role in floodplain management. Natural England has a particular interest in floodplain habitat, as well as access and land management. Local authorities are also concerned with biodiversity, access and mineral workings, the Forestry Commission with wet woodland, and English Heritage with historical sites and structures. Non-statutory bodies also have an active interest in floodplain management, especially wildlife NGOs who own or manage many floodplain habitats, including Wildlife Trusts, the RSPB, the National Trust and the Woodland Trust. Other landowners and those who occupy the floodplain, including farmers and residents, are also concerned with its management.

The insurance industry has taken a particular interest in floodplain management since the widespread floods of Easter 1998 and Autumn 2000. The latter event, including associated storm damage, cost insurers £1.3 billion and raised concerns about the viability of continuing to offer insurance in certain areas due to more frequent heavy rain, poor maintenance of flood defences and inadequate investment in protecting properties built in flood risk areas (ABI, 2001). The Association of British Insurers (ABI), the trade association for insurance companies operational in the UK, called for urgent action by the Government, specifically to invest more in flood defences, to curtail development in flood risk areas and improve decision making (ABI, 2001). Given fairly widespread concern about the availability of flood cover, ABI made a two-year (2001–2002) commitment to continue cover for existing policy holders, except in exceptional circumstances (ABI, 2001). This commitment was reiterated, but under revised conditions, in the *Statement of Principles* (ABI, 2002), which applied from 2003. This statement made a commitment to offer flood cover where the standard of protection was 1 in 75 years (for urban areas) or better, or where this would be achieved by new or improved defences within five years, contingent on action from Government including full implementation of PPG25[8] (ABI, 2002). Progress was reviewed by ABI in 2005 and while the change in Government policy was welcomed, its full implementation was considered to be urgently needed to protect all existing properties at risk (and prepare for climate change), to ensure new development was not being permitted in the floodplain, to complete flood defence databases and catchment strategies, and to adopt an integrated approach to urban drainage (ABI, 2005a). These actions were included in the *Statement of Principles*, which took effect from 2006 (ABI, 2005b). The most recent revised statement re-iterated early commitments for a further 5 years and noted that the commitment does not apply to houses built after 1 January 2009 (ABI, 2008). Guidance for new developments (ABI, 2009a) states that insurers expect to be able to insure developments that are built in line with advice from the Environment Agency.

[8] *PPG25: Development and Flood Risk* preceded and was replaced by PPS25.

2.3.3 Summary: current drivers and future challenges in floodplain management

There are a number of competing pressures on today's floodplains, and it can be argued that human-related processes of development, agriculture and recreation dominate natural processes centred on seasonal flooding. Flooding, especially in urban and peri-urban areas is managed (with some success), as is channel movement; biological functions are only fully realised in designated sites. However, there is increasing recognition of the benefits of restoring rivers and their floodplains. Although still managed environments, restoration can improve the ecological function of river–floodplain systems (Petts, 1998) as well as contributing to flood risk management. There are significant scientific and institutional constraints in delivering restoration (reviewed in Adams and Perrow, 1999), and although scientific research and practical guidance is available (e.g. Hughes, 2003), political and institutional issues remain (Petts, 1998; Adams and Perrow, 1999).

The challenge for the future management of the floodplain will be to balance changing resources and risks. The floodplain, under demand for myriad purposes, is likely to be a resource of greater value, while climate and socio-economic changes may increase risk. The challenge for scientists is summarised by Everard (1998: 481, emphases added):

> [While] much of the basic science is already in existence … the new challenge for scientists is not only to fill gaps in our knowledge of these underpinning principles, but to *integrate them across their respective disciplines*. Ultimately, the regulatory community and Government will require from the scientific community *comprehensive models* of the processes upon which floodplains and their ecosystems depend, in addition to the beneficial processes that floodplains perform, from which *scenarios may be tested and evaluated* in order to develop sound sustainable policies.

3. Review of climate change, implications for floodplain management and identification of research gaps

This chapter reviews climate models and scenarios of climate change for the UK, examines the implications for floodplain management, and identifies research gaps. As such, the chapter is split into the following sections:

1. **Climate change science, scenarios and uncertainty** briefly examines the science of global warming, before reviewing climate models, scenarios of climate change for the UK over the twenty-first century, and associated uncertainties.
2. **Floodplain management under climate change** reviews the impact of climate change on flooding, discusses the findings of three integrated assessments, and considers potential responses.
3. **Research gaps** outlines a number of significant research gaps based on the literature review.

3.1 Climate change science, scenarios and uncertainty

3.1.1 Climate change science

The Earth's climate is highly variable. From geological records it is clear that there have been distinct warm periods (e.g. the Cretaceous) as well as cold periods, perhaps resulting in a 'snowball Earth'. The causes of these changes are much debated but over time the climate has been influenced by a number of factors including solar radiation, orbital changes, meteorites, tectonic movements and continental drift, volcanoes, and large changes in biological processes, which have drastically altered atmospheric chemistry.

During the Tertiary period there was a gradual cooling of the Earth and the most recent, Quaternary period (approximately the last 2 million years) has been cool in a geological context, with the return of large ice sheets, and is often termed the 'Ice Age'. However, the Quaternary is characterised by distinct oscillations between colder glacial phases, when Northern hemisphere ice sheets extended to mid latitudes, and warmer interglacial phases, such as the Holocene epoch – approximately the last 10,000 years. Within each phase – glacials being some 90,000 years long and interglacials around 10,000 years (although around 50,000 years long 400,000 years ago) – there are lower-amplitude variations in climate.

The long-term cyclity of the Quaternary was related to variations in the Earth's orbit and axis by Croll and then Milankovitch, and orbital forcing is now accepted as the primary driving mechanism of Quaternary climatic change (Lowe and Walker, 1997). Lower-amplitude variations – but which nonetheless have caused significant climatic changes, often rapidly –

have been linked to internal changes in the climate system, for example in oceanic circulation. Volcanoes have also altered global climate, as the emitted aerosols reflect incoming solar radiation. The eruption of Mount Tambora in 1815 produced the 'year without a summer' in 1816 across much of Europe and eastern North America, with wider evidence suggesting that global volcanic activity has influenced recent climatic history (Lamb, 1995). Solar disturbances, including sunspots, have also been postulated as a cause of climatic change, but this has been highly debated (e.g. Friss-Christensen and Lassen, 1991; Kelly and Wigley, 1992). Overall, the evidence suggests that Quaternary climate change has been driven by orbital forcing and modulated by internal dynamics of the climate system and external factors such as volcanic activity and solar forcing. These modulating factors are more important drivers of variation over a short space of time, such as the past one to two millennia (Jones and Mann, 2004).

The natural changes in climate described above have had a profound influence on human evolution and activity (Lamb, 1995). However, as population has increased, humans have had an increasing effect on the Earth and its climate (Simmons, 1996). Initial activities that affected climate included changes in land use through deforestation, development of agriculture, irrigation and settlement. However, the most significant change in the context of contemporary climate change came as recently as the nineteenth century:

> Like the control of fire and the invention of agriculture, industrialization based on fossil fuel energy represents a turning point in the history of human-nature relations … In ecological terms, the stored photosynthetic energy of these fossil hydrocarbons has been added to the current energy of the sun, and used by human societies in a variety of ways to gain access to resources and to alter the structure and function of their surroundings.
>
> (Simmons, 1996: 208)

Whilst industrialisation has brought significant benefits to societies, the burning of fossil fuels and more widespread land-use change has released enormous quantities of greenhouse gases into the atmosphere. The possibility that this might lead to global warming was recognised in the nineteenth century, by scientists such as Jean-Baptiste Fourier, John Tyndall and Svante Arrhenius (Warr and Smith, 1993), but was not widely considered until observations of atmospheric carbon dioxide concentrations began in 1958.

The greenhouse effect is a natural process which keeps the Earth's surface some 33°C warmer than it otherwise would be. In simple terms, the greenhouse effect is the process where greenhouse gases in the troposphere transmit incoming solar radiation, but reflect and in particular absorb some of the outgoing radiation from the Earth, thus altering the heat balance of the combined lower atmosphere and surface system (Harvey, 2000). Natural greenhouse gases include water vapour, carbon dioxide, methane, (tropospheric) ozone and nitrous oxide. Vast quantities of greenhouse gases, especially carbon dioxide, have been released into the atmosphere from the burning of fossil fuels. Land-use change has also released carbon dioxide, as well as methane. In addition, industrial processes have added artificial greenhouse gases such as halocarbons. Pre-industrial atmospheric concentrations of carbon dioxide were about 280 parts per million by volume (ppmv) (Harvey, 2000) and had reached 379 ppmv by 2005 (Forster *et al.*, 2007). In contrast, some pollutants such as sulphates act to cool the climate by reflecting solar radiation (Hulme *et al.*, 2002). This has led to 'global dimming' in pollution hotspots, where global warming has been partially offset. However, tighter pollution controls may lead to greater warming in such areas as the full effect of global warming catches up (Jenkins and Haywood, 2005).

The enhanced greenhouse effect is measured by the *radiative forcing*, the change in net radiation at the tropopause, with *climate sensitivity* defining the ratio between resulting global mean surface air temperature and global mean radiative forcing (Harvey, 2000). Modelled climate sensitivities are often expressed as the equilibrium global average temperature in response to a doubling of atmospheric carbon dioxide (an *equilibrium climate sensitivity*), although a more useful measure is the *effective climate sensitivity* or *transient climate response* which does not require the model to reach equilibrium and is typically measured as the global average temperature at the time of doubling, after a 1% per year compounded increase for c. 70 years (Hulme *et al.*, 2002; Harvey, 2000). The *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) gives a range of 2.1°C to 4.4°C for modelled equilibrium climate sensitivity and 1.2°C to 2.6°C for the corresponding modelled transient climate response (Randall *et al.*, 2007).

Observations show that global mean surface temperatures increased by 0.74°C over the period 1906 to 2005, with two distinct phases of warming between 1910 and 1940 and from the 1970s onwards (Trenberth *et al.*, 2007). The relative contribution of natural and human factors to this warming (i.e. the problem of attribution) is a critical question for science and society. Climate model outputs perturbed using natural factors alone cannot explain the most recent warming; only when anthropogenic factors are added in can models satisfactorily reproduce observations (Hulme *et al.*, 2002; Jones and Mann, 2004). This clearly indicates that human activity is contributing to current climate change, a conclusion of the IPCC's *Fourth Assessment Report* (see Hegerl *et al.*, 2007).

3.1.2 Scenarios, models and downscaling

The climate of the twenty-first century is dependent on natural variability and human influences. It is not possible to simply predict changes in either component. Certain causes and patterns of natural variability are known, but there remains a large chaotic element. Similarly, human activity and consequences for emissions are hard to foresee. Models of the climate system can reproduce many elements of natural variability but, as discussed, it is now essential to include radiative forcing if current and future climate is to be understood.

Therefore, *scenarios* of future socio-economic change have been devised, which provide profiles of greenhouse gas emissions. These are used in climate models via an intermediate stage involving chemistry models, such as carbon-cycle models, which calculate the effect of anthropogenic emissions on atmospheric concentrations (Hulme *et al.*, 2002). Socio-economic scenarios therefore translate into climate change scenarios – possible climate futures (see Section 4.2.1 for a full review of socio-economic scenarios and their interaction with climate scenarios).

3.1.2.1 Climate models

Climate models describe the key processes of the climate system in mathematical terms. Due to computing and time constraints various simplifications are made (Harvey, 2000) including:

- In some cases empirically derived relationships are used instead of physical principles; these may not hold as the climate changes.
- Physical quantities which vary over space are represented by their values at points arranged on a grid, the spacing determining the spatial resolution; smaller-scale processes are then parameterised.
- Reduced dimensionality, by averaging over a complete spatial dimension.

Various models have been constructed and can be used for different purposes. For example, one-dimensional radiative-convective atmospheric and upwelling-diffusion ocean models have been used to study particular aspects of the atmosphere and oceans respectively. The most complex models are three-dimensional Atmosphere General Circulation Models (AGCMs) and Ocean General Circulation Models (OGCMs), which are coupled to give AOGCMs (Harvey, 2000). Use of three-dimensional models is the only reliable method for simulating key processes that determine climate sensitivity and longer-term feedbacks, and provide a transient picture of regional climate change, as well as changes to diurnal, seasonal and interannual climate (ibid.). There are important differences between transient and equilibrium patterns of climate change (ibid.); however, given the interest in relatively short-term (100 years) climate change, these will be ignored in this thesis. The main drawback of three-dimensional models is that they are highly demanding in terms of computing power, requiring supercomputers, and input data, some of which does not exist (ibid.). Therefore, there is a limited number of modelling groups worldwide that run AOGCMs. All are based on the same underlying physics, but each has a different structure, resolution and different representations of key processes (Hulme *et al.*, 2002). This means that each model has a different climate sensitivity and predicts different climatic changes for the same radiative forcing.

3.1.2.2 Downscaling

The spatial resolution of AOGCMs (about 250 km to 500 km over the UK) is typically too coarse to be used in all but the broadest impact assessments. Similarly, although the computed timesteps are frequent, there is little confidence in the predictions for timescales shorter than a month, especially for outputs such as rainfall (Prudhomme *et al.*, 2002). Xu (1999a) identifies three gaps between the data provided by GCMs and that needed for hydrological impact assessments:

1. GCM accuracy decreases towards the spatial and temporal scales of interest.
2. GCM accuracy decreases from free tropospheric variables to the surface variables of interest.
3. GCM accuracy decreases from variables such temperature to those of hydrological interest such as precipitation and potential evapotranspiration (PET).

Therefore it necessary to *downscale* the model outputs to more meaningful spatial and temporal scales. There are two broad approaches to downscaling: dynamic and statistical.

Dynamic downscaling involves the explicit solving of the process-based physical dynamics of the system (Xu, 1999b). The basic method involves the use of a higher-resolution limited-area model or regional climate model (RCM). The RCM is (one-way) nested within the GCM and uses GCM grid-point data as the boundary conditions. Dynamic downscaling provides information at a much better spatial resolution, one that can be useful as inputs to basin-scale hydrological models. However, the spatial resolution remains too coarse for some applications and still represents spatial averages, rather than local extremes (Xu, 1999b; Prudhomme *et al.*, 2002). Furthermore, RCMs are computationally expensive and depend on the veracity of the GCM grid-point data (Wilby and Wigley, 1997). Dynamic downscaling has limited potential for temporal downscaling, without the addition of further detail, but can be used to better inform statistical methods.

Statistical downscaling is based on statistical relationships between GCM atmospheric variables and station-scale meteorological data (Xu, 1999b; Prudhomme *et al.*, 2002). There a number of different methods, including those based on regression, weather patterns, and stochastic weather generators (Wilby and Wigley, 1997):

- The simplest regression techniques involve establishing linear or non-linear relationships between climate model grid-scale predictor variables and sub-grid parameters and then forcing the resulting equations using climate model data (Wilby and Wigley, 1997). Other regression approaches include artificial neural networks and methods based around alternative statistical parameters. Regression methods are simple, but require long observational series and application is limited to sites, variables and seasons when local climate is strongly related to wider atmospheric conditions (Xu, 1999b).

- Weather pattern or circulation-based methods involve statistically relating a weather classification scheme to station or locally averaged meteorological data (Wilby and Wigley, 1997). Then it is necessary to calculate conditional probabilities which link the likelihood of the variable of interest occurring with the weather type (Xu, 1999b). Finally, weather-type series are generated stochastically or extracted from GCMs and used to simulate meteorological series (Wilby and Wigley, 1997; Xu, 1999b). This method can provide daily sequences of meteorological data based on limited historical datasets and is appealing because it is based on physical linkages between large-scale climate processes and local weather; however, weather classification schemes are inherently locality specific and the relationships with local data can lack stability, even under the current climate (Wilby and Wigley, 1997; Xu, 1999b).
- Stochastic weather generators are similar to circulation-based methods, but variables are conditioned based on precipitation occurrence (Wilby and Wigley, 1997). Precipitation occurrence and amount are typically calculated using Markov renewal processes and depend on the precipitation over previous days and the observed daily rainfall record (Wilby and Wigley, 1997; Xu, 1999b). Weather generator parameters are then adjusted to represent future climate patterns. The main challenge in using weather generators is to ensure these adjustments are physically realistic and internally consistent (Wilby and Wigley, 1997). A further issue is that the method relies on GCM-predicted changes in mean precipitation, which can be unreliable (Xu, 1999b), and which is highly uncertain. However, weather generators generate realistic daily meteorological data, which offer much potential in impact assessments.

The recent STARDEX[9] project developed and tested 22 different statistical downscaling methods, with a particular focus on daily and seasonal extremes. In the majority of cases no consistently superior model was identified, particularly at the station scale, and although criteria were developed to indicate the most appropriate method for a particular application it was recommended that a range of the better methods are used (STARDEX, 2005).

Statistical methods provide a useful tool for downscaling both spatially and temporally. They are simpler to compute than dynamic approaches, and the stochastic approaches can incorporate a better representation of natural variability. The main weakness of statistical approaches is that they are based on relationships which describe historical climate and weather; this assumption of stationarity may not hold under climate change (Prudhomme *et*

[9] STAtistical and Regional dynamic Downscaling of EXtremes for European regions – see www.cru.uea.ac.uk/projects/stardex.

al., 2002; STARDEX, 2005). Furthermore they depend on significant, predictable changes in stochastic simulation parameters or downscaling predictor variables (Wilby and Wigley, 1997). As with dynamic approaches, statistical methods also rely on adequate data, the ability of the tools employed, and ultimately on the large-scale changes predicted by GCMs (Bardossy, 1997; Mitchell and Hulme, 1999).

Several studies have specifically examined downscaling for hydrological impact assessments (see reviews in Xu (1999b; 1999a), Prudhomme *et al*. (2002) and Fowler *et al*. (2007)), although Fowler and Wilby (2007) lament that they number a small proportion of all downscaling studies, and have lacked an applied nature. In terms of application those (non-academic) hydrological impact assessments which actually use scenarios (as opposed to sensitivity factors) have relied on dynamically downscaled change factors such as those contained in the UKCIP02 scenarios (Hulme *et al.*, 2002; see Section 3.1.2.3), although the current standard in the water industry, the UKWIR06 scenarios (UKWIR, 2007), provides change factors based on bias-corrected spatial disaggregation (see Vidal and Wade, 2008). The latter method was found to be most effective in a study by Wood *et al*. (2004), which compared three statistical downscaling techniques: bias-corrected spatial disaggregation, spatial disaggregation, and spatial linear interpolation. Bias correction removes the differences between observed and simulated baseline climate, often based on quantile mapping; spatial disaggregation involves interpolation of simulated baseline climate to a finer (observational) grid, then calculation of anomalies and application to future GCM climate; spatial linear interpolation only involves interpolation between climate model and hydrological model grids. All three techniques were applied to GCM and RCM output, but there was little benefit in including the dynamic downscaling step for bias-corrected spatial downscaling. Wood *et al*. (2004) concluded that although the method successfully reproduces the observed hydrology, the “minimum standard of any useful downscaling method for hydrologic applications”, the monthly temporal scale used in the separate corrections of precipitation and temperature fails to rectify more subtle differences between observed and simulated climate including interdependencies, seasonal variation and interannual variation.

Fowler *et al*. (2007) review new developments in downscaling for incorporation in hydrological impact assessments. Probabilistic and multi-model ensemble approaches (see also review by Darch in Sene *et al.*, 2007) offer much potential, particularly in quantifying uncertainty and in facilitating the weighting of models which perform well in reproducing relevant variables. For example, Wilby and Harris (2006) present an end-to-end probabilistic framework for assessing uncertainties, using a case study of low flows on the River Thames. GCMs were weighted according to their relative ability to reproduce meteorological variables critical to low-flow estimation, while two downscaling techniques (change factor and the statistical downscaling model SDSM) were given equal weight. Weights were applied separately to examine the influence of each component, with GCM uncertainty being greater than that associated with downscaling technique, but weights could also be applied based on the combined performance of the GCM and the downscaling method.

Fowler *et al*. (2007) present a Bayesian approach to weighting river flows downscaled using a stochastic weather generator, based on the River Eden in the north-west region of England. A Bayesian approach is used to produce probability distribution functions (pdfs) of regional precipitation and temperature change. Model reliability is estimated as a function of each RCM's performance in reproducing current climate and each model's agreement with the ensemble consensus for the future. However, the latter criterion of convergence is somewhat problematic given the similar physical basis of GCMs and the impossibility of future verification, and has been dropped elsewhere (see Goodess, 2006). Fowler *et al*. downscale the mean probabilities of regional change using a stochastic weather generator (EARWIG, see Box 6-1) and run an ensemble of sequences through a hydrological model. Finally the values of seasonal model reliability for precipitation produced in the Bayesian analysis are used to weight the ensemble members to produce a pdf of flow change.

Fowler *et al*. (2007) provide a number of conclusions useful for the application of downscaling in hydrological impact assessments:

- No single downscaling method appears to be best and if climate extremes are of interest a selection of methods is warranted. The methods chosen should perform well for the most sensitive climate variables.
- In statistical schemes, predictor variables must account for physical interactions in the climate system.
- Dynamic downscaling, as long as bias-corrected, is useful in representing sub-regional detail although it is unclear whether some elements of change are appropriately represented. Model ensemble projects such as PRUDENCE and perturbation of inputs and model parameters are providing useful insights into the uncertainties involved.
- Probabilistic methods offer much potential but a number of questions remain unresolved, largely related to weighting as well as presentation and communication (Patt and Schrag, 2003; Goodess *et al.*, 2007).

3.1.2.3 Hadley Centre models, UKCIP02 scenarios and UKCP09 projections

The most widely used models and scenarios for impact studies in the UK are those of the Hadley Centre. This section summarises the UKCIP02 scenarios and the models used in their creation, with information drawn from the UKCIP02 *Scientific Report* (Hulme *et al.*, 2002), and then briefly discusses the UKCP09 projections.

The UK Hadley Centre AOGCM HadCM3 has a spatial resolution of 2.5° latitude by 3.75° longitude (about 265 km by 300 km over the UK) with 19 atmospheric layers and an ocean component of 1.25° latitude by 1.25° longitude with 20 layers; the temporal resolution is typically 30 minutes. A double-nested dynamic downscaling approach was used, involving a high-resolution AGCM (HadAM3H) and then a higher-resolution (~50 km square, 5 minute timestep) RCM (HadRM3).

Due to the substantial computing costs, a limited number of experiments were run. For the full modelling described above, 'time-slice' experiments were undertaken just for the future period 2071 to 2100 (the '2080s') and the baseline period 1961 to 1990. Similarly it was only possible to adequately model one emissions scenario (IPCC SRES A2 – see Section 4.2.1). Data for the remaining timeslices (the '2020s', 2011-2040; the '2050s', 2041-2070) and emissions scenarios (A1FI, B2, B1) were generated using *pattern-scaling*. This technique scales the regional patterns from the A2 2080s to other time periods and emissions scenarios based on the differences in average temperature simulated by the full run of the HadCM3. Therefore, although the magnitude of climate change varies between scenarios and timeslices, the patterns are the same.

The UKCIP02 scenarios provide an indication of future seasonal climate and limited information relating to daily climate. The headline changes relevant to this thesis are summarised in Table 3-1. Uncertainties are discussed in Section 3.1.3.

The UK Climate Projections 2009 (UKCP09) include probabilistic representation of variables, although different emissions scenarios remain. Probabilistic scenarios are developed by running models repeatedly, each time adjusting different parameters. The resulting *ensemble* of outputs can then be used directly to form a frequency distribution, or can be weighted according to ability, resulting in a pdf (Jenkins and Lowe, 2003). The methodology in UKCP09 involves a perturbed physics ensemble, emulation of full parameter combination uncertainties and weighting based on hindcast performance, with the resulting distribution then modified to account for the structural uncertainties represented by different climate models (Murphy *et al.*, 2009).

Table 3-1 Key projected changes in UK climate (from the UKCIP02 scenarios)

Variable	**Scenario**	**Relative confidence**
Temperature	Annual warming by 2080s of between 1°C and 5°C by the 2080s, depending on scenario and region	High
	Greater summer warming in the south-east than in the north-west	High
	Greater warming in summer and autumn than in winter and spring	Low
	Summer and autumn temperatures become more variable	Low
	Number of very hot days increases, especially in summer and autumn	High
Precipitation	Generally wetter winters	High
	Substantially drier summers	Medium
	Winter and spring precipitation becomes more variable	Low
	Snowfall totals decrease significantly	High
	Intensity increases in winter	High
Cloud cover	Reduction in summer and autumn, small increase in winter	Low
Humidity	Specific humidity increases all year round	High
	Relative humidity falls in summer	Medium
Soil moisture	Decreases in summer and autumn in the south-east	High
	Increases in winter and spring in the north-west	Medium
Storm tracks	Winter depressions become more frequent, including the deepest ones	Low
North Atlantic Oscillation	Tends to become more positive, indicating more wet, windy, mild winters	Low

Information from Tables 9 and 10 of Hulme *et al*. (2002).

3.1.2.4 Other models and scenarios

It is widely recognised that any impacts study should utilise the outputs of more than one GCM, to gain an appreciation of uncertainty (see Section 3.1.3). However, until relatively recently, models and scenarios from modelling groups other than the Hadley Centre have, for various reasons, been ignored in the UK, with the vast majority of impact assessments utilising only the UKCIP02 scenarios.

The PRUDENCE[10] project has recently produced new high-resolution (50 km maximum) climate change scenarios for the 2080s using four AOGCMs (principally HadAM3H, but also Arpege, CCM3 and ECHAM) and ten RCMs, based on two emissions scenarios (primarily IPCC SRES A2, but also with B2) (PRUDENCE, 2005).

The ENSEMBLES[11] project, which ran from 2004 to 2009, developed an ensemble prediction system based on several high-resolution global and regional earth system models. The outputs have been used in this thesis (see Chapter 7).

[10] Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects – see http://prudence.dmi.dk.
[11] See http://ensembles-eu.metoffice.com.

3.1.3 Uncertainty in scenarios, models and downscaling

There are several sources of uncertainty in the process of developing climate change scenarios for use in impact assessments. These are related to:

- Emissions
- Atmospheric concentrations
- Radiative forcing
- Climate sensitivity and climate system responses (including feedbacks)
- Natural variability
- Pattern scaling
- Downscaling

Emissions uncertainty can be categorised as a socio-economic uncertainty, whereas the remainder are essentially scientific uncertainties (uncertainties associated with impact assessment and adaptation are discussed in Section 4.4.2). Each source of uncertainty is discussed further below.

Emissions uncertainties exist because it is impossible to predict the social, economic and political pathway that humanity will adopt over the coming century. Neither is it possible to foresee what this will mean for greenhouse gas emissions (and land-use change), for example through technological developments. The only viable method for dealing with emissions uncertainties is to develop emission scenarios (see Section 4.2.1) and to ensure that several are used in any climate modelling or impact assessment.

The change in atmospheric concentrations of greenhouse gases as a result of emissions is uncertain, because the fate of emissions is not fully understood (Hulme *et al.*, 2002). For example, different carbon cycle models give atmospheric carbon dioxide concentrations of between 700ppm and 1100ppm by 2100 for the SRES A2 emissions scenario (ibid.). Feedbacks are also important; for example, as the climate warms the carbon cycle begins to work differently and initial modelling at the Hadley Centre suggests a significant enhancement in atmospheric carbon dioxide concentrations by the end of the century (Hulme *et al.*, 2002). Based on current data, it is therefore difficult for end users to incorporate this within risk assessments. However, the development of ensemble scenarios using earth system models (e.g. through the ENSEMBLES project, see above) should capture this uncertainty.

The uncertainty associated with radiative forcing from greenhouse gases is small. However, the effect of changing aerosol concentrations is very uncertain. This uncertainty should be reduced, or at least quantified, through further research or use of ensembles, but until then it remains part of the overall GCM uncertainty (see below).

There are considerable differences between the climate sensitivities of different GCMs (see Section 3.1.1). GCM uncertainty is often quoted to be the single largest source of uncertainty (Jenkins and Lowe, 2003; Prudhomme *et al.*, 2003; PRUDENCE, 2005; UKWIR, 2005). It incorporates all uncertainties related to aerosols, any empirical relationships, parameterisations and feedbacks; in essence all large-scale climate processes. Evaluating the credibility of climate models in an objective way is not straightforward, requiring detailed knowledge of climate modelling, the climate system, and a comprehensive database of observations (Jenkins and Lowe, 2003). However, this is the aim of ensemble-based approaches. Although a complex and computer intensive way to deal with model uncertainties, ensembles provide the most rigorous method (ibid.).

Feedbacks in the climate system, triggered by global warming, are uncertain, and those relating to thresholds are of particular concern, especially where irreversible or rapid climate change may ensue. Some of these uncertainties are broadly understood (e.g. changes to thermohaline circulation), others are less well known (e.g. abrupt forest dieback), and without a perfect knowledge of the climate system, significant unknowns may exist. Changes to thermohaline circulation are of particular relevance to the UK, as the North Atlantic Drift currently brings warm water to north-west Europe, helping to maintain higher temperatures than might be expected for the latitude. If the deepwater formation in the North Atlantic, which forms an integral part of the global oceanic circulation, was to stop, due to a reduction in surface salinity, there would be a reduction in the flow of warm water to the UK. It is possible that this mechanism, triggered by the sudden release of fresh water from the melting of the North American ice sheet, was responsible for the Younger Dryas climatic reversal around 11,000 years ago, although this is disputed (see review in Lowe and Walker, 1997). At the beginning of this period temperatures may have fallen by 5°C within a few decades, and the British Isles also became drier; the increase in temperature at the end of the Younger Dryas, some 1000 years later, appears to have been equally abrupt (Lowe and Walker, 1997; Hulme *et al.*, 2002). There is some evidence that thermohaline circulation is weakening (Bryden *et al.*, 2005) and HadCM3 projects a decrease under all four emissions scenarios, declining by about 25% by 2100 (Hulme *et al.*, 2002). Other climate models also show a weakening but no shut-down, although a shut-down may become more likely as a weakened circulation is more unstable (Hulme *et al.*, 2002). Given the current state of knowledge regarding climate shocks, it is hard to incorporate such uncertainties, except where they are implicitly included in climate models. UKCIP suggests they emphasise the importance of flexible, no/low regret adaptive options (UKCIP, 2006) (see Section 3.2.3).

As discussed, the climate is inherently variable, and this variability, and any change in variability caused by global warming, is uncertain. Most current scenarios from climate models are deterministic climate *change* scenarios, which, when applied to an observed baseline climatic record, provide scenarios of future climate. The resulting climate sequence will incorporate natural variability, but it will inherit this entirely from the baseline record. This reliance removes the stochastic nature of climatic variability (unless appropriately downscaled) and does not allow for changes in variability, which may be important on a variety of timescales. A potential solution would involve the modelling of many ensemble members, each with different initial climate conditions, resulting in a pdf for (absolute) climate in a given future time period. Limited ensemble modelling was undertaken during the development of the UKCIP02 scenarios, which demonstrated the importance of natural variability. Full exploration would be computationally expensive and would represent a departure from the final presentation of 'change' factors. Furthermore, it only incorporates internal climate system variability and not that from external changes such as volcanic and solar forcing (Hulme *et al.*, 2002). Various techniques have been developed to incorporate natural variability in climate change impact assessments, including the addition of factors that characterise mean monthly maximum range in natural variability (Arnell, 2003a), resampling of historical climate data (UKWIR, 2007) and the extension of baseline series, although none of these incorporate future changes in variability. At present, the best method for assessing uncertainties such as natural variability is to utilise a stochastic weather generator, appropriately adjusted to account for the kind of future climate variability that GCMs project.

The technique of pattern scaling (see Section 3.1.2.3), a convenient solution to the scarcity of climate model experiments (Hulme *et al.*, 2002), also introduces uncertainties to the synthetic scenarios. Pattern-scaling applications rely on the following assumptions (from Hulme *et al.*, 2002: 84):

- The simulated anthropogenic climate change patterns are a function of global temperature.
- The patterns are independent of the history of greenhouse gas forcing.
- The anthropogenic climate change signal can be adequately defined from climate model results.

Hulme *et al*. (2002) report that assessments of the technique have concluded that these assumptions were reasonable for the contemporary generation of GCMs. However, their own comparison of a real and pattern-scaled B2 emissions scenario revealed some significant differences, especially for precipitation. Without more comparisons, and while model runs are so expensive, pattern scaling is likely to continue, with the uncertainties unquantified.

Downscaling also introduces uncertainties. Dynamic methods (i.e. RCMs) have similar issues to GCMs and ultimately any model which does not adequately represent the climate (or differences in climate between periods) will add uncertainty, although uncertainties in driving GCMs tend to dominate overall. The PRUDENCE project investigated the uncertainties in dynamic downscaling in detail. RCM uncertainties were found to be smaller than GCM uncertainties, although there were seasonal and geographical exceptions (PRUDENCE, 2005). In general, the RCMs were less good at reproducing summer climate, with most but not all models being too warm and dry (ibid.). Rowell (2004), applying PRUDENCE data to the UK, found that uncertainty in projected surface air temperature due to RCM formulation alone is relatively small in all four seasons. Uncertainty due to large-scale internal variations of the climate system was slightly smaller. The uncertainty from emissions was larger, but the biggest uncertainty related to the driving GCMs. For precipitation, RCM uncertainty was greater and the relative contributions of uncertainty from RCM, GCM, natural variability and emissions were more equal (ibid.).

Statistical downscaling also introduces uncertainties. Statistical downscaling uncertainties arise due to choice of statistical method, predictors and their domain (STARDEX, 2005). The STARDEX project analysed these uncertainties, along with emissions and intra-model uncertainty. The study found that differences between methods were at least as large as differences between emissions scenarios in some cases. As with dynamic approaches, uncertainties were generally smaller for temperature than rainfall, with the largest uncertainties – unacceptably high for many regions and indices – related to summer rainfall (STARDEX, 2005).

There is no overall measure of uncertainty in the UKCIP02 scenarios. Emissions uncertainties are dealt with by providing four emissions scenarios. Scientific uncertainties are represented by quantifying the scatter of GCM results over the UK. There is no quantification of the uncertainty related to natural variability or downscaling. Partly in response to user needs, recent work, as part of UKCP09 and other projects, has attempted to better quantify the uncertainties and present probabilistic predictions which include these uncertainties for use in risk analysis.

The SWURVE[12] project, which aimed to aid assessments of climate change impacts on water-related activities, has produced pdfs for regional temperature and precipitation in five case study regions of Europe (Ekström *et al.*, 2007a). These were based on a combination of a uniform pdf fitted to the range of annual global mean temperatures from the GCM experiments used in PRUDENCE (see above) and a second uniform pdf to scale global to regional changes. An alternative set of pdfs was created using non-uniform distributions, which assume some reliability in future projections. The pdfs incorporate uncertainty due to the spread in global temperature increase amongst different GCMs, uncertainty relating to different RCM parameterisations, and uncertainty in future emissions; however, it was noted that the uncertainties are likely to be underestimates, due, for example, to a limited number of GCMs and emissions scenarios (ibid.). Both methods for deriving pdfs agree on how

[12] Sustainable Water: Uncertainties, Risk and Vulnerability in Europe – see www.ncl.ac.uk/swurve.

temperature and precipitation are likely to change in the case study regions, although there were differences in magnitude, especially for precipitation (ibid.). It is not possible to state which method is correct (ibid.), and this remains a highly relevant debate given the development and use of probabilistic scenarios.

The CRANIUM[13] project developed new methods for analysing uncertainties in key climate variables, utilising tools developed in the BETWIXT[14] project and building on the outputs of SWURVE (see above). The project developed the first daily probabilistic scenarios of weather extremes for point locations[15], a technique that was extended for the UKCP09 weather generator (Jones *et al.*, 2009).

3.2 Floodplain management under climate change

This section reviews the implications of climate change for floodplain management. It starts by providing a brief overview of impact studies before considering three significant integrated assessments in more detail, including the research that led to the 20% indicative sensitivity range for climate change in flood defence project appraisal guidance (Defra, 2006). It then concludes by considering some of the implications for floodplain management, including potential adaptation strategies.

3.2.1 Hydrological and fluvial geomorphological impacts

A large number of studies have examined hydrological impacts of climate change at scales ranging from the global (e.g. Arnell, 2003b) to major river basins (e.g. Arora and Boer, 2001) to the individual catchment. There are numerous examples of the latter from the UK, with a particular focus on the change in flood frequency and understanding uncertainty (e.g. Boorman and Sefton, 1997; Prudhomme *et al.*, 2003; Reynard *et al.*, 2005; Fowler and Kilsby, 2007; Kay *et al.*, 2009; Prudhomme and Davies, 2009b). Although there is no detectable change in river flow records yet (Robson, 2002; Robson *et al.*, 1998; Wilby *et al.*, 2008) nor likely in the near future (Wilby, 2006), these studies indicate that climate change will have a significant effect on runoff. Impacts vary considerably based on scenarios, method and catchments, but in general there is a greater seasonality of flows and an increase in the magnitude and frequency of (winter) high flows. However, not all changes can be deemed significant when natural variability is included (see e.g. Prudhomme and Davies, 2009b).

[13] Climate change Risk Assessment New Impact and Uncertainty Methods – see www.ncl.ac.uk/cranium
[14] Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes – see http://www.cru.uea.ac.uk/cru/projects/betwixt/
[15] See http://www.cru.uea.ac.uk/cru/projects/cranium/

Studies have become increasingly sophisticated in their use of information from climate models from use of proportional change factors (Sefton and Boorman, 1997) to a range of factors representing potential changes in rainfall regime (Cameron *et al.*, 2000; Prudhomme *et al.*, 2002; Reynard *et al.*, 2001; Reynard *et al.*, 2005; the latter two are discussed below) to bias-corrected RCM output (Fowler and Kilsby, 2007). Bell *et al*. (2007) explore use of a grid-to-grid hydrological model, which can be linked to a land surface model and ultimately used to assess the performance of a RCM. The future use of information from climate models is unclear. The ability to fully use the probabilistic information provided in UKCP09 is yet to be realised, but it could be argued that the demand for information on climate change for use in impact studies has outpaced the development of climate models.

Recent work has provided a more balanced view of uncertainties across the cascade (see Section 4.4.2), including natural variability and hydrological model structure and parameters (Kay *et al.*, 2009; Prudhomme and Davies, 2009a, 2009b). In terms of future changes, uncertainties associated with GCMs are generally found to be the most significant, and those relating to hydrological models the least significant. However, Kay *et al.* (2009) demonstrate that the order and relative size of the uncertainties varies between catchments; for example, in terms of the size of impact ranges, emissions uncertainties was ordered second in one catchment and sixth (out of seven) in the other.

Based on the evaluation of uncertainties, Prudhomme and Davis (2009b) present nine recommended steps for a robust assessment of climate change impact on river flow, which are summarised as:

1. Consider different GCMs.
2. Where possible, use different downscaling techniques.
3. Evaluate future variability by using many time series representative of future projections.
4. Consider several emissions to capture the range of SRES scenarios.
5. Assess the significance of changes by comparing the Confidence Interval of future projections with that of the baseline.
6. Account for known bias in downscaled GCM climate when assessing future changes.
7. Build Confidence Intervals of future flow from multiple runs representative of different climate change assumptions.
8. Consider hydrological uncertainty.
9. Undertaken catchment-specific modelling.

Other emerging studies are explicitly 'scenario-neutral' and are focused on understanding the sensitivity of hydrological (e.g. Reynard *et al.*, 2009) and other systems (ongoing work with Natural England involving the author) to a wide range of possible future climates. These approaches use climate model information to guide a vulnerability assessment, but without reference to specific scenarios. Potential future approaches are further discussed in Chapter 10.

Future flood risk will also be influenced by hydrological responses to land-use change, either related to climate change, or other pressures. In summary, whilst the effects of urbanisation are well understood (reducing time to peak and increasing runoff), prediction of the impact of rural land-use change on hydrological systems remains challenging, not least due to lack of monitoring data; in both cases there is a multi-scale modelling problem of upscaling local effects to the catchment level (Wheater and Evans, 2009). A detailed review of the impacts of rural land use and management on flood generation was completed in 2004 (O'Connell *et al.*, 2004) and updated in 2007 (Environment Agency, 2007b); the conclusions relevant to the prediction of impacts are summarised in Box 3-1.

Box 3-1 Impacts of rural land use on flood generation and management: conclusions relevant to impact prediction

The following is a summary of conclusions relevant to impact prediction from O'Connell *et al*. (2004: v–vi) and Environment Agency (2007b: 34):

- There is substantial evidence that changes in land-use and management practices affect runoff generation at the local scale, but the effects are complex.
- There is only very limited evidence that local changes in runoff are transferred to the surface water network and propagate downstream.
- For large catchments, existing modelling studies suggest that a large extent of land-use or land management change is required to produce a relatively modest reduction or delay in downstream flood peaks. Furthermore, the location of local changes or interventions within a catchment is critically important.
- Multiple interventions have and continue to hamper the ability to predict the impacts from specific land-use changes or practices.
- Analysis of peak runoff records has so far produced very little firm evidence of catchment scale impacts of land use management.
- Rainfall-runoff modelling to predict impacts is in its infancy: there is no generally accepted theoretical basis for the design of a model suitable to predict impacts; it is not known which data have the most value when predicting impacts; and there are limitations in the methods available for estimating the uncertainty in predictions.
- A considerable amount of high-quality field data on impacts will be needed to support the development of robust methods for predicting impacts.
- Climate variability is the dominant factor in influencing the frequency and magnitude of flood events within any given catchment.

In contrast to the research on future climate change and hydrology, and historical climate change and fluvial systems (see Chapter 2), relatively little work has been undertaken regarding the implications for fluvial geomorphology. This is evident for example by examining the references in Goudie's (2006) review article *Global warming and fluvial geomorphology*, which concludes that there is much work to be done to establish the full range of geomorphological responses that may take place in fluvial systems. In global terms, river systems in temperate climates may be less sensitive to change but, in general, changes in flow will likely cause changes in river morphology (Goudie, 2006). Rainfall intensity is an important factor in determining runoff but also erosion, and interactions with land use including adaptations to climate change will be significant (ibid). Two UK studies have examined responses in upland catchments. Coulthard *et al*. (2000) used a fine-resolution cellular model to assess the impact of increases in rainfall and changes in vegetation cover and found that although both have a significant effect on sediment discharge, increases in rainfall are more significant. The increase in sediment discharge was caused by an expansion of the drainage network, with existing channels widening and incising and new channels forming, which were found to be where relict channels existed (ibid.). Lane *et al*. (2007), undertaking flood inundation modelling using the UKCIP02 scenarios, found significant short-term bed aggradation, which would lead to more frequent floodplain inundation; however, as the authors note, research into the longer-term response of river beds and banks to sediment delivery is required (particularly as flood defence design standards have long return periods).

3.2.2 Integrated assessments of future flood risk

There now exists a significant body of research into floodplains covering their evolution, function and classification, and human use, impact and management. There is also a rapidly growing understanding of the science of global warming and the impact of climate change on natural and socio-economic processes, such as flooding and flood risk management. These fields of research – climate change, catchment hydrology, fluvial geomorphology, flood risk management, palaeohydrology – are maturing disciplines within Earth Systems Sciences. Although multi-disciplinary in nature, full interaction across these fields has been limited, particularly in application. However, it is evident that future floodplain management will require an inter-disciplinary approach:

> "Echoing the view of Chorley *et al*. (1984), it is probably true to say that there is no matter of prime significance to the river engineer (and for that matter the geomorphologist) on which ignorance is so profound as that of climate change and how it affects river form and process" (Macklin and Lewin, 1997: 38)

Recent research into flood risk management has started to adopt a more integrated nature, particularly with respect to climate change, land-use change and catchment hydrology, although fluvial geomorphology and palaeohydrology remain peripheral.

This section reviews three recent integrated assessments: the UK Foresight Future Flooding project; research at the Centre for Ecology and Hydrology (CEH) using the CLASSIC model; and the EU IRMA-SPONGE project.

3.2.2.1 Foresight Future Flooding

The Foresight project on future flooding (Evans *et al.*, 2004a) has examined the impact of climate change and socio-economic scenarios on catchment, coastal and urban flooding. This was a significant study that identified drivers of flood risk and how these may change over the twenty-first century under scenarios of climate and socio-economic change. Climate (Hulme *et al.*, 2002) and socio-economic (UKCIP, 2001; OST, 2002) scenarios were coupled in the conventional manner (i.e. High emissions with World Markets etc). However, as there is no direct or unique correspondence between the two sets of scenarios, with the former describing global emissions and the latter relating to the UK, a fifth scenario (World Markets/Low emissions) was also used (Evans *et al.*, 2004a). Change in flood risk was quantified using a tool called RASP, or Risk Assessment for flood and coastal defence for Strategic Planning (Hall *et al.*, 2003; HR Wallingford and University of Bristol, 2004). RASP uses data on the location of river channels, type of floodplain and standard of flood defences to produce depth–probability curves, which, combined with information on land use, are used to estimate economic damages as well as social impacts (Evans *et al.*, 2004a). The results are highly dependent on the scenario, and also on the region of England and Wales, but show significant increases in the annual probability of flooding and in the number of people at high risk (of a greater than 1 in 75 year flood). Expected annual damages increase dramatically, with most fluvial-related damage expected in lowland floodplains under the World Markets and National Enterprise scenarios, where more significant climate change is coupled with poor rural land management and urban sprawl upstream, and floodplain development downstream. Achieving Low emissions under World Markets (the fifth scenario) would reduce average annual damage by 25%.

The Foresight project also considered the possible ways in which future flood risk could be managed (Evans *et al.*, 2004b), as the assessment of future risks (Evans *et al.*, 2004a) was based on the assumption of no change in flood defence policy. A range of responses was considered and grouped into four portfolios which matched the four socio-economic scenarios. The residual risk following implementation of each portfolio was quantified using RASP, and costed. Again, the risks were dependent on scenario and location, but the annual probability of flooding and the number of people at high risk were generally lower in the World Markets and National Enterprise scenarios than under Local Stewardship or Global Sustainability. This was largely because the responses of the former scenarios concentrate on structural measures such as flood defences to reduce flood risk. Similarly, expected annual damages were dramatically reduced under the World Markets and National

Enterprise scenarios, making the damages of the same order as those under Local Stewardship and Global Sustainability. However, the cost of portfolios is very different, with the structural measures (catchment and coastal defences) costing approximately £80 billion in the former scenarios compared with £20 billion in the latter.

The Foresight project provided a landmark perspective of future flooding in England and Wales (and Scotland – Werritty and Chatterton, 2004), and although useful at the most strategic, policy level, the results are of limited application at the scale of floodplain management. This is because the study necessarily employed a top-down, broad-brush approach that did not involve fluvial modelling or consideration of socio-economic change (e.g. land-use plans) at the catchment scale. However, the analytical framework employed by the study (especially by combining the Pressure-State-Impact-Response and Source-Pathway-Receptor models) and the rigorous assessment of drivers and responses (the latter including assessments of sustainability and governance) will be valuable for studies at the catchment scale.

One such study has been commissioned by ABI, which has for several years promoted a long-term view for planning development and flood defences re-iterated in its review of the summer 2007 floods (ABI, 2007). Planning for the long term requires the assessment of flood risk under climate change, which would necessitate "a high degree of interpretation of [floodplain] maps based on current data" (ABI, 2003: 10). Furthermore, given the stated importance of assets for insurance assessments (ABI, 2004a), future socio-economic scenarios are of significance. ABI has taken a particular interest in the previous Government's *Sustainable Communities Plan*, a strategy for the development of 200,000 new homes in south-east England by 2016, many of which will be in flood risk areas (ABI, 2004b). The ABI study suggests that 10,000 properties may be built in areas of significant flood risk (greater than 1.3% annual probability) with one third of designated developments located within the floodplain (ABI, 2005c). With no flood risk measures in place, this would increase the financial costs of river and coastal flooding by £54.6 million per year on average, with consequential losses (due to transport and infrastructure disruption) adding up to £27 million. However, these losses could be offset to a varying degree by measures such as avoiding high risk areas, building resilient properties and improving flood defences. By applying factors from the *Foresight Future Flooding* study (Evans *et al.*, 2004a), future flood losses under scenarios of climate and socio-economic change were calculated for the growth areas and under the High emissions/World Markets scenario; these showed that flood damages could increase eight to twelve times (ABI, 2005c). More recent research, just focused on climate change, has found that average annual insured inland flood losses in Great Britain could rise by 14% to £633 million assuming a global temperature rise of 4°C (ABI, 2009b).

3.2.2.2 CLASSIC

More detailed analysis of climate change and land-use impacts have been undertaken at CEH using a continuous flow simulation model called Climate and LAnd use Scenarios Simulation In Catchments (CLASSIC). This contains a soil water balance model, drainage model and routing model; the same routing parameters apply for all discharges, with no consideration of the hydraulics, but the calibrated model gives a good fit (Reynard *et al.*, 2001).

Early work on the Thames and Severn catchments in relation to climate change (Reynard *et al.*, 1998; Reynard *et al.*, 2001) led to the 20% indicative range for investigating potential sensitivities to climate change, which appeared in the Defra flood defence project appraisal guidance (Reynard, 2003; MAFF (Defra), 2000) and is still current (Defra, 2006).

Climate change scenarios were applied by perturbing baseline climatologies for each catchment. PET was calculated using the Penman–Monteith equations with monthly climatic data from Hulme *et al*. (2002) applied proportionally to baseline daily totals, disaggregated from monthly observations (Reynard *et al.*, 2001). Daily precipitation is a direct output from HadRM3, but because of the relatively poor representation of daily rainfall patterns, three methods of applying monthly rainfall scenarios to a daily time series were investigated: proportional change, change in number of rain days, and enhanced storms (Reynard *et al.*, 2001; Reynard, 2003). Reynard *et al*. (2001) also combined the proportional rainfall method with three different land-use scenarios, a best estimate (slight increase in urban area) and two more extreme scenarios (a large increase in urban area and major reforestation).

Flood frequency analysis was based on the partial duration or peaks-over-threshold (POT) method. The original modelling (Reynard *et al.*, 2001) had showed a large increase in flood frequency by the 2050s, using the proportional rainfall method (see Table 3-2). In contrast a more recent analysis (Reynard, 2003) using the UKCIP02 scenarios gave a more mixed picture with many reductions in flood frequency, particularly for the Thames (Table 3-2). This was attributed to the change in climate change scenarios (effectively the climate model), with the UKCIP02 scenarios indicating a reduction in annual rainfall (although the UKCIP02 scenarios are 'dry' in comparison with the output from other models[16]). Reynard (2003) also suggested that the change in flood frequency reflects the seasonal distribution of flood events in the baseline series, with autumn and early winter floods reduced under climate change due to lower effective rainfall and higher soil moisture deficits; this delays and shortens the flood season. However, the method used to derive daily rainfall exerts a strong influence on flood frequency, with enhanced storms increasing flood frequency and change in the number of rain days decreasing flood frequency when compared with the

[16] All recent RCMs give an increase in rainfall for the UK.

proportional method. As none of the methods provided patterns consistent with those indicated in Hulme *et al*. (2002), further research was undertaken to achieve this, resulting in a 'combined' method based on monthly rainfall change and an indicator of change in frequency of the 20-year return period rainfall (Reynard *et al.*, 2005). However, this method is more time intensive to implement and may require revision to mimic the behaviour of other climate models.

Table 3-2 Percentage change in discharge for given return period flows for the Thames and Severn catchments under climate change scenarios for the 2050s using the proportional rainfall method

Source	Climate change scenario	Thames		Severn	
		5-year return period	50-year return period	5-year return period	50-year return period
Reynard *et al*. (2001)	HadCM2 GGx	+10.7	+15.7	+14.7	+19.8
Reynard (2003)	UKCIP02 Low emissions	-2.7	-0.1	+1.5	+4.5
	UKCIP02 High emissions	-3.8	-2.8	+2.6	+6.3

Constructed from sources cited. Flood frequency determined using POT method.

In terms of land use, for the best estimate of change there were only small increases in flood frequency above the climate change only scenario, whereas there were large increases in flood frequency associated with urbanisation (see Table 3-3) (Reynard *et al.*, 2001). In contrast major afforestation greatly reduces the effect of climate change.

The studies did not consider the impact of the changes in flood frequency on floodplains. The small effect of the best estimate land-use scenario may suggest that *floodplain* land use (as the receptor) may be more important than *catchment* land use in determining the impact of flooding (e.g. damages) with respect to land-use change. Floodplains are also important as the pathway of floods, both for conveying flood waters and in terms of deriving runoff itself. Despite this, it is clear that catchment land use can significantly affect the frequency of flooding, and a scenario-based approach allows sensitivity testing and the quantification of uncertainty.

Table 3-3 Percentage change in discharge for given return period flows for the Thames and Severn catchments under climate change and land-use scenarios for the 2050s using the proportional rainfall method

Scenario	**Thames**		**Severn**	
	5-year return period	**50-year return period**	**5-year return period**	**50-year return period**
Climate change only	10.7	15.7	14.7	19.8
Climate change + 'best guess'	15.5	20.5	16.6	23.6
Climate change + triple urban area	34.1	47.0	23.7	28.2
Climate change + 50% forest cover	2.7	5.7	7.0	6.3

Adapted from Reynard *et al*. (2001). Flood frequency determined using POT method.

3.2.2.3 IRMA-SPONGE

The impact of climate change and land use on flood risk has also been considered as part of the EU INTERREG Rhine Meuse Action Scientific Programme ON GEnerating sustainable flood control (IRMA-SPONGE) research programme (Hooijer *et al.*, 2004; Klijn *et al.*, 2004). The aim of this programme was "the development of methods and tools to assess the impact of flood risk reduction measures and of land-use and climate change scenarios, in order to support the spatial planning process for the Rhine and Meuse River Basins" (Klijn *et al.*, 2004). Most hydrological simulations of the Rhine and Meuse catchments suggest an increase in flooding probability (Pfister *et al.*, 2004). The Rhine is likely to change from a pluvio-nival to a pluvio-evaporal type river, with an increase in winter and spring runoff from earlier snow and glacier melt, whereas the Meuse may experience an increase in average discharge in later winter and early spring (ibid.), similar to the Thames and Severn catchments. A further increase in westerly atmospheric fluxes, which have been correlated to an increase in flooding over the twentieth century at least along the Rhine, could have significant impacts on the large Rhine and Meuse basins (ibid.). In contrast, land-use changes are expected to have a limited effect on discharge in the main branches of the lower Rhine and Meuse basins, although this may be more pronounced in smaller tributary catchments, especially when combined with extreme precipitation events (ibid.).

The IRMA-SPONGE programme included a scenario study, which combined physical modelling with cultural theory to inform flood risk management (Middelkoop *et al.*, 2004). The study aimed "to produce a limited set of integrated scenarios that include climate and socio-economic developments in a coherent and consistent way" (ibid.). The 'Perspectives' method, based on cultural theory, was used in which a 'perspective' is defined as "a consistent description of the perceptual screen through which people interpret the world, and which guides them in acting" (ibid.). When people act in the same way as they interpret the world, then utopia is said to exist. In contrast, a distopia exists when the world develops differently to how it was envisaged, for example when the change in climate is different from the perspective (ibid.). Three perspectives were defined for the study and linked to water management in the Rhine Basin, focusing on the environment (Egalitarian), control (Hierarchist) and economy (Individualist). Although there are distinct similarities between the these perspectives and socio-economic scenarios, the way in which they were combined with climate change scenarios was very different to studies such as Foresight (Evans *et al.*, 2004a). In the Foresight study, the scenario associated most with economic growth (World Markets) is likely to lead to higher emissions and is therefore linked to the UKCIP02 High emissions scenario. Therefore, under the three perspectives defined, it would appear that the Individualist scenario, based around growth and risk seeking, would also lead to the highest emissions. However, under Perspectives, the Individualist views climate as insensitive, with only some change expected. Utopia can therefore only exist if little climate change occurs, which would match the management style – resistant of change and relying on cost-effective technical measures if necessary.

In order to fully evaluate the scenarios under Perspectives, the study established a matrix that compared each world view with each management style. With world views equated to particular changes in climate and land use, the matrix then compared these external conditions (albeit reversed from the conventional sense) with management measures. A water balance model was then used to examine certain combinations. The results were clustered into three regimes, which coincided with the three climate change scenarios that were modelled, indicating the dominance of climate change over land-use change and management style in the model. Each combined scenario was also tested against various criteria covering safety, environment, cost–benefit and resilience, which allowed an evaluation of the management styles. None of the styles was preferred, although the Individualist style was not advocated given the possibility, albeit uncertain, of serious climate change (Middelkoop *et al.*, 2004) i.e. a more precautionary approach is recommended. The Egalitarian style may be robust, but is it doubtful that society would be willing to pay for the costs, both financial and in terms of land needed (ibid.). The Hierarchist style, the dominant style used in the Rhine–Meuse basins, is also considered a risk, particularly because it avoids real choices and only implements measures that are deemed acceptable (ibid.).

Although the Perspectives method provides a useful insight into world views and management styles, there appears to be an inevitability of distopia *within* each scenario when climate change is included. So, for example, the Individualist may expect little climate change and manage for this, but the scenario will lead to a large change so only distopia can occur. It is therefore not surprising that no management style will deal appropriately with a change in flood risk that is not anticipated under the associated world view. However, when the management styles are viewed independently, they provide a very useful tool for analysing potential responses to changes in climate and flood risk.

The IRMA-SPONGE programme reached a number of relevant conclusions (Hooijer *et al.*, 2004). Firstly, flood risk is increasing due both to climate change and to continued investment in areas at risk (ibid.). This demonstrates the requirement for studies examining the impact of climate change to include consideration of non-climatic changes, particularly in the floodplain, which may exacerbate or ameliorate the risk. Secondly, it was found that the most effective and sustainable reduction of flood risk could be achieved by reducing vulnerability in flood-prone areas through adapted land use and spatial planning (ibid.). Although upstream measures such as water retention were effective in small basins, extreme floods in the lower Rhine and Meuse basins could not be prevented by such measures. This emphasises the need to consider scale, but again stresses the intuitive importance of the floodplain in flood risk management. Finally, it was concluded that flood risk management can only be sustainable when integrated with other river basin management objectives such as enhancing ecological quality of rivers and floodplains (ibid.). This requires strategies to include multiple objectives, to be resilient and flexible in the face of uncertainty, to recognise public perception and to include societal cost–benefit evaluation of alternative strategies (ibid.).

3.2.3 Responses

There are a number of potential generic responses to climate change. In simple terms, following UKCIP (see for example UKCIP, undated) these can be classified as building adaptive capacity or undertaking specific adaptation actions. In terms of fluvial floodplain and flood risk management, almost all activities to date fall within the former response and relate to research focused on uncertainties and changes to flood frequency (see review above), methods for assessing impacts (e.g. Simonovic and Li, 2003), guidance for applying scenarios (e.g. HR Wallingford, 2003) and development of indicators (e.g. Law *et al.*, 2003). Also included are many practical applications of climate change scenarios and of the 20% indicative sensitivity range (see Chapter 4). In contrast, there are few instances of specific anticipatory actions. For example, ‘freeboard’, the allowance made for modelling and engineering uncertainties, is often deemed sufficient to account for the modelled effects of climate change in terms of flood defences. This differs from coastal defences, where allowances for sea level are included.

There are two broad types of potential actions or measures: structural and non-structural. Structural measures are those based on large engineered solutions such as flood defences, whereas non-structural measures include flood warning, insurance, and land use and management. Non-structural measures are increasingly favoured as they are seen as potentially cheaper, more flexible, and complementary to natural systems. However, a key challenge in conventional decision analysis is how to quantify the benefits and residual risks associated with non-structural measures. This will help facilitate the aim that "the sensitivity analysis of these options should become a more important component of appraisal and decision making" (Defra, 2006: 5).

The current decision-making approach advocated in UK flood defence appraisal guidance in relation to fluvial flooding is adaptive management (Defra, 2006). Adaptive management is "the sequential and continual process of making the best decision at each decision point and reviewing the performance of previous decisions" (Willows and Connell, 2003: 30). Although it is not necessarily the best long-term option, it is flexible and is an appropriate strategy for managing large uncertainties (ibid.).

The overarching decision-making paradigm in flood risk management policy appraisal is centred on cost–benefit analysis. However, given the large uncertainties in benefit assessments associated with future strategies, Olsen (2006) argues that other decision methodologies could be considered, including minimising the regret of making a 'wrong' decision or minimising vulnerability. Olsen *et al*. (2000), using a dynamic decision model of floodplain management, demonstrated that optimal policy changes through time as discharge frequency changes. The model derives some rather unrealistic scenarios. For example, in situations where there were no defences originally, the optimal future policy was to remove defences constructed in earlier years, even in areas of moderate or intensive development, as long as flooding had not occurred. Furthermore, if a flood occurred, the optimal policy was to restrict floodplain development, buying out home owners, and reducing the potential for future damage. Such a scenario, particularly in areas of intensive development, seems implausible. However, the study helps to illustrate three points: firstly that adaptive management may be sub-optimal, secondly that traditional flood defence cost–benefit analysis (focused on the minimisation of flood damage and flood management costs) can produce perverse outcomes, and thirdly that the actual management of floodplains cannot be the outcome of scientific exercises alone. In terms of the latter point, Olsen (2006: 421), drawing on Lowrance (1976), notes that whilst "measuring risk is an empirical, scientific activity … judging the acceptability of risk is a normative, political activity".

3.3 Research gaps

The review of literature has identified a number of research gaps concerning climate change and floodplain management in the UK:

- **The stability of river channels under climate change and implications for floodplains**. It is apparent both from a theoretical perspective and from a review of Holocene environmental change that climate change may result in channel instability and the systematic change of one channel–floodplain regime to another. Despite this there have been few assessments of the effect of future climate change on channel stability and the implications for floodplain management.
- **The potential changes in land use in the catchment and the effects on flooding at the catchment scale**. There is a growing body of research into the impact of land use and management on flood flows, but issues remain regarding data, modelling and the upscaling of impacts to the catchment level.
- **The potential changes in land use on floodplains (beyond development plans)**. CFMPs recognise that changing land use in floodplains will alter assets at risk. However, given that floodplain land use is the critical factor in defining flood impact (it is the only receptor and therefore determines damage), more research in this area would be valuable, particularly in relation to long-term scenarios and uncertainties.
- **The potential impacts of climate change on future flooding**. Most academic studies have been case studies, focused on a particular catchment, using a variety of climate change scenarios and rainfall–runoff models but generally do not have hydraulic components that provide levels. Therefore, while the results of such studies are informative, they are not generally intended or applicable for use in decision making. In contrast, the treatment of climate change in those models explicitly developed for decision making is rudimentary. The current Defra (2006) indicative sensitivity range has been applied in a variety of ways to catchments across the UK, most typically by uplifting hydrographs from rainfall–runoff models before they are input to hydraulic models. Therefore, there remains an impasse between academic studies, which have generally used catchment-specific scenarios, and information being used in decisions, based on a national indicative sensitivity range. Recent research has demonstrated that the sensitivity range may no longer be sufficient and that a national figure may not be appropriate (Reynard *et al.*, 2009).

- **The analysis of interactions between scenarios of climate and land-use change (in the floodplain and wider catchment) at the catchment scale**. This has been generally missing from catchment-based studies examining flood risk and its management, but is important to enable consideration of all possible floodplain futures and the development of appropriate policy and management responses.

Similar recommendations for research were made by the Acacia project, an assessment of impacts and adaptation in Europe (Parry, 2000). In relation to water resources and their management, the report concluded that research was required in four priority areas: scenario definition; effects on the hydrological system; impacts under different socio-economic futures and under different adaptive responses; and techniques for managing uncertainty.

Although the impact of climate change on channel regime and stability, and the implications for floodplains, is an important issue it is not considered as part of this thesis. The controls on channel morphology which may be influenced by climate change are principally discharge and sediment load, although a change in vegetation may affect sediment delivery and bank stability, and a rise in sea level could alter valley slope. A change in flow regime in the UK is expected under climate change, with wetter winters and drier summers. The overall balance depends on location within the UK and is subject to much uncertainty. The critical issue for channel stability is whether climate change will alter the effective or channel-forming discharge. An increase in discharge, or more importantly an increase in the frequency of discharges above entrainment velocity, will increase effective discharge. This is likely to cause an increase in channel cross-section or an increase in slope, for example by meander cut-off. In both cases the increase represents instability in both the channel and floodplain. A key limiting factor may be sediment availability: it may be an oversimplification to assume that an increase in flow will lead to higher sediment loads from the action of the river (i.e. ignoring sediment supply from land-use change). Active rivers, where sediment supply is potentially more plentiful and banks are more easily eroded, are prone to change. In contrast, passive rivers, with cohesive banks and little ability to transport their bed material, are likely to be more resilient: an increase in discharge may simply lead to more flooding, rather than the adjustment of channel morphology to accommodate a greater bankfull discharge.

To summarise, it is possible that climate change may initiate or enhance channel instability in active rivers (see review above), but passive rivers are likely to remain relatively stable. In both cases it may be assumed that any change in channel stability would be managed where it caused problems (e.g. scour of bridge foundations), as at present, and that climate change may simply increase the need for such management. It is considered unlikely that a radically new management approach would be adopted, even given a repeat of the instability during the latter half of the eighteenth century, which included the destruction of bridges on the River Wear (see Higgitt, 2001); the alternative – allowing rivers space to migrate across floodplains – would be prohibitively expensive. On this basis, the implications of channel instability on floodplain management are not explored in this research.

4. A framework for integrated assessment and research methodology

This chapter presents a framework for the integrated assessment of floodplain futures and identifies the specific areas within this that the research presented in this thesis focuses on. There are five phases of the integrated assessment framework: scoping, modelling, consultation, reporting results, and evaluation (Figure 4-1). This chapter considers each phase in turn, with the majority of attention applied to the modelling phase, to demonstrate the potential use of climate change and socio-economic scenarios to explore floodplain futures. A final section sets out the focus of the research presented in the remainder of the thesis.

4.1 Scoping

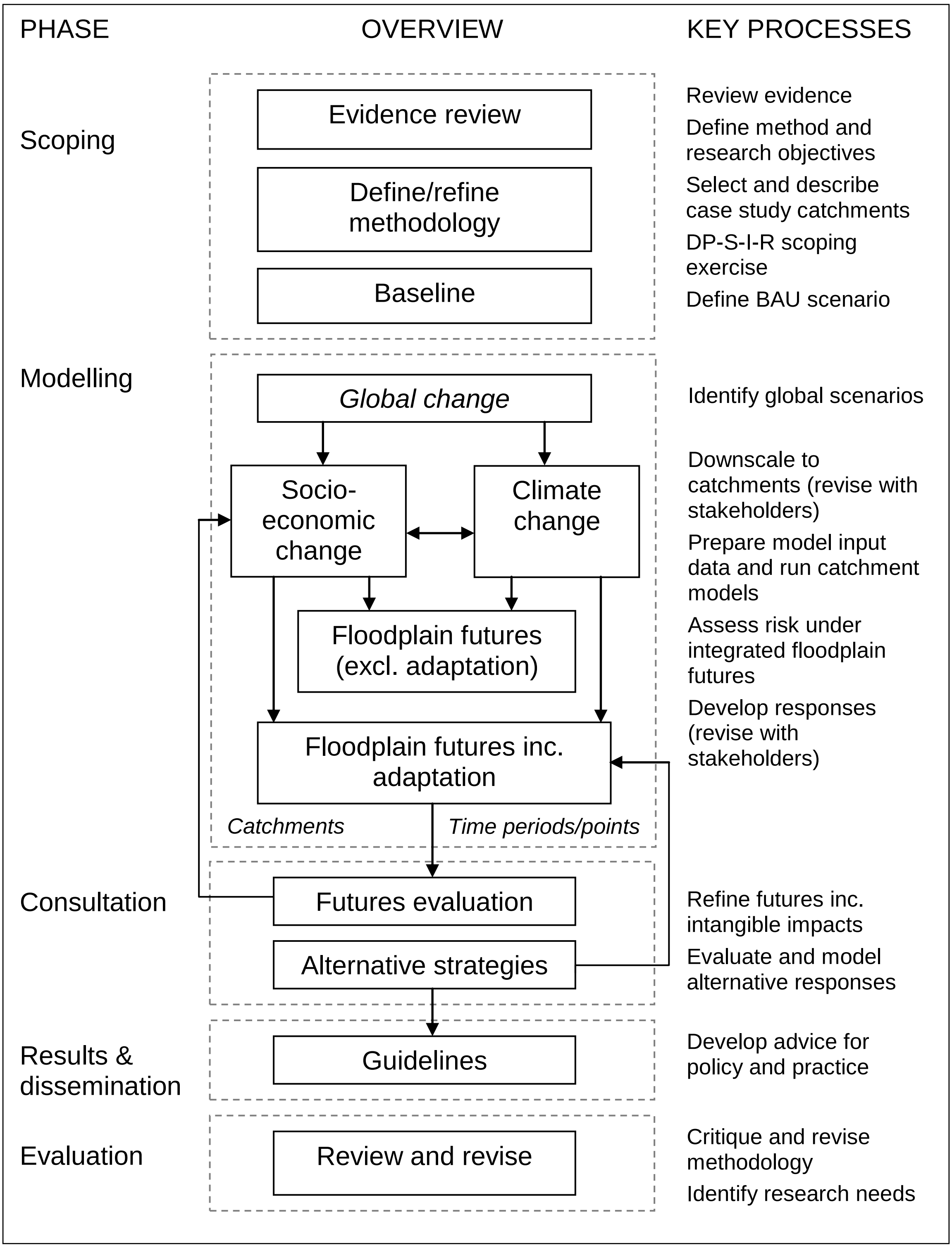
The scoping phase involves three activities: literature review (see Chapters 2 and 3), definition of the methodology (this chapter), and establishment of the baseline (Chapters 5 and 6 and Appendix 1). Establishing the baseline involves selection of the case study catchments, description of these catchments, a Driving Pressure–State–Impact–Response (DP-S-I-R) scoping exercise, and construction of a baseline (business as usual) scenario for each catchment.

Catchment selection may be driven by a particular interest, but a number of criteria are useful to consider:

- Flood risk. Flooding must currently be, or likely to become, a problem within the catchment.
- Contrast. It may be desirable to select catchments to provide contrasts in terms of land use (urban and rural), landscape and climate.
- Hydrological response. Catchments should have hydrological response that can be modelled using reliable input data. For example, small, flashy catchments will require sub-daily input data and the reliability of such data under scenarios of climate change is currently limited.
- Availability of catchment models. Available, calibrated hydrological and hydraulic models that can explicitly represent the scenarios are useful.
- Availability of socio-economic information suitable for constructing short-term land-use scenarios.
- Willingness of stakeholders to participate in the research.

Describing catchments involves a review of relevant literature and data (local evolution of floodplains, flood history, flood management and land-use plans), review of potential hydrological and hydraulic models, and site visits. Thus the necessary information regarding the catchments is collated and gaps in this information are identified.

Figure 4-1 A framework for the integrated assessment of floodplain futures



Following the description of catchments an analysis of the main driving pressures in each catchment is undertaken to inform the subsequent development of detailed scenarios. This utilises the DP-S-I-R scoping framework described by Turner (2005).

The final part of setting the baseline involves the definition of a baseline scenario for each catchment. The baseline, or business as usual (BAU) scenario, is based on an extrapolation of current socio-economic trends (i.e. is likely to be similar to conventional development in Figure 4-2). As with the construction of other scenarios (see below), the global and national socio-economic trends require 'downscaling' to the catchment level, although the baseline scenario is likely to be consistent with current land-use plans at least to some extent and in the short term.

4.2 Modelling

The modelling phase forms the main part of the framework. This comprises scenario development, modelling, assessment of future flood risk within the integrated futures, and the development and modelling of scenario-specific adaptation strategies. These elements are described in turn below, preceded by a review of scenarios and their integration.

4.2.1 Scenarios and scenario integration

In the absence of a certain, predictable future, any forward-planning activity requires an analytical tool that can be used to explore different possibilities. *Scenario planning* was originally conceived by military agencies and in the 1970s was adopted by multi-national companies, most notably Royal Dutch Shell, to improve decision making (Turner, 2005). More recently scenarios have been used in Government and by Government agencies such as the Environment Agency (e.g. in water resources planning) and have been widely adopted by scientists and policy makers addressing climate change.

A scenario is not a forecast with associated probabilities, but an imagined future applied as a coherent, internally consistent and plausible description of a possible future state of the world (Stout, undated; Parry, 2000; Turner, 2005). Scenarios are typically presented as qualitative storylines and are often supplemented by quantitative indicators. Generic socio-economic scenarios (e.g. OST, 1999, 2002) have been used in forming emissions scenarios (e.g. IPCC, 2000), which drive climate change scenarios (e.g. Hulme *et al.*, 2002) and in turn a host of other scenario-based climate change studies (e.g. Parry, 2000; Holman *et al.*, 2002; Evans *et al.*, 2004a).

A review of global futures literature by Berkhout *et al*. (1999) identified five main dimensions of change:

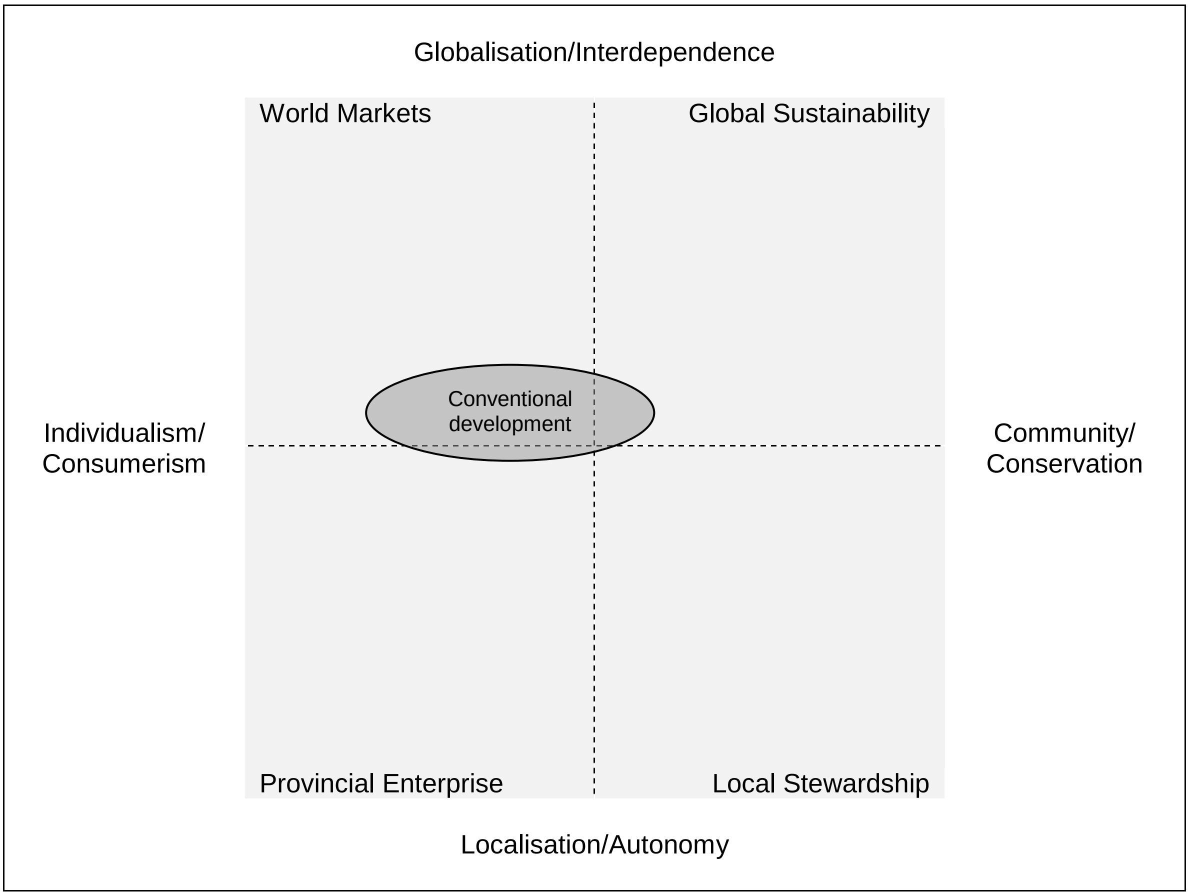
- Demography and settlement patterns.
- The composition and rate of economic growth.
- The rate and direction of technological change.
- The nature of governance.
- Social and political values.

The nature of governance and social and political values were considered by Berkhout *et al*. (1999: 7) to be "foundational and independent determinants of future change". They are also harder to quantify using traditional forecasting techniques. Dahlström and Salmons (2005) related these to the two dimensions of sociality in grid–group cultural theory, permitting further insight into the resulting cultural types or scenarios.

The two dimensions are commonly set on orthogonal axes (Figure 4-2). The social values (group) dimension considers social and political priorities and patterns of economic activity; plotted on the horizontal axis it provides a spectrum from individualist, consumerist, market-based preferences to community-oriented preferences more concerned with sustainable development, social cohesion and equity (OST, 1999, 2002; Turner, 2005). The governance systems (grid) dimension represents the structure of government and decision-making; plotted on the vertical axis, it ranges from the local level (or in some scenario sets, national autonomy) to the global level (or to a situation of greater interdependence, with greater power invested in supra- and sub-national bodies).

Four basic scenarios (cultural types) are produced (Figure 4-2) and these are described further in Table 4-1. Although these scenarios are typically used to characterise very distinct perspectives, it may be more appropriate to consider the four quadrants as "contextual background conditions", not sharply differentiated but bounded by overlapping transitional zones (Turner, 2005), which reveal numerous potential intermediate forms (OST, 1999).

Figure 4-2 Futures scenarios



Adapted from OST (2002) and Turner (2005).

Table 4-1 Foresight Futures scenarios

Scenarios	Descriptive overview
World Markets	People aspire to personal independence, material wealth and mobility to the exclusion of wider social goals. Integrated global markets are presumed to be the best way to deliver this. Internationally co-ordinated policy sets the framework conditions for the efficient functioning of markets. The provision of goods and services is privatised wherever possible under a principle of 'minimal government'. Rights of individuals to personal freedoms are enshrined in law.
Provincial Enterprise	People aspire to personal independence and material wealth within a nationally rooted cultural identity. Liberalised markets together with a commitment to build capabilities and resources to secure a high degree of national self-reliance and security are believed to best deliver these goals. Political and cultural institutions are strengthened to buttress national autonomy in a more fragmented world.
Local Stewardship	People aspire to sustainable levels of welfare in federal and networked communities. Markets are subject to social regulation to ensure more equally distributed opportunities and a high quality local environment. Active public policy aims to promote economic activities that are small-scale and regional in scope, and acts to constrain large-scale markets and technologies. Local communities are strengthened to ensure participative and transparent governance in a complex world.
Global Sustainability	People aspire to high levels of welfare within communities with shared values, more equally distributed opportunities and a sound environment. There is a belief that these objectives are best achieved through active public policy and international co-operation with the European Union and at a global level. Social objectives are met through public provision, increasingly at an international level. Markets are regulated to encourage competition amongst national players. Personal and social behaviour is shaped by commonly held beliefs and customs.

Descriptive overviews are taken directly from Foresight Futures 2020 (OST, 2002).

The UK socio-economic scenarios (OST, 1999, 2002) include a significant amount of qualitative information covering the drivers, international context, the economy and sectoral trends, employment, regional development, social welfare, and the environment. A limited amount of quantitative data is also included, and this was expanded on in the UKCIP socio-economic scenarios (2001), which provides a range of sectoral data for the 2020s and some basic data for the 2050s. The BESEECH[17] project (see Dahlström and Salmons, 2005) provided a much greater amount of quantified data, including population (broken down by region, sex and age), Gross Value Added (GVA) (by region and sector) and households (by region), all in five-year intervals ending in 2061. Data that may be used from these sources includes GVA, population, household numbers and land use, whilst inferences could be drawn from data covering water quality, biodiversity and coastal zone management. However, it is necessary to generate bespoke scenarios that, whilst being consistent with the main storylines, will identify relevant information and data for specific catchments and floodplains.

A key conceptual issue with regards to socio-economic scenarios is their treatment of responses to climate change. The UK socio-economic scenarios produced under Foresight and by UKCIP all describe mitigation activities and their success, as well as "propensities for adaptation" (UKCIP, 2001: 12). For example, under World Markets weak international agreements are made with emissions trading playing a major role, while the UK becomes increasingly vulnerable to climate change (OST, 1999). However, none of the scenarios actually includes adaptation measures: "in order to identify what the impacts of climate change might be, it is not appropriate to take account of response to climate change within the socio-economic scenarios" (UKCIP, 2001: 75). This approach has distinct analytical advantages, allowing full realisation of impacts before selecting the most appropriate adaptation measures. However, it is unrealistic to assume no adaptation (particularly autonomous adjustments) and it reduces the coherence of the storylines where response to climate change should be inter-linked with responses to all other drivers. An intermediate position may be more pragmatic, in which impacts are identified based on the projection of current management responses (included in the BAU scenario) before adaptation measures rooted in the storylines are considered. Such scenarios will therefore be largely exploratory, although could be normative if agency via adaptation is included (see Section 4.2.5).

Emissions scenarios have been developed specifically for use in the analysis of climate change impacts and mitigation options (IPCC, 2000). The scenarios are determined by driving pressures including demographic development, socio-economic development and technological change (IPCC, 2000). The most recent emissions scenarios of the IPCC, contained in the *Special Report on Emissions Scenarios* (SRES) (IPCC, 2000), developed four narrative storylines, each representing different developments in the driving pressures.

[17] Building Economic and Social Information for Examining the Effects of Climate cHange

These storylines are based on similar drivers to those used in the socio-economic scenarios created under the UK Foresight programme (OST, 1999). In SRES, for each storyline, several different scenarios were developed using different integrated assessment frameworks and resulting in 40 scenarios that encompass the range of uncertainties in modelling and in the driving forces (IPCC, 2000). None of the storylines or scenarios is more probable than any other. However, illustrative marker scenarios were selected from each of the scenario groups based on the storylines A1, A2, B1 and B2 (see Table 4-2). In addition, the A1 family was also used to explore alternative energy technology developments leading to A1FI (fossil fuel intensive), A1B (balanced) and A1T (predominantly non-fossil fuel). Although A1B was the recommended illustrative marker scenario in SRES for the A1 storyline, the more extreme A1FI scenario has generally been adopted by climate modellers, although the recent ENSEMBLES project and the UKCP09 projections use A1B.

The SRES scenarios assume no climate change mitigation (i.e. no implementation of the United Nations Framework Convention on Climate Change), although emissions are directly affected by non-climate change policies (IPCC, 2000). This assumption is unrealistic and not fully internally consistent, especially over the long term where climatic impacts will occur. However, at the global level, SRES is the best available scenario set. It contrasts with the UK socio-economic scenarios, which include qualitative information on mitigation activities and their success. This mis-match is not an issue for the creation of floodplain futures, which is principally concerned with adaptation (but see discussion on linkages between scenarios below).

The SRES scenarios of greenhouse gas and sulphate aerosol emissions are used to drive the climate modelling process that results in climate change scenarios. For example, in the UKCIP02 climate change scenarios (Hulme *et al.*, 2002) the B1, B2, A2 and A1FI SRES scenarios are used to create the Low, Medium-Low, Medium-High and High UKCIP02 scenarios respectively.

The linkages between the socio-economic, emissions and climate change scenarios effectively fixes the interaction between socio-economic change and climate change. Four basic scenarios are produced (Table 4-2). This assumes that the linkages between socio-economic and emissions scenarios, and between emissions and climate change scenarios, remain the same as they are conventionally. In the latter case, although there is ongoing scientific debate over climate sensitivity, the fundamental relationship between emissions and climate change is likely to remain; so ignoring aerosols (and non-anthropogenic influences), scenarios with a higher cumulative total of GHG emissions will lead to a greater change in climate. In the former case a fixed relationship between socio-economic development and emissions is more difficult to sustain in the long term; for example, it is plausible to have a world of high growth, rapid technological development, medium-low emissions and more constrained climate change. Although the SRES scenarios make provision for different technological pathways (e.g. A1T, predominantly non-fossil fuel), these are not used in the production of most climate change scenarios and therefore not in impact studies. Fortunately, this does not preclude use of the alternative climate change scenarios as proxies for different emissions scenarios. For example, the Foresight Future Flooding study (Evans *et al.*, 2004a) adopted the UKCIP02 Low Emissions scenario in combination with the World Markets socio-economic scenario to simulate a high-growth, low-emissions world. However, full de-coupling of the relationship set out in Table 4-2, i.e. assuming no direct relationship between scenario sets, is problematic and results in some implausible combinations (e.g. Global Sustainability and High Emissions).

Table 4-2 Relationship between UK socio-economic scenarios, SRES storylines and the UKCIP02 climate change scenarios

UK Foresight scenario	UKCIP socio-economic scenario	IPCC SRES storyline	UKCIP02 climate change scenario
Global Sustainability/ Responsibility	Global Sustainability	B1	Low
Local Stewardship	Local Stewardship	B2	Medium-Low
Provincial/National Enterprise	National Enterprise	A2	Medium-High
World Markets	World Markets	A1FI	High

Maintenance of a direct relationship between the scenario sets depends on consistency between the UK socio-economic scenarios and the global socio-economic scenarios that drive the SRES storylines and climate change scenarios. It is possible that the UK (or Europe) may progress along a different socio-economic scenario to that driving emissions at a global level. Or, more likely, the UK may experience elements of scenarios that are different to those envisaged in the scenario driving climate change. For example, the approach to catchment management in the UK and implementation of the EU Water Framework Directive appears to be more akin to Global Sustainability than World Markets, which is consistent with current global development and emissions. At the level of catchment processes and floodplain management, a scenario combining the socio-economics of Global Sustainability with High emissions (considered implausible above) is now appealing. However, the whole storyline (socio-economics and emissions) must be internally consistent and plausible, and this would need to include rational explanation for a divergence in socio-economic scenarios at different spatial levels. Is a catchment to UK level scenario of Global Sustainability really consistent with a global scenario of World Markets? Can the creation of floodplain washlands in the UK only be conceived under Global Sustainability (or Local Stewardship), or is it entirely plausible (and more consistent with other changes) under World Markets, where there is a reduced demand for agricultural land (with cheaper food stuffs imported) and growing funds for local environmental improvements?

It is recommended that three or four scenarios are developed, based on the conventional coupling illustrated in Table 4-2. One or two alternative scenarios (e.g. Global Sustainability/High emissions, World Markets/Low emissions) can be generated to explore alternative coupling (e.g. divergent socio-economics, technological change/mitigation). As in the Foresight Future Flooding study, adoption of an alternative scenario will allow comparison of the relative influence of socio-economics on flood risk where the influence of emissions is held constant.

4.2.2 Scenario development

Conceptually, flood risk can be affected by any driver, where a driver is defined as "any phenomenon that may change the state of the flooding system" (Evans *et al.*, 2004a). The state of the flooding system is made up of sources (e.g. rainfall), pathways (e.g. fluvial flows, floodplains) and receptors (e.g. people, property) (ibid.). If a driver can be controlled (at least to some extent), it can be considered a response to flood risk, for example land management (ibid.). The Foresight Future Flooding study contains a comprehensive review of drivers, including their interaction with other drivers, role under different socio-economic scenarios, importance to flood risk, and uncertainty. The drivers were grouped together and those relevant to fluvial flood risk are climate change, catchment runoff, fluvial processes, human behaviour, and socio-economics (Table 4-3)[18]. This review provides a useful starting point for the consideration of drivers within scenario development, and a sense check for model preparation and risk assessment. However, within the framework, the drivers (and responses), and the scenarios they form part of, should be catchment specific. Precipitation and temperature (Table 4-3) are included in the climate change scenarios; all other drivers are incorporated in the socio-economic scenarios (although there are some interactions, which are discussed in the next section).

It is necessary to develop scenarios to examine short-, medium- and long-term futures because the influence of socio-economic and climate change, and the storylines in which they are embedded, will change through time. Furthermore, although the period of the next 25 years is a relevant planning horizon for many activities (including flood management), it is important to consider long-term changes which might have serious implications for actions based on short-term decisions. For example, a short-term perspective on climate change may suggest no increase in flood extent so permission for development may be granted on

[18] A revised list of drivers combining all sources was published by Evans *et al*. in 2008, but those presented here remain relevant to fluvial flooding.

the edge of the floodplain. However in 50 years time, flood extent may increase, requiring the development to be protected.

Table 4-3 Drivers of future flood risk used in Foresight Future Flooding study

Driver group	Driver*	S-P-R^ type	Parameters
Climate change	Precipitation	Source	Derived using numerical analysis of available data
	Temperature	Source	
Catchment runoff	Urbanisation	Pathway	Urban extent, adoption of stormwater management
	Rural land management	Pathway	Effects of land management practices on runoff
	Agricultural impacts	Receptor	Flood damage to agricultural land use
Fluvial processes	Environmental regulation	Pathway	Standard of protection
	River morphology and sediment supply	Pathway	Degradation of defence condition, standard of protection
	River vegetation and conveyance	Pathway	Standard of protection
Human behaviour	Stakeholder behaviour	Pathway	Prediction of stakeholder behaviour (complex)
	Public attitudes and expectations	Receptor	Demand for reduction in risk (but see note*)
Socio-economics	Buildings and contents	Receptor	Annual expected losses (residential and non-residential)
	Urban impacts	Receptor	Urban area at risk, rate of change of building stock, development intensity, secondary hazards
	Infrastructure impacts	Receptor	Value of infrastructure, direct and indirect losses due to disruption
	Social impacts	Receptor	Social Flood Vulnerability Index
	Science and technology	Receptor	See note*

Based on tables and information in Evans *et al*. (2004a). **Public attitudes and expectations* and *Science and technology* affect flood risk indirectly via other drivers and were not quantified in the Foresight Future Flooding study. ^Source-Pathway-Receptor.

Socio-economic storylines, based on SRES and the Foresight scenarios, should be developed with a focus on catchment processes and floodplain management, in a similar way that the UKCIP socio-economic scenarios encompassed agriculture, water (but not flood risk management), biodiversity and coastal zone management.

In the short term (perhaps to the 2020s) existing (or at least emerging) norms and plans associated with land use and catchment management are likely to dominate alternative scenarios. With development plans (which set out land-use provision) looking a decade or more ahead, the near future becomes more predictable and the need for scenario planning is reduced. However, the actual course of development is contingent on wider socio-economic developments (e.g. the health of the economy) and development plans themselves are not predictions. In the long term (to the middle and end of the century), scenario planning is used exclusively to provide socio-economic futures. Looking so far forward (particularly to 2100) involves huge uncertainties, and it may be difficult to produce scenarios which clearly distinguish between the 2050s and 2080s. The Foresight socio-economic scenarios only provide for the 2020s, whilst the UKCIP socio-economic scenarios extend some information to the 2050s. However, the Foresight Future Flooding study applied the basic elements of these socio-economic scenarios to the 2050s and 2080s.

The framework also advocates the application of catchment-specific climate change scenarios, rather than the indicative sensitivity range for peak flows (Defra, 2006), which takes no account of catchment hydrology or regional variations in climate change. The climate change scenarios used or developed will depend on availability of scenarios or data to create scenarios, but should try to capture a range of emissions scenarios, GCMs and downscaling techniques, with GCMs being the most important (see Chapter 3). Methods for representing natural variability, such as weather generators or resampling, should also be considered. In general, the key parameters are rainfall and PET, although this is model dependent (see below).

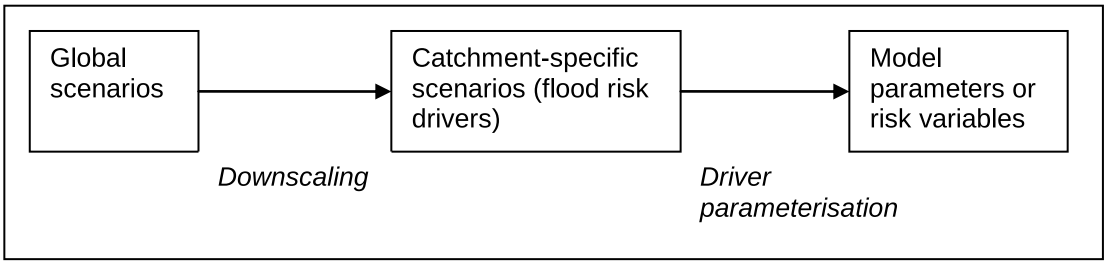
4.2.3 Modelling socio-economic and climate change scenarios

The modelling of socio-economic and climate change scenarios depends on the availability and quality of models for the catchments of interest. Ideally, suitable existing models are available, but in practice compromises are required between model availability and the resources for model adjustment or build. In this section the approaches to modelling climate change and socio-economic scenarios are introduced, followed by a discussion of their integration. The final section reviews the approaches recommended and used in CFMPs.

4.2.3.1 Modelling future scenarios

The implications of the scenarios are assessed through catchment flood modelling and in subsequent calculations of risk. In order to undertake this assessment the scenarios, or more specifically the drivers of flood risk, need to be parameterised (Figure 4-3). The driver parameterisation is dependent on the models available.

Figure 4-3 The process from global scenarios to assessment parameters



There are a number of different ways to model catchment processes in relation to flooding. These range from discrete event-based models through continuous lumped conceptual models to continuous fully distributed models; any can be linked to hydraulic models which describe the movement of water downstream, including over the floodplain when out of bank. As model complexity increases, more data are required to calibrate it and the longer it takes to set up and run. For flood risk management purposes models tend to be either of the first two, with the third currently reserved for academic purposes in small catchments. This presents challenges for the modelling of socio-economic scenarios in particular, as discussed below. The following overview describes the modelling in relation to two different models:

- The rainfall–runoff model within MIKE11, NAM (Nedbør-Afstrømnings-Model, Danish for precipitation-runoff-model) (DHI, 2007) is typical of continuous lumped conceptual rainfall–runoff models based on physical processes or semi-empirical relationships.
- The *Flood Estimate Handbook* (FEH) rainfall–runoff model (Houghton-Carr, 1999) uses an empirical approach based on regression equations to produce a unit hydrograph for discrete events.

Continuous conceptual models (such as NAM) explicitly represent climate, with inputs of rainfall and PET (and temperature and radiation if snowmelt is relevant). Such models are capable of the continuous simulation of runoff based on continuous meteorological input. Climate change will alter the amount, intensity and timing of rainfall throughout the year as well as PET. These complex changes, superimposed on large seasonal and interannual variations, are easier to consider and represent in the context of long time periods, rather than for a single event. Therefore, nearly all studies investigating the response of catchment runoff to climate change (e.g. Sefton and Boorman, 1997; Cameron *et al.*, 2000; Reynard *et al.*, 2001; Pilling and Jones, 2002; Prudhomme *et al.*, 2003; Reynard, 2003; Simonovic and Li, 2003; Diaz-Nieto and Wilby, 2005) have adopted models capable of continuous simulation. This also applies to the study by Bronstert *et al*. (2002), who modelled the impact of climate change on one historical water year in the Selke catchment during which there were a number of severe flood events. However, the preparation of continuous meteorological data and continuous simulation of hydrological and hydraulic models is significantly more time consuming than modelling a single event. It is possible to isolate events – either from meteorological records (historical or perturbed) or after the hydrological modelling – which would reduce the time required for hydraulic modelling and risk assessment (see Chapter 8 for an example).

Lumped models are typically not designed to explicitly represent land use and management. Their lumped, rather than distributed, nature means that land surface and subsurface processes are averaged, sometimes over large areas. In models such as NAM, some parameters can be estimated using catchment data but final parameter estimation is achieved by calibration using observed flows (DHI, 2007). Therefore, perturbations have to be undertaken by proxy.

The unit hydrograph approach (such as the FEH rainfall–runoff model) is designed for event-based simulation, where antecedent conditions are specified and the hydrograph is factored based on the depth and duration of the storm. Generally, only for modelling in the urban environment have event-based models been used in climate change impact studies (e.g. UKWIR, 2010 forthcoming). Perturbing this model to account for a change in climate is more difficult because there is no straightforward input of PET, whilst climate influences a large number of the variables which represent the initial catchment conditions (prior to the rainfall event). Furthermore, accounting for changes in the intensity and amount of rainfall falling in random individual storms of short duration (minutes to hours) is highly uncertain.

Unit hydrograph models have a limited ability to model socio-economic changes, although urban extent is a variable within the FEH rainfall–runoff model. Other changes can be modelled by proxy, for example by adjusting time to peak and standard percentage runoff.
The methods for driver parameterisation will therefore depend on the models available. An indicative modelling approach, assuming no distributed model is available, is summarised in Table 4-4; the actual methods will depend on the models used and the nature of the scenarios developed. Responses are considered in Section 4.2.5.

In general it may only be possible to use a single rainfall–runoff and hydraulic model, perhaps with only a single set of estimated parameters. This is a limitation, as the uncertainties inherent in the model structure and in the representation of physical processes will not be captured. However, when compared with other uncertainties, those relating to hydrological models have generally found to be lower (see Section 3.2.1). Furthermore, using a single existing model structure is beneficial given the need to model several scenarios. Nonetheless, it is important to check the calibration to ensure that the range of flows over which calibration was undertaken is adequate for modelling future scenarios.

Table 4-4 Scenario data for flood modelling and risk assessment

Scenario driver*	Example change	Indicative modelling approach^	Model
Climate change (rainfall)	Different timing, intensity and amount of rainfall	Various, but generally involving perturbation	Rainfall–runoff
Climate change (temperature)	Increase in PET	Perturb baseline PET	Rainfall–runoff
Land use (catchment)	Urbanisation	Adjust runoff co-efficients and time to peak	Rainfall–runoff
Land use (floodplain)	Urbanisation	Adjust floodplain storage and conveyance	Hydraulic
Land management (catchment)	Different crops; irrigation	Adjust runoff co-efficients and time to peak	Rainfall–runoff
Land management (floodplain)	Different crops and harvesting patterns	Adjust floodplain storage and conveyance	Hydraulic
Agricultural impacts	Increase in crop value	Adjust economic losses	Risk
Environmental regulation	Protection of floodplain habitat	Adjust standard of defence or conveyance	Hydraulic or Risk
River morphology and sediment supply	Channel widening (as flows increase)	Adjust standard of protection and defence condition	Hydraulic or Risk
River vegetation and conveyance	Channel and floodplain vegetation encouraged	Adjust standard of protection or conveyance	Hydraulic or Risk
Stakeholder behaviour	Risk adverse society	Adjust standard of protection	Hydraulic or Risk
Buildings and contents	Increase in property value (ahead of GDP)	Adjust economic losses	Risk
Urban impacts	High density development	Adjust economic losses	Risk
Infrastructure impacts	Extensive, well-used transport system	Adjust economic losses	Risk
Social impacts	Vulnerability increases for poorest	Adjust Social Flood Vulnerability Index	Risk

*Scenario drivers adapted from Foresight Future Flooding study (Evans *et al.*, 2004a). ^Indicative only and assuming no distributed model is available; the specific parameters or input data that require adjustment will depend on the particular model used, as well as the scenario developed.

4.2.3.2 Interactions between scenarios

A key part of the framework is to apply comprehensive storylines involving integrated scenarios. This means that interactions between the socio-economic and climate change scenarios are explicitly modelled. Ignoring responses, there are two principal interactions: the impact of climate change on land use (e.g. vegetation) and the impact of future land use on runoff. In the second case, current land-use characteristics are reflected (generally indirectly) in the same hydrological model as the climate data, and so the interaction is automatically assessed; however, few hydrological models explicitly parameterise land use (or are very selective e.g. URBEXT in FEH) and so taking into account future land use is complex. This also applies to the first interaction. If the effect of land-use change on hydrology was easy to model, then the first interaction would initially be concerned with the effect of climate change on land use provided in the socio-economic scenario in the absence of planned adaptation. However, to sustain plausibility, autonomous adjustments to climate change within the socio-economic setting would have to be included. Socio-economic changes are significantly easier to incorporate in the assessment of flood risk (e.g. through higher crop prices), which offers a ‘partial’ approach that covers several of the scenario drivers (see Table 4-4).

4.2.3.3 Modelling of scenarios in CFMPs

The recommended method for modelling in CFMPs depends on the particular task. For investigating the impact of land use, urbanisation and climate change on catchment response, sensitivity checks are recommended which modify parameters in either the FEH Packman spreadsheets or distributed rainfall–runoff and routing models (Environment Agency, 2005c). The sensitivity factors are drawn from a framework for selecting CFMP scenarios (see Table 4-5), from which relevant combinations of drivers are selected (Environment Agency, 2005d). In general, a simplistic approach to rainfall–runoff modelling is advocated using single lumped models for each tributary catchment and only applying distributed models to volume-dominated catchments where flood storage is important. Once flood flows have been generated it is recommended that water levels are predicted using rating curves (derived from a routing model or from detailed models) or using a sparse hydraulic model (Environment Agency, 2005c). The models included in CFMPs are deterministic rather than stochastic, although the Modelling and Decision Support Framework (MDSF) includes a procedure for assessing overall uncertainty based on uncertainty in flood depth as well as flood damages and social impacts.

Table 4-5 Framework for selecting CFMP scenarios

Driver	Low projection	Medium projection	High projection
Land use	Tp & SPR depending on type of change	Tp & SPR depending on type of change	Tp & SPR depending on type of change
Urban growth	Current trend - 25%	Current trend	Current trend + 25%
Climate change (fluvial flows)	+ 5% flows	+ 10% flows	+ 20% flows

From Table 2 of Environment Agency (2005d). Tp = Time to peak; SPR = Standard Percentage Runoff.

In the CFMP pilot studies[19], flow inputs to hydraulic models were generated using FEH (Burton *et al.*, 2003). Scenarios were modelled by adjusting catchment descriptors in FEH; for example, URBEXT was varied to account for changes in urban extent. In the River Ely pilot CFMP (Atkins, 2003a), the NAM lumped rainfall–runoff model was used to derive hydrographs for tributaries, which were then fed into a hydraulic model. The hydraulic model routed full flood hydrographs down the main channel. Inclusion of floodplain areas and adoption of a time-variant modelling approach permitted analysis of the effects of floodplain storage (ibid.). With no explicit variable for urban extent in the NAM model, FEH was used to derive changes in percentage runoff and peak discharge. The overland flow co-efficient in NAM was then increased by the same percentage as the change in percentage runoff in FEH and the overland flow routing constants in NAM were adjusted to give the same percentage increase in peak discharge. The effects of changes in rural land use were assessed by calculating the potential change in percentage runoff produced by the model. For climate change, the CFMP guidance (Environment Agency, 2005c) recommends applying a 20% increase to peak flows (of any return period) over 50 years. However, in the Ely model set-up it was not possible to alter the hydrographs directly, so a 20% increase in rainfall was applied to tributary catchments to examine sensitivity. This resulted in the full indicative 20% increase in flood flows in the upper tributaries, but in the lower part of the catchment the effect of floodplain storage resulted in smaller increases.

4.2.4 Assessment of flood risk in floodplain futures

The full realisation of the floodplain futures, following the development of scenarios and flood modelling, will be the assessment of flood risk. This will complete the combination of scenarios within each storyline, particularly as many aspects of socio-economic change principally affect flood consequences (i.e. receptors), rather than the probability of the flood occurring (sources and pathways).

A number of possible measures are used to define flood risk, and different measures reflect particular interests. Traditionally, the focus of engineers and hydrologists was on flood probability, but more recently new measures have been produced, in collaboration with disciplines such as economics and geography, which also encompass impact. Annual Average Damages (AAD) evaluates economic losses expected by flood events (Penning-Rowsell *et al.*, 2005) and the Social Flood Vulnerability Index (SFVI) predicts the areas and populations most vulnerable in terms of health and other intangible impacts (Tapsell *et al.*, 2002). Consideration has also been given to environmental impacts, particularly with respect to water level management in national and European protected sites.

[19] Initial pilot studies on the Severn, Irwell, Medway, Parrett and Yorkshire Derwent.

The framework is concerned with floodplain management in a broad sense. It extends beyond an evaluation of a change in flood probability to examine the impacts in relation to changes on the floodplain. Similarly, responses should not be restricted to flood management, but should encompass management of the whole floodplain, to involve *inter alia* landowners, planners, insurers and conservationists, as well as flood managers and engineers. Therefore, in order to fully represent the storyline and to inform management across floodplain interests, a number of flood risk measures are required. These include:

- Economic damages to property and agriculture. These are calculated using standard techniques (Penning-Rowsell *et al.*, 2005).
- Social impacts including population at risk and their social vulnerability. These can be calculated from census data and the SFVI (Tapsell *et al.*, 2002).
- Direct economic damages to infrastructure, for example erosion of railway embankments. These can be estimated based on previous flooding events.
- Indirect economic damages associated with infrastructure disruption, for example knock-on effects from power outages. These can be estimated based on previous flooding events or by calculation where techniques are established (e.g. Department for Transport delay costs).
- Environmental impacts, for example deterioration of floodplain Sites of Special Scientific Interest (SSSIs). These can be assessed qualitatively against conservation objectives and management targets (e.g. those included in Public Service Agreements), which will depend on the storyline.
- Intangible impacts, for example social effects not included in the SFVI. These can be assessed qualitatively and quantitatively where applicable (e.g. number of hospitals and schools affected).

A cost–benefit analysis should be undertaken for each scenario, which can be used in the evaluation of response measures. This would additionally require:

- Costs and benefits (losses avoided) of flood management measures, for example defences, flood warning. These are derived from standard figures used in project appraisal (MAFF, 2000).
- Costs and benefits of response measures, for example land management. Costs should be estimated based on consequential costs such as changes in land value or productivity. Benefits will require quantification of the reduction in flood impact due to the response.

A cost–benefit analysis would weigh the costs of flood management, response measures and residual damages against damages avoided. However, given the issues associated with cost–benefit analysis (see Section 3.2.3), it is important that it should form part of a multi-criteria approach to decision making, which also incorporates less tangible aspects.

Flood risk will vary throughout the catchment, depending on the probability of a flood occurring and the potential impact at a particular location. The spatial pattern of flood risk may be altered under different scenarios, and responses to these changes will be largely contingent on the nature of the risk at a local level. Therefore the floodplain would ideally be split into a number of basic flood risk zones (in a similar way to that in which the catchment is split into ‘policy units’ in CFMPs). Each zone would be distinct from immediate neighbours and internally homogenous in terms of flood probability, impact or/and land use. For example: rural areas may be considered separately to urban areas; and rural flood meadows, where flooding is beneficial, may be delineated from vulnerable and highly productive agricultural land. In practice the flood risk assessment may focus on the most vulnerable receptors, receptors which have recently flooded, or that can be reliably modelled, perhaps providing a number of case study zones and receptors within such zones, for example downstream urban area, key agricultural land or designated environmental site.

Flood risk will also change through time in response to the different scenarios, possibly resulting in different patterns of flood risk for example if topographic thresholds on the floodplain are reached, or if land use is altered. Therefore the boundaries and nature of flood risk zones, and the flood risk at different receptors, could change between timeslices. This may have significant implications for response measures and will provide an indication of the usefulness of taking a long-term perspective.

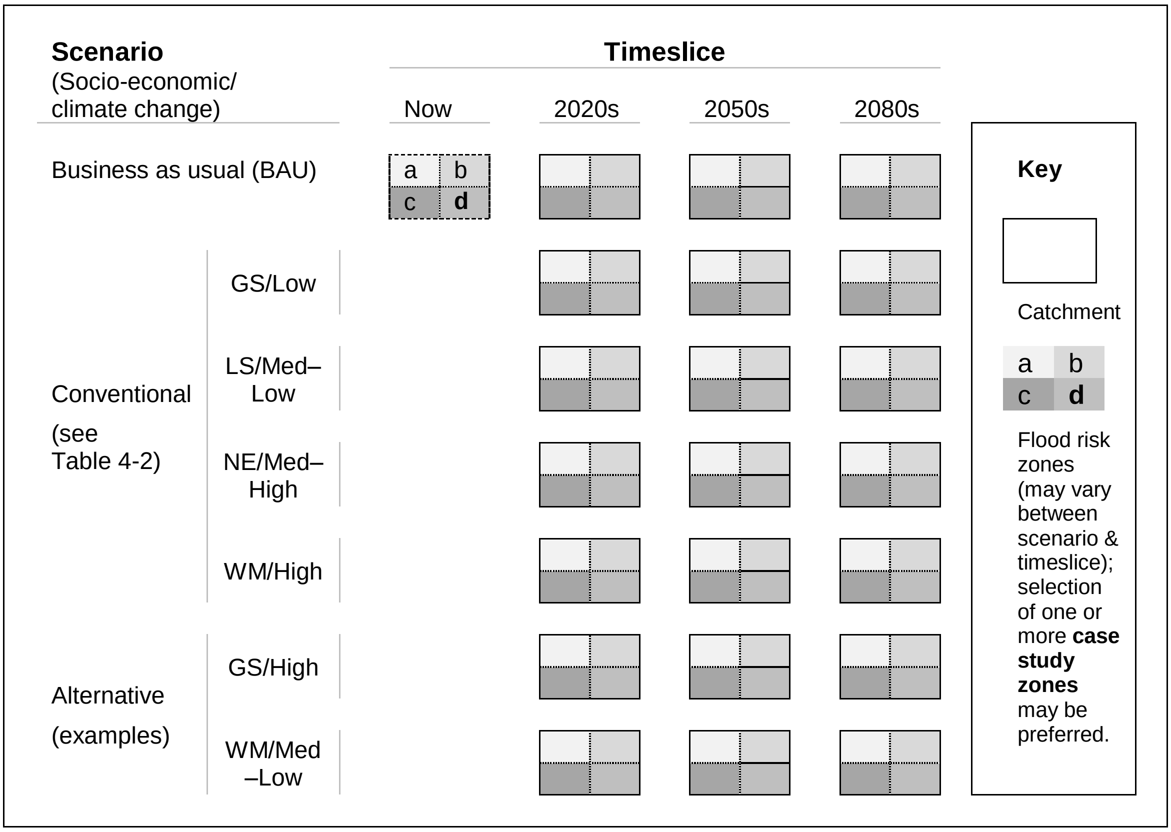
As discussed, the assessment of risk represents the final stage in forming the floodplain futures (with response measures providing an alternative set). For each catchment and component flood risk zone, a range of conventional and alternative scenarios can be explored over different future periods (see for example Figure 4-4). These floodplain futures can be compared to the BAU scenario.

4.2.5 Responses to flood risk: scenario-specific adaptation strategies

If no planned adaptation is assumed then flood management will encompass only those aspects present in the BAU scenario. The resulting risk would therefore represent the potential impact of climate change within each socio-economic setting (this could be represented in Figure 4-1 as an intermediate outcome between floodplain futures excluding adaptation and those including adaptation).

However, as discussed above, the assumption of no adaptation is implausible. Furthermore, within a full scenario approach, it would be methodologically illogical to apply any adaptation measure to any or all of the scenarios, because responses to flood risk are as much a part of the scenarios as the drivers (although under the intermediate outcome discussed above, application of BAU measures to all scenarios would be an immediate strategy for selecting the measures that perform best across the futures considered). Therefore, adaptation measures should be applied in a context-specific manner; the full scenarios should then be re-modelled and the residual risks assessed.

Figure 4-4 A possible set of floodplain futures for the catchment and risk zones



Responses should be applied to the flood risk zones (and in detail to any case study zones), with consideration of wider catchment effects. In the absence of future catchment policies for floodplain management, it would be difficult to use the appraisal of measures as the process for selecting a preferred option. However, sufficient information can be included in the storylines to ensure that attitudes to floodplain management can be distilled. For example, a scenario in which biodiversity is important may be consistent with a response of floodplain restoration. In this way adaptation measures can be selected for each flood risk zone. Finally, a review of measures across different scenarios can be undertaken to identify effective measures, which are likely to provide robust adaptation to future changes (see below).

Response measures were comprehensively reviewed in the Foresight Future Flooding study (Evans *et al.*, 2004b). A literature review and consultation generated approximately 80 responses to future flood risk, which included physical actions as well as governance issues. The responses were collated into five broad themes and 26 groups, of which 21 are relevant to fluvial flood risk (Table 4-6)[20]. For each response group, the expert review describes the efficacy in reducing flood risk, issues of governance and sustainability, costs and funding mechanisms, and interactions with other responses (Evans *et al.*, 2004b). Four portfolios of responses were constructed in line with the four socio-economic scenarios. In a similar manner, Middelkoop *et al*. (2004) devised three flood management styles consistent with three world views (Egalitarian, Hierarchist, Individualist) using the Perspectives method (see Section 3.2.2.3). These reviews – Foresight using SRES scenarios (but not based on catchments) and Middelkoop *et al*. based on catchments (but using an alternative construction of world views) – provide an excellent starting point for the consideration of catchment and scenario-specific responses.

Table 4-6 Responses to future flood risk used in Foresight Future Flooding study

Response theme	Response group	Element of flood system affected	Example responses
Managing the rural landscape	Rural infiltration	Pathway	Field drainage, afforestation
	Catchment-wide storage	Pathway	Washlands, impoundments
	Rural conveyance	Pathway	Channel re-alignment
Managing the urban fabric	Urban storage	Pathway	Temporary flood storage
	Urban infiltration	Pathway	Permeable land cover
	Urban conveyance	Pathway	Maintain assets
Managing flood events	Pre-event measures	Pathway & Receptor	Flood risk assessment, education, planning
	Forecasting and warning	Pathway & Receptor	Improved sensing, forecasting, dissemination
	Flood fighting actions	Pathway & Receptor	Control structures, emergency operations
	Collective damage avoidance actions	Receptor	Evacuation of floodplains, demountable defences
	Individual damage avoidance actions	Receptor	Temporary flood proofing, moving assets
Managing flood losses	Land-use management	Receptor	Relocation (voluntary, encouraged, compulsory)
	Flood-proofing	Receptor	Building alterations, barriers
	Land-use planning	Receptor	Restrict development
	Building codes	Receptor	General codes, planning conditions
	Insurance, shared risk and compensation	Receptor	Insurance, state aid, charitable relief, bear loss
	Health and social measures	Receptor	Post-flood assistance, counselling
River engineering	River conveyance	Pathway	Alter hydraulic geometry
	Engineered flood storage	Pathway	Flood storage reservoir
	Floodwater transfer	Pathway	Pumped diversions
	River defences	Pathway	Flood embankments, gates

Based on tables and information in Evans *et al*. (2004b).

[20] A combined list of responses from all sources was published by Evans *et al*. in 2008 but those presented here remain relevant.

An indicative approach for modelling different responses is set out in Table 4-7. Many of the adjustments required are outside of the rainfall–runoff and hydraulic models and would involve fairly simple adjustments to risk, although deciding on how to adjust losses to account for some of the responses is highly subjective and uncertain. Those changes required in fluvial models would be more time consuming to implement, and adequate representation of the effects of storage adjustments would require a detailed hydraulic model. The actual responses adopted, and the precise way in which they are evaluated, will depend on the models used, the scenarios developed and the nature of the change in flood risk.

Table 4-7 Response data for flood modelling and risk assessment

Response group*	Indicative modelling approach^	Model
Rural infiltration	Adjust runoff co-efficients or time to peak	Rainfall–runoff
Catchment-wide storage	Adjust floodplain storage and conveyance	Hydraulic
Rural conveyance	Adjust conveyance	Hydraulic
Urban storage	Adjust floodplain storage	Hydraulic
Urban infiltration	Adjust runoff co-efficients or time to peak	Rainfall–runoff
Urban conveyance	Adjust conveyance (or model?)	Hydraulic
Pre-event measures	Adjust losses	Risk
Forecasting and warning	Adjust losses	Risk
Flood fighting actions	Adjust conveyance (but event specific?) and losses	Hydraulic or Risk
Collective damage avoidance actions	Adjust losses	Risk
Individual damage avoidance actions	Adjust losses	Risk
Land-use management	Adjust losses and conveyance (and land use)	Hydraulic or Risk
Flood-proofing	Adjust losses	Risk
Land-use planning	Adjust losses and conveyance (and land use)	Hydraulic or Risk
Building codes	Adjust losses	Risk
Insurance, shared risk and compensation	Adjust losses	Risk
Health and social measures	Adjust losses; Social Flood Vulnerability Index	Risk
River conveyance	Adjust conveyance	Hydraulic
Engineered flood storage	Adjust storage	Hydraulic
Floodwater transfer	Adjust model	Hydraulic
River defences	Adjust conveyance, storage and losses	Hydraulic or Risk

*Response groups adopted from Foresight Future Flooding study (Evans *et al.*, 2004b). ^Indicative only and assuming no distributed model is available; the specific parameters or input data that require adjustment will depend on the particular model used, as well as the scenario developed.

4.3 Consultation

The aim of this stage of the framework is to engage a variety of stakeholders with the floodplain futures, to jointly evaluate these futures and to consider alternative responses. As the framework is concerned with floodplain management in a broad sense, stakeholders should encompass a wide range of interests in the floodplain, including river users, land owners, farmers, residents, businesses, infrastructure providers, planners, insurers and conservationists, as well as flood managers and engineers.

4.3.1 Evaluation of floodplain futures

The floodplain futures (with and without embedded responses) should be presented to stakeholders, along with an introductory explanation of the research objectives. This may take the form of a written briefing, followed by a face-to-face presentation as part of small focus groups. A brief initial aim of the consultation should be to test stakeholder reaction to the floodplain futures, and to the methodology employed. This will inform the Evaluation phase of this research (see Figure 4-1).

Evaluation of floodplain futures is required to:

- Review the socio-economic scenarios.
- Fully assess the flood risk.
- Evaluate the responses embodied in the storylines.

In terms of the socio-economic scenarios, these could be drafted prior to engaging stakeholders, or stakeholders could be engaged more directly in the scenario development process. A top-down approach utilising passive stakeholder engagement is suitable for exploratory studies where a range of perspectives is important (Kloprogge and Van der Sluijs, 2006). However, in the EU SIRCH[21] project it was concluded that participatory scenarios are more insightful than ‘imposed’ scenarios, with the latter being difficult to downscale (Paul-Wostl, 2002). For further detail, see the review of socio-economic scenarios in Appendix 1.

Several measures of flood risk can be provided in the Modelling phase of the framework, including flood extent and depth, the number of people and buildings flooded, and the economic damages. However, intangible impacts will be harder to measure and there is no objective way of considering the overall impact. Stakeholder engagement may also be useful in this regard and could help design a multi-criteria assessment approach to risk assessment, as well as the evaluation of response measures (see below).

Finally, the responses themselves require evaluation and although this will be partly implicit in the assessment of residual risk, it will be necessary to consider a wider range of criteria (Table 4-8).

Table 4-8 Criteria used to evaluate response measures in flood management studies

Foresight Future Flooding*	**Flood Management in the Rhine and Meuse^**	**River Ely Draft CFMP#**
(Flood risk) Cost-effectiveness Social justice Environmental quality Robustness Precaution	Safety Nature Agriculture Costs Economic benefits Flexibility/reversibility Quality of life Resilience	Technical effectiveness Economic efficiency Environmental effects Stakeholder support Safety and social vulnerability Sustainability

*Evans *et al*. (2004b); ^Middelkoop *et al*. (2004); #Atkins (2003a).

Therefore, a stakeholder evaluation of floodplain futures can contribute to a multi-criteria analysis of risk and response measures for each flood risk zone. For each scenario and timeslice, stakeholders could be asked to score the collective response measures included in the scenario against wide-ranging criteria. These scores can be qualitative (e.g. based on a five-point scale). Quantitative data from the modelling and risk assessment (measuring the effect of response measures collectively) can be used to inform the scoring of some criteria, for example reduction in flood risk. These could be scored objectively, but it is considered important for stakeholders to assess such criteria based on their own perceptions, for example regarding flood risk reduction. The scores would then be aggregated to provide an overall assessment of the response measures within each scenario.

4.3.2 Alternative responses

A second part of the consultation exercise would ascertain possible solutions to managing flood risk that were not modelled in the original scenarios. Stakeholders should represent a wide pool of expertise and are likely to come up with a range of adaptive measures. Such measures should be re-modelled or used in a re-assessment of flood risk as appropriate.

[21] Social and Institutional Responses to Climate Change and Climatic Hazards: Drought and Floods.

4.4 Results and dissemination

This phase of the framework summarises the results and discusses uncertainties. Following this, advice for policy makers and practitioners can be developed and disseminated.

4.4.1 Effectiveness of responses

The effectiveness of different response measures should be evaluated to identify robust adaptation measures. This should consider the response measures included in the storylines as well as those devised by stakeholders during the consultation phase. The effectiveness of response measures will depend on their contribution to flood risk management, as well as their potential success in meeting other criteria (see Table 4-7). Comparisons should be made across scenarios and timeslices, and response measures which are effective under more than one storyline should be highlighted.

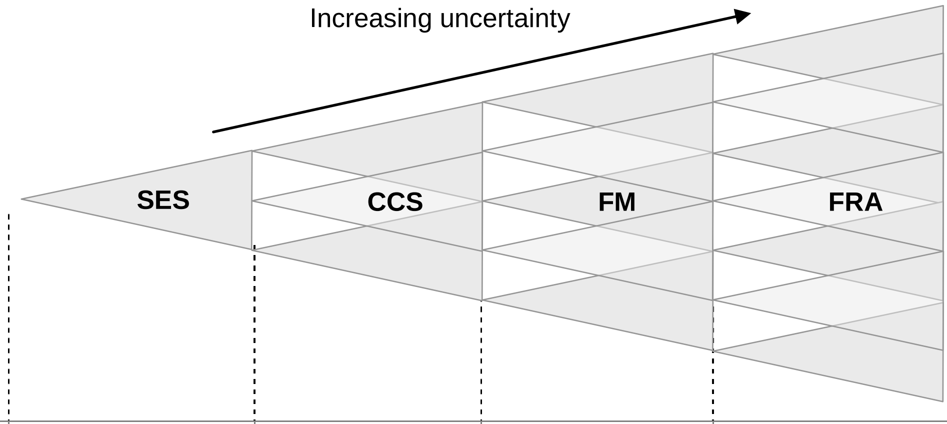
4.4.2 Uncertainty

An assessment of uncertainty should be made to inform the robustness of the risk assessment and response measures. This should consider the “cascade of uncertainty” (Mitchell and Hulme, 1999; Viner, 2002) through the whole process: from global socio-economic and SRES scenarios to catchment socio-economic and climate change scenarios, through hydrological and hydraulic modelling to the assessment of flood risk and responses (Figure 4-5). The effect of methodological decisions on the treatment of this uncertainty (the structural uncertainty of the framework) at each stage (e.g. assess, partially assess or ignore) should be discussed; one possible approach is set out in Figure 4-5.

4.4.3 Recommendations and dissemination

Pragmatic advice should be developed for the range of policy makers and practitioners concerned with floodplain management. This should include lessons learnt in using a scenario approach to explore floodplain futures, potentially robust response measures and an assessment of the related uncertainty. Dissemination of the findings should include the policy, practice and research communities.

Figure 4-5 The cascade of uncertainty through a scenario-based impact assessment



Stage	Socio-economic Scenarios (SESs)	Climate change scenarios (CCSs)	Fluvial modelling (FM)	Flood risk assessment (FRA)
Uncertainties	Socio-economic change; effect on emissions	Climate sensitivity; model structure; downscaling	Model structure; calibration; perturbation method	Exposure; warning; assistance; damage; costs
Basic Approach	One scenario	One model and one scenario	One deterministic model	One value for risks, losses etc.
Advanced Approach	Multiple scenarios	Several models, ensemble runs, different downscaling techniques and multiple scenarios	Several stochastic models	Range or probability density function for risks, losses etc.
Possible approach	Four IPCC SRES scenarios	Multiple GCMs, dynamic downscaling, use of a weather generator	One deterministic model	One value for risks, losses etc.

4.5 Evaluation

The final phase of the framework should evaluate the methodology set out in this chapter. It should critically assess the overall approach, the methods used and the value of the output with respect to the objectives of this research as well as to the policy and practice communities. The methodology should be revised as appropriate. Finally, further research can be identified.

4.6 Focus of research within the framework

Not all of the phases of the framework described above are covered in this thesis. The quantification and parameterisation of socio-economic scenarios proved problematic for several of the socio-economic driving pressures, especially those relating to land use and management and river channels. For example, although some scenarios provide proportions of broad land-use types for the future, there is no objective basis on which to downscale these to the local level (assumptions would have to be made regarding the location and sub-types). More critically, there remains a high level of uncertainty regarding the impact of land use on flood flows, especially where the changes are minor (e.g. an increase in woodland of a few per cent) and where the catchments are large (see Section 3.2.1). Furthermore, with the exception of urban extent, the hydrological models commonly in use (and used for this thesis) do not have parameters that represent different land-use types. Adjustments can be made to other parameters to simulate land-use changes (e.g. time to peak), but this is not straightforward given the influence of other factors on such parameters (e.g. soil type, land management).

It would remain possible, and is much simpler, to assess the effect of socio-economic scenarios on the change in risk associated with climate change alone. However, for the remainder of this thesis it was decided to end the socio-economic side of the framework at the development of potential methods for developing baseline and future socio-economic scenarios (this is presented in Appendix 1). Therefore, the floodplain futures element of the framework, and the related consultation, will not proceed here.

Instead more attention has been given to the assessment of climate change, in particular relating to the fourth research gap identified in Section 3.3, to address the identified impasse between academic studies, which have generally used catchment-specific scenarios, and information being used in decisions, based on a national indicative sensitivity range. **The research presented here therefore seeks to combine these approaches, by using climate model information directly in design models, to assess the implications for future flooding and to examine the associated methodological benefits and drawbacks.**

5. Case study catchments and flood risk driving pressures

This chapter introduces and describes the two case study catchments and identifies the major driving pressures with the potential to affect flood risk with particular reference to selected exemplar receptors. Two contrasting catchments have been selected: the Bedford Ouse in the east of central England, a predominately lowland catchment containing significant urban settlements and agricultural development, and the Eden in north-west England, a largely rural upland catchment. The DP-S-I-R scoping framework (Turner, 2005) has been used to facilitate the identification of driving pressures that affect flood risk in terms of environmental, social and economic impacts.

5.1 Case study catchments

5.1.1 Catchment selection

The two catchments have been selected to provide a contrast between different geographies of landscape, land use and climate. In addition, a number of other criteria have been used to ensure that the catchments are suitable for the proposed modelling. Table 5-1 summarises the catchment selection criteria and how they are met.

5.1.2 Bedford Ouse catchment

The Great Ouse catchment comprises the Bedford Ouse and Ely Ouse catchments. The Bedford Ouse is the catchment of the River Great Ouse upstream of Earith, while the Ely Ouse covers the eastern and southern parts of the Great Ouse catchment draining to Denver (Environment Agency, 2005e). This thesis is considering the Bedford Ouse only, to limit the modelling to one more straightforward catchment which is not dominated either by tidal effects or by large-scale controls. The environment of the Great Ouse catchment has been reviewed in Environment Agency (2005e) as part of the Great Ouse CFMP. This section summarises the detail contained in this review that is relevant to the Bedford Ouse, and is supplemented by additional information where referenced.

5.1.2.1 Overview

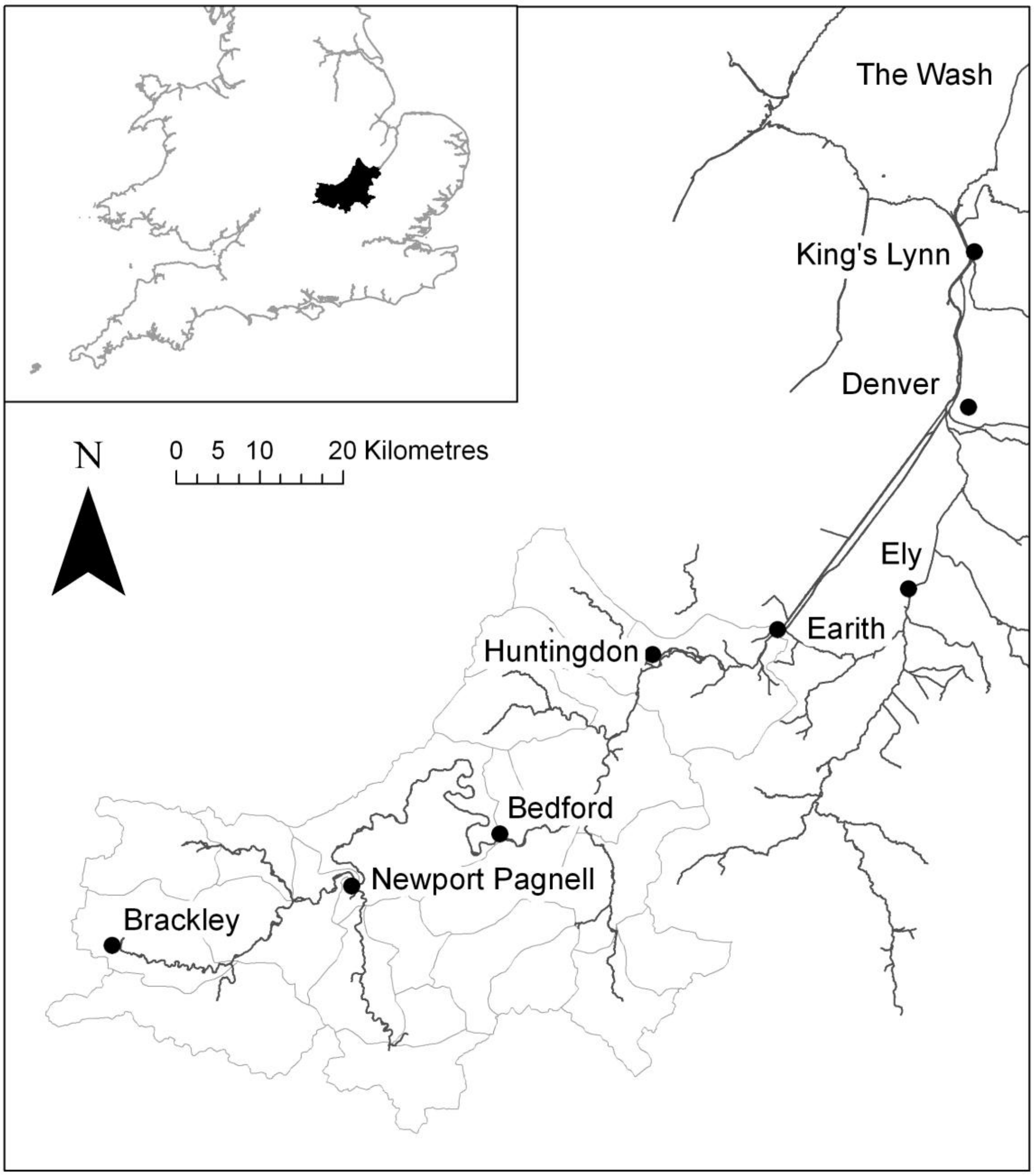
The Bedford Ouse catchment is located in the east of central England, extending from Northamptonshire in the west to Cambridgeshire in the east. The River Great Ouse rises on high ground (around 170 mAOD) near Brackley and travels through Newport Pagnell, Bedford and Huntingdon (Figure 5-1; see Figure 5-2 for a detailed map). At Earith, the downstream limit of the Bedford Ouse (close to sea level), the river becomes tidal and embanked and flows across the Fens via Ely and the Denver complex to The Wash close to King's Lynn. Water can also spill from the Bedford Ouse at Earith into the Ouse Washes, a large winter flood storage reservoir. Tributaries rise on higher ground to the south and north-west of the Bedford Ouse as it meanders north eastwards and include the Rivers Twin, Tove, Ouzel, Ivel, Kym and Alconbury Brook (Figure 5-3).

Table 5-1 Catchment selection criteria

Criteria	Description	River Bedford Ouse	River Eden
Flood risk	Flooding must currently be or likely to become a problem within the catchment.	Average SFVI; £43.3M AAD in high impact areas; infrastructure and environmental assets at risk. Major recent flooding e.g. 1998, 2000.	High SFVI; 'High' to 'Extreme' risk to people; £39.5M AAD; infrastructure and environmental assets at risk. Major recent flooding e.g. 2005.
Contrast	Catchments should provide contrasts in terms of land use (urban and rural), landscape and climate.	Catchment 3,100 km^2; 7% urban, 84% agricultural*; 0 to 170m elevation; <550 to ~750mm annual precipitation.	Catchment 2,400 km^2; 1% urban, 94% agricultural; 0 to 950m elevation; <800 to >2,800 mm annual precipitation.
Hydrological response	Catchment should have hydrological response that can be modelled using reliable input data.	Upper catchment requires sub-daily rainfall, although daily rainfall suitable for output in middle and lower catchment.	Data from three flood events available for perturbation.
Fluvial models	Catchment should have available calibrated hydrological and hydraulic models.	Bedford Ouse Flood Forecasting Model: MIKE11 rainfall–runoff and hydraulic model (continuous flows).	Various, including Carlisle & Eden Flood Defence Strategy Model: FEH hydrology, ISIS routing and hydraulics (discrete event).
Socio-economic data	Catchment should have information available to inform construction of the BAU scenario.	Draft Regional Spatial Strategy, Local Plans, Regional Economic Strategy.	Draft Regional Spatial Strategy, Local Plans, Regional Economic Strategy.
Stakeholder engagement	Catchment should have stakeholders willing to participate in the consultation phase.	Consultees engaged with flood defence strategies and CFMP.	Consultees engaged with flood defence strategies and CFMP.

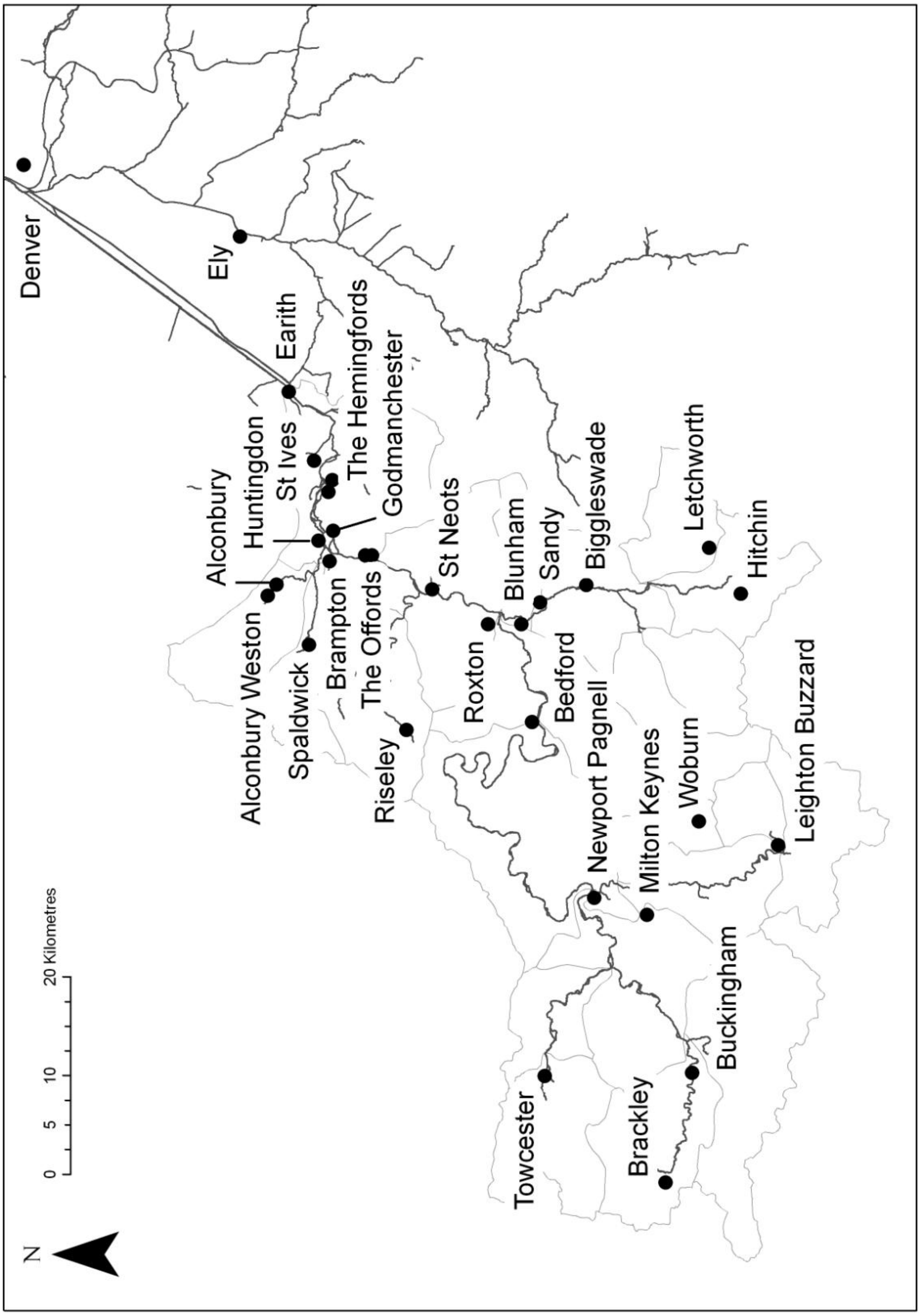
*Land use for Great Ouse catchment.

Figure 5-1 The Bedford Ouse catchment overview



The grey lines show the boundaries of the 21 catchments in the Bedford Ouse system (see Figure 5-3 and Table 5-2). The rivers shown outside of the Bedford Ouse are in other parts of the Great Ouse catchment.

Figure 5-2 The Bedford Ouse detailed settlement map



5.1.2.2 Geology, geomorphology and soils

The solid geology of the Bedford Ouse catchment largely consists of mudstones. To the north-west of a line between Buckingham and Bedford the geology is limestone, with the exception of the River Tove catchment, which is dominated by mudstone. A band of sandstone runs in a north-westerly direction from Leighton Buzzard through Biggleswade, while the very south-east of the catchment, especially around Hitchin at the headwaters of the Ivel, is underlain by chalk.

The drift is largely composed of gravelly clay, while river valleys include extensive sand and gravel deposits. The clay is relatively impermeable and contributes to more rapid runoff. In contrast some areas of the limestone and chalk have no drift cover and these areas are slower to respond to rainfall events.

The rivers of the Bedford Ouse catchment are largely constrained geomorphologically, with most of the River Bedford Ouse and some of its tributaries provisionally classified under the Water Framework Directive as heavily modified. The modifications include straightening, dredging, in-channel structures (e.g. locks) and raised banks relating to infrastructure construction, navigation and flood control.

5.1.2.3 Hydrology, flood history and current flood risk

The catchment is relatively dry, with much of the central and downstream areas receiving less than 600mm of precipitation per year. On the higher ground to the west and along the catchment boundaries, precipitation is higher, but only up to around 750mm. The dominant flood season is winter, when the ground is at or close to saturation. Catchment response to rainfall can then be rapid and of relatively high magnitude. The catchment alignment from south-west to the north-east also makes it susceptible to dominant winter frontal rainfall systems. Although the headwaters and tributary catchments contribute rapid runoff, significant areas of floodplain storage, particularly downstream, mean that flood peaks can take a few days to move through the catchment. Groundwater is not thought to be a significant input to river flooding, although direct groundwater flooding does occur in places. The tidal limit is Brownshill Staunch, just upstream of Earith, and therefore tidal effects are largely ignored here.

There is a long history of flooding in the Bedford Ouse catchment. Widespread flooding was experienced in 1947 as a result of rapid snowmelt and heavy rainfall. Recently there have been a series of flood events, notably Easter 1998 and Autumn 2000 (see Boxes 2-1 and 2-2) and again in early 2003. In some locations, properties were flooded in all three events. More recently, in the summer of 2007, properties were flooded in the upper catchment.

Data on flood risk in the Bedford Ouse catchment have been extracted from the *Great Ouse CFMP Final Scoping Report* (Environment Agency, 2005e). Assuming no defences, the number of residential and commercial properties at risk (from a 1% annual probability event, APE) in the high-impact area of Zone 3 is 12,371 and the associated AAD is £54.3 million, with a further agricultural AAD of £0.4 million. Defences identified as of May 2005 reduce the number of properties at risk (from 1% APE) to 8,846 and AAD to £43.1 and £0.2 million respectively; these figures are declining further with the construction of new flood defence schemes, for example at St Ives in Cambridgeshire. In addition, there is a large number of properties at risk within the lower impact areas of Zone 3; however, these figures could not be extracted for the Bedford Ouse catchment. A wide variety of infrastructure is also at risk including major national road and rail infrastructure, schools and police stations.

The Social Flood Vulnerability Index (Tapsell *et al.*, 2002), which is embedded in the CFMP MDSF was used in the preparation of the Great Ouse CFMP to highlight populations particularly vulnerable to flooding. Within the Bedford Ouse catchment, the SFVI of the high risk areas was generally 2 or 3 (low to average), although it was 4 (high) in Towcester and Letchworth.

5.1.2.4 Flood risk management

Current flood risk management measures include flood storage, flood defence and flood warning.

The Ouse Washes is a large (20 km^2) flood storage area which lies between Earith in the south-west and Denver in the north-east. It is bordered by the New Bedford River or Hundred Foot Drain to the east and the Old Bedford River (and beyond the embankment, the Counter Drain) to the west (Figure 5-3). Discharge from the Bedford Ouse at Earith is diverted into the Ouse Washes when it exceeds the downstream capacities of the Great Ouse towards Ely and the New Bedford River, both of which are tidal. The Ouse Washes are used extensively in winter and early spring; over the past two decades late spring and early summer use has become more common. This is causing a conflict of interest with the nesting of birds in the Washes, which have been designated as a European Special Protection Area (SPA) and Ramsar site. A flood storage reservoir has recently been constructed upstream of Towcester, providing protection to the 2% APE. In addition, there are a number of storage reservoirs to attenuate runoff from the new city of Milton Keynes.

Flood defences, including walls and embankments, protect Bedford, Towcester, Newport Pagnell, Sandy, Blunham, The Hemingfords, St Ives and Biggleswade. The standard of protection varies between 16% and 1% annual probability.

Flood warning areas cover the floodplain for virtually the entire length of the Great Ouse within the Bedford Ouse catchment, along with tributaries including the Tove, Ouzel, Ivel and Alconbury Brook. The Flood Warning Service aims to provide a minimum warning time of 2 hours. A key element of this is the Bedford Ouse flood forecasting model, which is similar to the model being used in this study (see below).

Internal Drainage Boards (IDBs) manage flood risk across parts of the Bedford Ouse catchment. The majority of IDBs rely on gravity discharge to main rivers. In more low-lying areas, such as close to Earith, IDBs rely on pumping to remove water from behind flood embankments.

5.1.2.5 Land use

Land use in the Bedford Ouse catchment is dominated by arable farming on good quality (largely Grade 2 and Grade 3) agricultural land, with grassland pre-dominant in upper reaches beyond the Ouzel confluence. There a few large urban areas in the upper catchment, including Milton Keynes, Hitchin and Letchworth, with many of the other towns situated along the Bedford Ouse including Brackley, Buckingham, Newport Pagnell, Bedford, St Neots, Huntingdon and St Ives. Gravel extraction is a major activity within the floodplain and some former sites have been flooded for recreation and wildlife purposes, for example Marston Vale (south-west of Bedford) and Needingworth (east of St Ives). Another large area of water is the reservoir Grafham Water, which is largely fed by abstractions from the Great Ouse at Offord.

5.1.2.6 Hydrological and hydraulic models

A number of models have been used to map floodplain extent and to inform local flood defence strategies. Recently, the Bedford Ouse flood forecasting model has been completed; it provides a comprehensive suite of models for design and forecasting purposes, implemented in the Danish Hydraulic Institute (DHI) MIKE-11 modelling package.

The rainfall–runoff model within MIKE11, NAM, is a lumped conceptual model, with continuous input of rainfall and PET (DHI, 2007). Excluding snow, it has three stores: surface, lower or root, and groundwater. Runoff is partitioned into overland flow, interflow and baseflow.

Figure 5-3 The Bedford Ouse hydrological system

The grey lines show the boundaries of the 21 catchments in the Bedford Ouse system (see Table 5-2).

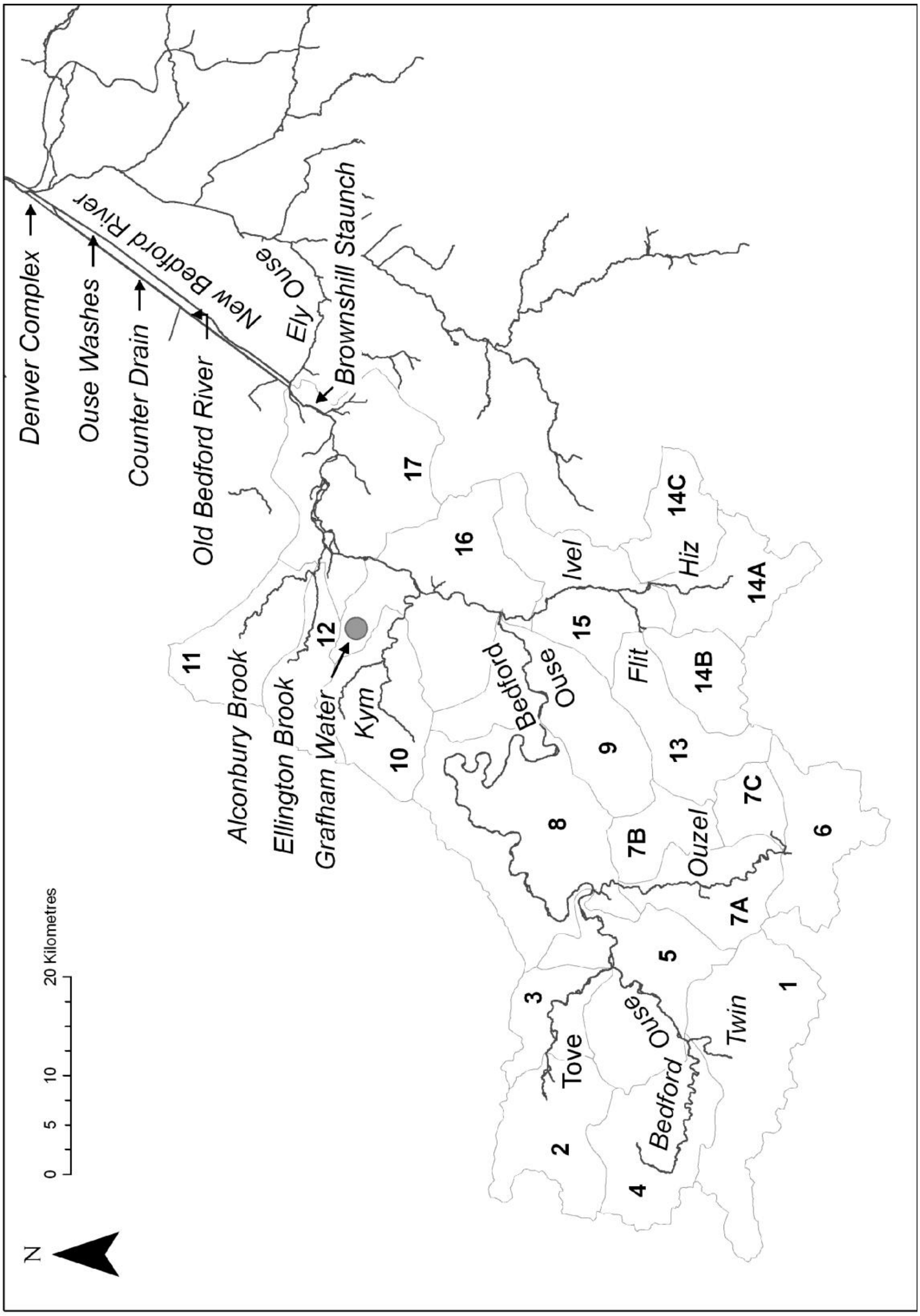


Table 5-2 Catchments of the Bedford Ouse, characteristics and classification

#	Name	Abbrev.	Area (km^2)	BFI-HOST	SPR-HOST	SAAR (mm)	HRC	Notes
1	Twin	Twin	235.6	0.4	42.5	645	Rapid	
2	Upper Tove	UpperTove	136.9	0.5	37.4	641	Semi-regulated	12% urban
3	Lower Tove	LowerTove	76.7	0.4	39.5	639	Semi-regulated	
4	Upper Ouse	UpperOuse	153.4	0.6	31.1	668	Semi-regulated	3% urban
5	Ouse between Buckingham and Milton Keynes	OuseB2MK	195.8	0.4	42.3	641	Rapid	18% urban
6	Upper Ouzel	UpperOuzel	124.4	0.5	40.6	645	Semi-regulated	
7A	Middle and Lower Ouzel	7A	157.7	0.4	43.1	640	Rapid	14% urban
7B		7B	66.3	0.5	40.9	628		
7C		7C	49.0	0.4	48.8	637		
8	Ouse between Milton Keynes and Bedford	NP2Bed	311.5	0.4	41.0	631	Rapid	
9	Tributaries of the Middle Ouse between Bedford and Roxton	Bed2R	192.1	0.4	48.0	592	Rapid	10% urban
10	Kym	Kym	136.9	0.3	49.0	589	Rapid	
11	Alconbury Brook	Alconbury	116.2	0.3	52.3	560	Semi-regulated	
12	Ellington Brook	Ellington	84.6	0.3	53.7	572	Rapid	
13	Flit	Flit	119.6	0.6	36.6	586	Semi-regulated	
14A	Hiz	Hiz	108.9	0.7	28.5	605	Semi-regulated	4% urban
14B	Tributary of Flit	TribFlit	74.4	0.6	35.5	593		
14C	Tributary of Hiz	TribHiz	81.7	0.7	21.7	587		
15	Ivel	Ivel	158.2	0.6	37.2	562	Regulated	
16	Ouse between Roxton and Offord	Rox2Off	245.7	0.4	46.0	571	Semi-regulated	
17	Ouse between Offord and Earith	Off2Ear	257.7	0.5	41.5	560	Regulated	5% urban

BFI-HOST, SPR-HOST and SAAR from Atkins (2003); note that these values are approximate as based on arithmetic means and have been adjusted in this research to account for the current catchment configuration in the Bedford Ouse model. HRC = hydrological response classification of Atkins (2003), explained in the text above.

The Bedford Ouse model includes 21 separate rainfall–runoff models above Earith, each hydrologically homogenous and falling into one of three categories (Table 5-2) (Atkins, 2003b):

1. Regulated response to rainfall, low volume of runoff and high groundwater storage.
2. Semi-regulated response to rainfall, medium volume of runoff and medium groundwater storage.
3. Rapid response to runoff, high volume of runoff and low groundwater storage.

Flow routing in the Bedford Ouse model is undertaken using the hydraulic model MIKE11, which computes unsteady flows using a finite difference scheme (DHI, 2007). The hydraulic network was divided into three units (Atkins, 2003b):

1. Upper headwaters: natural, single channels with little floodplain and few significant structures.
2. Lower section: meandering and bifurcating channel with wider, flatter floodplain. Flows strongly influenced by structures, and peaks attenuated by storage.
3. Artificial section: close to and downstream of Earith, where the river is embanked.

Output from each rainfall–runoff model comprises a single hydrograph for each sub-catchment, which is injected into the hydrodynamic model as a point inflow (Atkins, 2004). Floodplain flows are integrated into the main channel where the floodplain is narrow and has a steep slope; where the floodplain is wider with a shallow slope, separate floodplain channels are included (Atkins, 2004), although the model remains one-dimensional.

The rainfall–runoff and hydraulic models have been calibrated and validated using observed flows and levels for the periods March 1996 to March 2002 (covering two key flood events and a drought) and February 1993 to August 1995 respectively (Atkins, 2004).

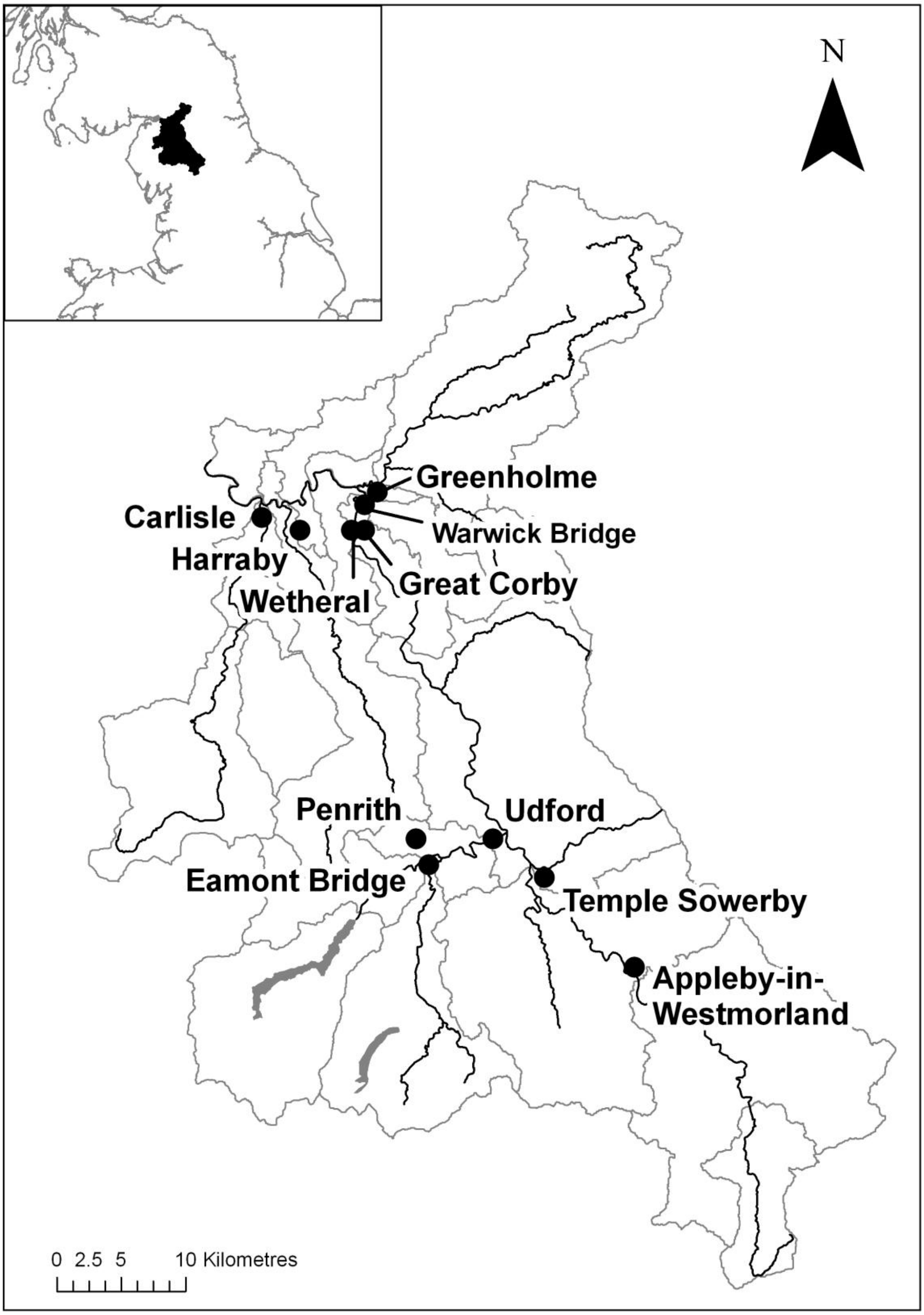
5.1.3 Eden catchment

The environment of the Eden catchment has been reviewed in Atkins (2005) and Environment Agency (2005f) as part of the Eden CFMP. This section summarises the detail contained in these reviews and is supplemented by additional information where referenced.

5.1.3.1 Overview

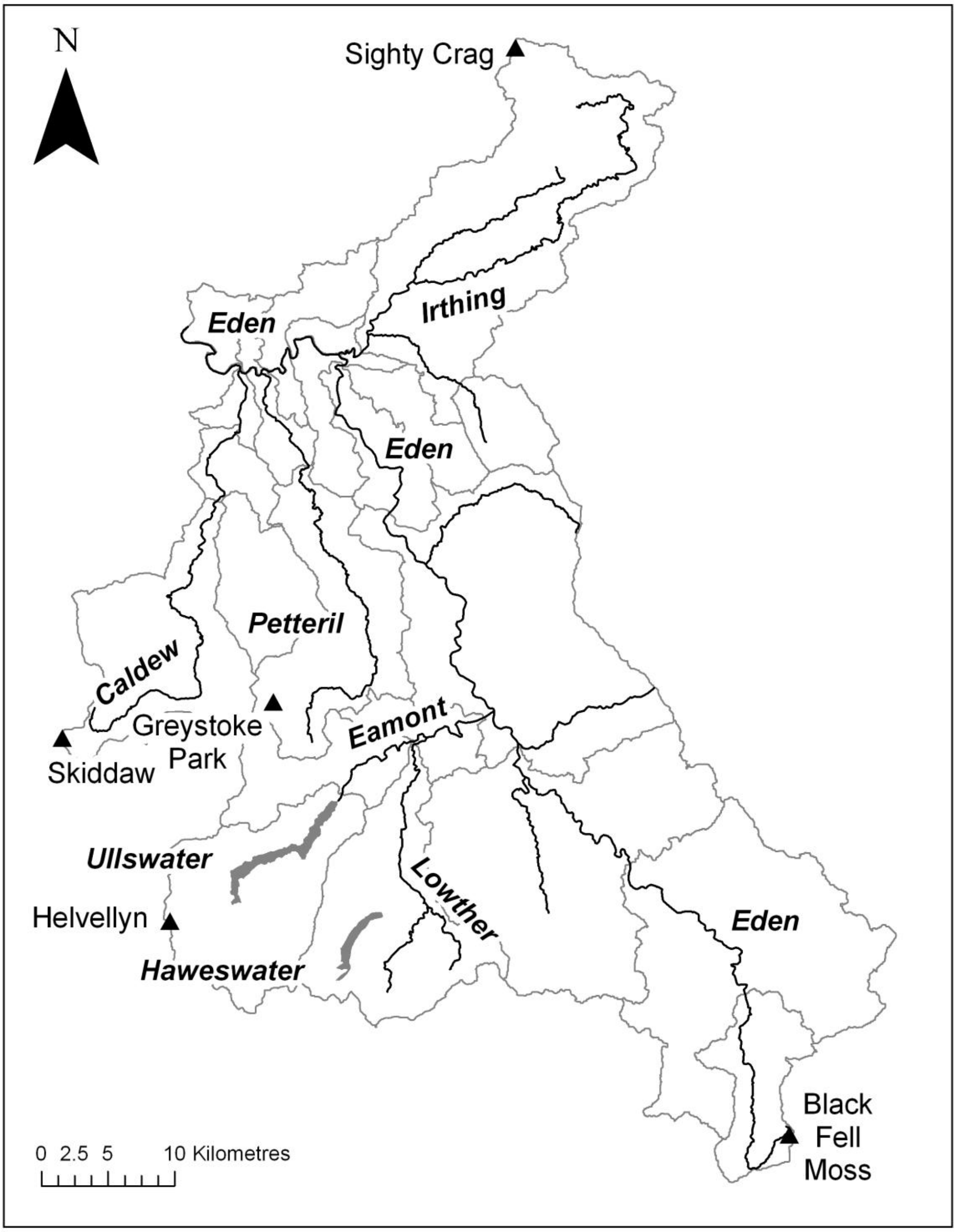
The Eden catchment is located in north-west England and is bounded by the Lake District to the west and south-west, the Pennines to the south-east, east and north-east, with the Esk catchment to the north. The River Eden is the principal river, rising at Black Fell Moss (690 mAOD) and travelling the length of the catchment in a north-north-west direction before turning west, through Carlisle and discharging into the Solway Firth (see Figure 5-4). There are four main tributaries (see Figure 5-5): the River Eamont, which rises on Helvellyn (950 mAOD) and includes Ullswater and Haweswater Reservoir which discharges via Haweswater Beck and the River Lowther; the River Irthing, which rises on Sighty Crag (518 mAOD); the River Petteril, which rises at Greystoke Park (361 mAOD); and the River Caldew, which rises on Skiddaw (931 mAOD).

Figure 5-4 The Eden catchment overview



The grey lines show the boundaries of the 25 catchments in the Eden system (Dow Beck not shown).

Figure 5-5 The Eden hydrological system



The grey lines show the boundaries of the 25 catchments in the Eden system (Dow Beck not shown).

5.1.3.2 Geology, geomorphology and soils

The solid geology of the Eden catchment consists of highly altered metamorphic rocks and thick sedimentary series. At the upstream end of the River Eden catchment, the moorland is characterised by Millstone Grit. The high ground to the south-west, source of the Rivers Eamont and Caldew, is made of impermeable metamorphic rocks of the Borrowdale Volcanic and Skiddaw Slate series. In the middle reaches of these tributaries, along with the upper Petteril, the solid geology is formed of Carboniferous Limestones, while lower reaches and the Eden itself lie above the permeable Penrith Sandstones. The eastern watershed is defined by a Carboniferous rock escarpment, generally dipping to the east and therefore removing groundwater from the catchment. However, there are numerous small, steep streams which quickly run off the escarpment to the River Eden. The area between the escarpment and the River Eden is composed of lower-permeability St Bees Sandstones, which outcrop extensively around Carlisle.

The contemporary landscape is heavily influenced by Quaternary climatic change (see Chapter 2). The high fells of the Lake District and the limestone outcrops around the southern and eastern boundaries have little or no drift cover. However, most of the catchment is covered by some drift, with the thickest deposits, of diamicton, sealing the Penrith Sandstones in the central area. Alluvium is found adjacent to the Rivers Eden, Irthing and Caldew, while peat has formed in upland areas, particularly in the Irthing catchment. There are two main soil types: firstly, well-drained permeable sandy or loamy soils around the River Eden, and secondly a band of clayey or loamy over clayey soils, possibly underlain by an impermeable layer, which lies to the west.

A geomorphological study of the lower Eden indicates that the upland channels are fairly stable, single-bed, meandering gravel and cobble bed channels. In contrast, the lower reaches of the Rivers Caldew and Irthing are active and contributing significant quantities of sand and gravel to the lower Eden. The River Eden is largely unmodified by hard engineering but livestock erosion of the river banks is common in the middle sections of the Eden, Irthing, Caldew and Petteril (Environment Agency, 2008).

5.1.3.3 Hydrology, flood history and current flood risk

Precipitation is strongly influenced by catchment topography, and varies from over 2,800 mm per year in the highest upland areas to less than 800 mm per year around Carlisle and the low-lying coastal fringe. The hydrology of the Eden catchment is complex and each sub-catchment responds differently. In general, the topography and geology of the upper catchment areas lead to fairly rapid runoff, with resulting times to peak being typically less than 12 hours. In the lower catchment, runoff is moderated by lower topography, floodplain storage and distance downstream, producing times to peak of about 40 to 50 hours. Peak flows are summarised in Table 5-3.

Table 5-3 Catchment areas and peak flows

Catchment	Area (km^2)	Location of flow	Q_{MED} (m^3s^{-1}) from FEH	100 year flow (m^3s^{-1})	Highest recorded flow (m^3s^{-1}) and year
Eden	1,158	Temple Sowerby	257	587	391 (2005)
Eamont	410	Udford	173	335	316 (1985)
Irthing	333	Greenholme	132	260	278 (2005)
Petteril	164	Harraby Green	28	76	83 (2005)
Caldew	258	Holme Head	86	242	204 (1984)
Eden	2,400	Sheepmount (Carlisle)	604	1,275	1,479 (2005)

Adapted from Atkins (2005).

There is a long history of flooding problems in the Eden catchment, especially in Carlisle where key tributaries join the Eden, but also at Appleby (22 significant events since 1822), Penrith and Eamont Bridge. The flooding of January 2005 was particularly severe. In Carlisle, flows through the Eden Bridge were 1 m higher than the 1822 flood mark (Environment Agency, 2005b) and the previous highest recorded flow (1,075 cumecs[22] recorded in 1987) was exceeded by 38%; more than 1,900 properties were flooded. The same event caused flooding of properties upstream: 53 in Appleby (from the River Eden), 35 in Penrith (Thacka Beck) and 35 in Eamont Bridge (Eamont/Lowther). The source of flooding was largely fluvial, although surface water drains and sewerage infrastructure also contributed.

The Eden CFMP (Environment Agency, 2005f) considers current flood risk in relation to three different receptors: people, property and the environment. The risk to people is based on guidance contained in Ramsbottom (2003) and considers the rate of rise of and means of flooding, time available to react to flood warnings, flood depth and velocity of flow. The risk was ranked as high or extreme for the principal communities (see Table 5-4). A total of 2,760 residential properties are at risk from flooding in a 1% APE, along with key transport routes, schools, hospitals and emergency services' facilities. The expected annual average damage to property and agriculture is £39.5 million. There are also risks to environmental assets, although many sites benefit from flooding as seasonal inundation is part of the habitat's natural system.

The Social Flood Vulnerability Index (Tapsell *et al.*, 2002) highlights populations particularly vulnerable to flooding. Within the Eden catchment there is a high number of wards at risk from flooding where the SFVI is 4 (high), particularly in Carlisle (Environment Agency, 2008).

[22] Cubic metres per second.

Table 5-4 Flood risk to communities in the Eden catchment

Community	Flood depth in 1% APE (m)^	Risk to people	Economic damage (£M AAD)
Appleby	3.2	High	1.6
Penrith	1.4	Extreme	0.9
Eamont Bridge	1.4	High	0.1
Eden Valley: Warwick Bridge, Low Crosby	3.3	Extreme	0.3
Carlisle	3.2	High	7.6
Carlisle (Denton Holme)	1.3	Extreme	

From Environment Agency (2008). ^Excluding effect of flood defences.

5.1.3.4 Flood risk management

Current flood risk management measures include flood defence and flood warning. Flood defences are mainly embankments and are located throughout the catchment, including in the upper reaches of the Caldew and Eamont sub-catchments, Appleby and in Carlisle and on the lower Eden. In total there are 63 km of defences, of which 7 km protect the main urban areas, with the remainder defending agricultural land. The urban defences offer a standard of protection of 1% annual probability in Appleby and between 2% and 10% annual probability in Carlisle (although the latter are being improved).

There are five Flood Warning Areas covering a total of 3,500 properties. The Environment Agency provides a Flood Warning Service to these areas with a minimum warning time of one hour.

5.1.3.5 Land use

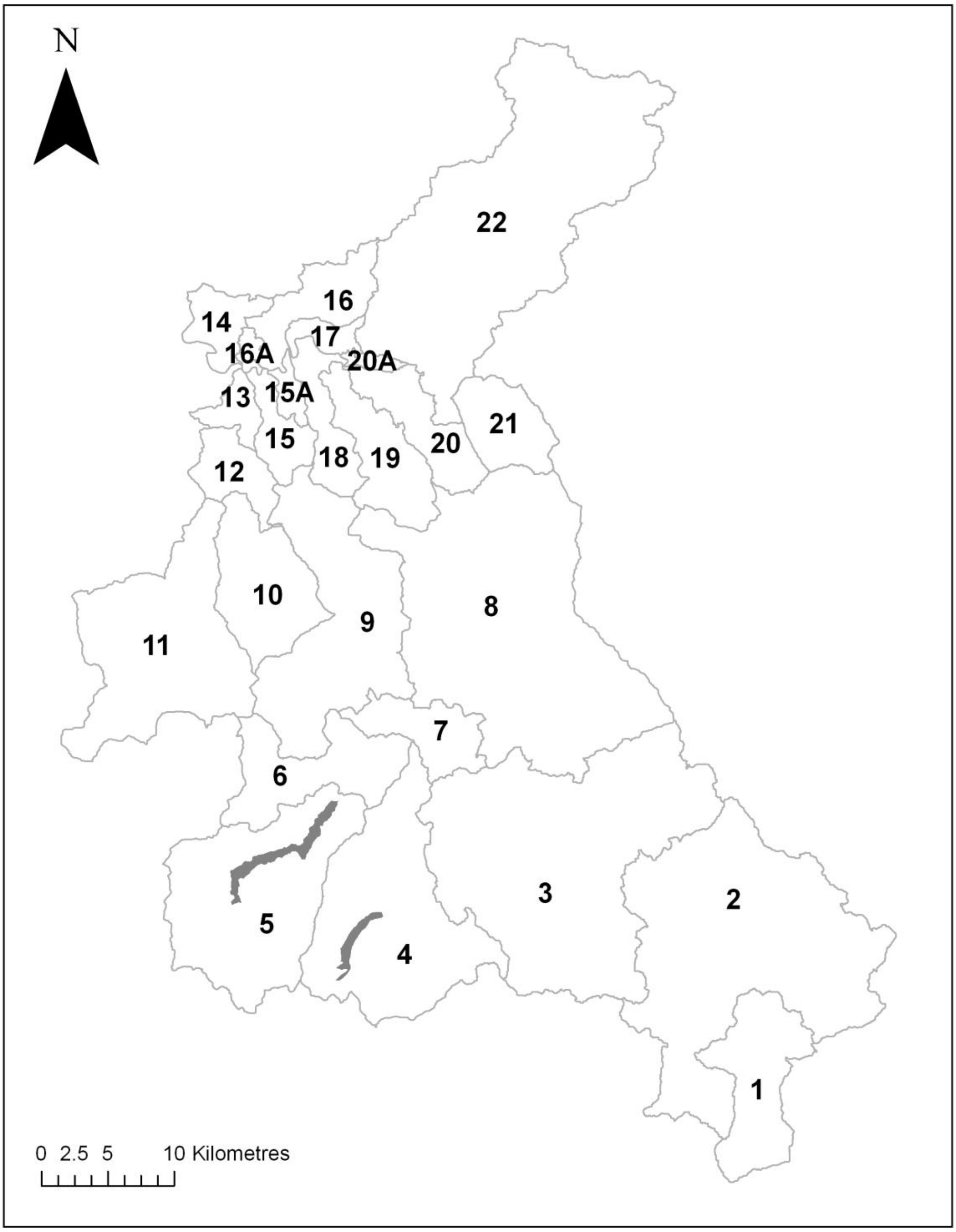
The River Eden catchment is largely rural, with land use dominated by low-grade agricultural land. Approximately 244,000 people live in the catchment, largely in Carlisle, Penrith and Appleby, with only 1% of the land area classified as urban. Agriculture accounts for 94% of land area, with 4% of this being Grade 1 or 2, 36% being Grade 3, and 54% being Grade 4 or 5 (of poor quality). The remaining 5% of land relates largely to the Wark Forest, in the north-east of the catchment. Tourism and recreation are important elements of the local economy, which includes hill walking and water-based activities at Ullswater and on the River Eden.

5.1.3.6 Hydrological and hydraulic models

A number of models have been used to map floodplain extent (Section 105 models) and to inform local flood defence strategies. The Lower Eden and Carlisle Strategy model, described in Atkins (2006a), updates the former Section 105 model and covers the River Eden and tributaries including the Eamont, Lowther, Caldew, Irthing and Petteril. The model is based on inflows from 26 catchments (see Figure 5-6 and Table 5-4) which are routed in a hydraulic model. It has been implemented in the Halcrow model ISIS. The inflows are calculated using FEH and can be generated statistically (for design events) or using the FEH rainfall–runoff model (Houghton-Carr, 1999). The latter, further described in Section 7.3, is used to calibrate and validate historical events. Three calibration events (February 1990, February 1995 and January 1999) are used to assess the effects of climate change in this thesis[23]. Flows are routed using the ISIS hydraulic model in which flow depths and discharges are calculated using the Saint-Venant equations, with unsteady conditions solved using the Preissmann four-point implicit finite difference scheme[24].

[23] No calibrated model for the January 2005 event was available; the 2009 floods in Cumbria did not severely affect the Eden.
[24] ISIS User Manual (in ISIS Free software)

Figure 5-6 The Eden model catchments



Dow Beck not shown.

Table 5-4 Catchments of the Eden and characteristics

#	Name^	Area (km^2)	SOIL	SPR	SAAR (mm)	URBEXT (%)
1	Headwaters of the Eden[ed1]	67.93	0.34	86.0	1484	0.3
2	Tributaries of the Upper Eden[ed2]	267.60	0.34	73.4	1085	0.0
3	Tributaries of the Upper Middle Eden[ed3]	281.50	0.32	60.8	1072	0.2
4	River Lowther	156.13	0.48	46.3	1828	0.1
5	Upper Eamont and Ullswater[ea1]	149.31	0.50	59.6	2148	0.1
6	Tributaries of the Middle Eamont[ea2]	65.35	0.46	51.2	1395	0.1
7	Tributaries of the Lower Eamont[ea3]	36.90	0.40	43.6	915	10.8
8	Tributaries of the Lower Middle Eden[ed4]	299.70	0.28	18.9	963	0.1
9	Upper Petteril[p1]	141.82	0.41	39.6	958	0.1
10	River Roe	67.91	0.45	38.3	975	0.1
11	Upper Caldew[c1]	147.84	0.46	48.9	1402	0.0
12	Tributaries of the Middle Caldew [c2]	27.39	0.45	27.6	852	0.0
13	Tributaries of the Lower Caldew [c3]	16.82	0.38	34.6	808	2.7
14	Cargo and Rockcliffe Becks	23.07	0.41	42.1	818	16.5
15	Tributaries of the Lower Petteril[p2]	22.55	0.19	18.7	823	0.1
15A	Durranhill and Wash Becks	8.13	0.15	8.2	794	11.1
16	Brunstock Beck	39.15	0.23	17.9	854	0.3
16A	Gosling and School Sikes	4.80	0.15	6.4	811	16.4
17	Gill Gutter and Willow Beck	11.22	0.15	9.8	825	0.0
18	Pow Maughan	30.55	0.15	12.2	804	0.5
19	Tributaries of the Lower Eden[ed5]	49.30	0.15	10.4	816	0.5
20	Cairn and Trout Becks	40.81	0.23	20.0	873	0.3
20A	Greenholme Beck	4.37	0.15	9.5	831	0.0
21	Upper Gelt	38.95	0.50	56.9	1157	0.0
22	River Irthing	294.45	0.45	72.5	1071	0.2
	Dow Beck	2.35	unknown	37.8	830	34.0

^Names attributed from 1 in 10,000 map, with further detail: [c1] to Highwath Bridge; [c2] Highwath Bridge to Cummersdale Bay; [c3] Cummersdale Bay to Eden confluence; [ea1] to just downstream of Ullswater; [ea2] just downstream of Ullswater to Eamont Bridge; [ea3] Eamont bridge to Eden confluence; [ed1] to just downstream of Kirkby Stephen; [ed2] just downstream of Kirkby Stephen to just upstream of Appleby; [ed3] just upstream of Appleby to just upstream of the Crowdundle Beck confluence; [ed4] just upstream of the Crowdundle Beck confluence to Armathwaite Bridge; [ed5] Armathwaite Bridge to just downstream of Warwick Bridge; [p1] to Scalesceugh Hall; [p2] Scalesceugh Hall to Eden confluence. *Dow Beck lies to the north of the River Eden in north-west Carlisle and was assumed to have the same precipitation change factors (see Section 7.3.2) as catchment 16A. Area, SPR, SAAR, URBEXT from Eden FEH rainfall–runoff model. SOIL from Flynn and Rothwell (2000).

5.2 Scoping assessment

5.2.1 Method

The DP-S-I-R scoping framework (Turner, 2005) is used to facilitate the identification of driving pressures that affect flood risk in the case study catchments in terms of environmental, social and economic impacts, and to draw out current responses. As discussed in Chapters 3 and 4, the Foresight Future Flooding study contained a comprehensive review of flood risk drivers (Evans *et al.*, 2004a); these are used in this scoping exercise as generic drivers from which specific catchment drivers are defined. Similarly, the Foresight Future Flooding study also reviewed response groups (Evans *et al.*, 2004b); these are used here to classify the range of flood risk management measures currently employed in the Bedford Ouse and Eden catchments. The scoping exercise concentrates on current drivers and responses to flood risk, drawing on Section 5.1 above, but also considers driver and response sensitivity based on an understanding of the flooding process within each catchment. This ensures that sensitive drivers and responses which are currently less significant, or for which there is little evidence at present, are also taken forward for assessment in the future scenario analysis. Finally, the scoping assessment identifies a number of exemplar receptors, for which detailed scenarios will be prepared and modelling undertaken (see Chapters 6 and 7 respectively).

5.2.2 Bedford Ouse catchment

Current driving pressures of flood risk in the Bedford Ouse catchment are described in Table 5-5. Evidence (third column) has been collated from catchment-related documents including the CFMP (reviewed in Section 5.1.2), the Water Framework Directive Characterisation Report for the Anglian River Basin District (Defra, 2005b) and knowledge of the catchment gained through field visits and various Atkins projects for the Environment Agency, in particular through compilation of the Environmental Impact Assessment for the St Ives and Hemingfords Flood Alleviation Scheme. Based on the evidence a subjective classification of significance (fourth column) has been made, with the most significant driving pressures of flood risk in the Bedford Ouse catchment identified as:

- Climate change.
- Buildings and contents.
- Urban impacts.

Table 5-5 Current driving pressures of flood risk in the Bedford Ouse catchment

Scenario driver*	**S-P-R^ type**	**Evidence for driving *pressure***	**Significance#**
Climate (change): precipitation and temperature	Source	Prolonged heavy rainfall was trigger for recent flood events; snowmelt was significant in 1947.	+++
Catchment land use and management	Pathway	Potentially significant, but evidence limited. Several urban areas in upper and mid catchment. However, runoff balancing for Milton Keynes and in Marston Vale.	++
Floodplain land use and management	Pathway	Urbanisation and infrastructure, including flood defences, affect the pathway of floods, although there remains significant floodplain storage in areas managed for habitat and grazing.	++
Agricultural impacts	Receptor	Agricultural AAD £0.2M (<0.5% of total AAD); however, agricultural impacts were significant in 1947 flood[25].	++
Environmental regulation	Pathway	Floodplain connectivity historically reduced, but current activity aims to improve this; CFMP promoting whole-catchment approach.	+
River morphology and sediment supply	Pathway	Most of Bedford Ouse and some tributaries provisionally classified under WFD as heavily modified; modifications include straightening, dredging, in-channel structures (e.g. locks) and raised banks relating to infrastructure construction, navigation and flood control.	++
River vegetation and conveyance	Pathway	River vegetation managed for flood control, navigation and habitat; conveyance affected by in-stream locks and also bridges.	+
Stakeholder behaviour	Pathway and Receptor	Professionally led engineering-based approach demanded by public in response to floods; environmental agencies desire a more holistic approach.	++
Buildings and contents	Receptor	8,846 properties in high-impact areas of Zone 3; schools and police stations at risk; extensive property flooding in Easter 1998, Autumn 2000 and January 2003 events.	+++
Urban impacts	Receptor	Urban areas at risk include historical town centres, Victorian terraces and more recent developments including flats and houses; pressure for further development including an increase in density.	+++
Infrastructure impacts	Receptor	Infrastructure at risk includes major national road and rail infrastructure; evidence of flooding of local roads.	++
Social impacts	Receptor	SFVI generally low to average; lack of evidence from flooding events, but high potential for disruption and isolation of small communities.	++

*Scenario drivers adapted from Foresight Future Flooding study (Evans *et al.*, 2004a). ^Source-Pathway-Receptor. #Significance: +++ = very significant; ++ moderately significant; + minor to insignificant.

[25] The *Hunts Post* describes a “Farmers’ Tragedy” with damage to building and stock (*Hunts Post*, Thursday 27 March 1947).

Current responses to flood risk are summarised in Table 5-6 under the response groups used in the Foresight Future Flooding study (Evans *et al.*, 2004b). Evidence has been collated from the CFMP and knowledge of the catchment. Based on this, a subjective classification of significance has been made, with the most significant current responses to flood risk in the Bedford Ouse catchment identified as:

- Forecasting and warning (although the benefits are somewhat unknown given that they are mediated by other actions such as individual damage avoidance).
- Land-use planning.
- Insurance.
- River defences.

There are a number of important receptors in the Bedford Ouse catchment as described in Section 5.1.2. Rather than assessing flood risk across the entire floodplain, this research focuses on a number of exemplar receptors. Future flooding will be assessed at the following receptors (in order downstream; see Figure 5-7):

- Bedford Ouse at Newport Pagnell, to demonstrate the application of the stochastic weather generator, which is limited to the upper catchment (see Section 7.2).
- Bedford Ouse at Offord, close to the location of the abstraction to Grafham Water.
- Mill Channel at Godmanchester, which has experienced recent flooding.
- Portholme Meadow, a European Special Area of Conservation (SAC) sensitive to water levels, on the Bedford Ouse floodplain.
- Bedford Ouse at St Ives, which has experienced recent flooding and is now protected by a flood defence scheme.
- Fen Drayton Lakes, in the floodplain downstream of St Ives.
- Bedford Ouse just upstream of Brownshill Staunch, the tidal limit.
- Bedford Ouse at the inflow to the Ouse Washes (near Earith), a winter flood storage area which has become designated as a European Special Protection Area (SPA), SAC and Ramsar site.

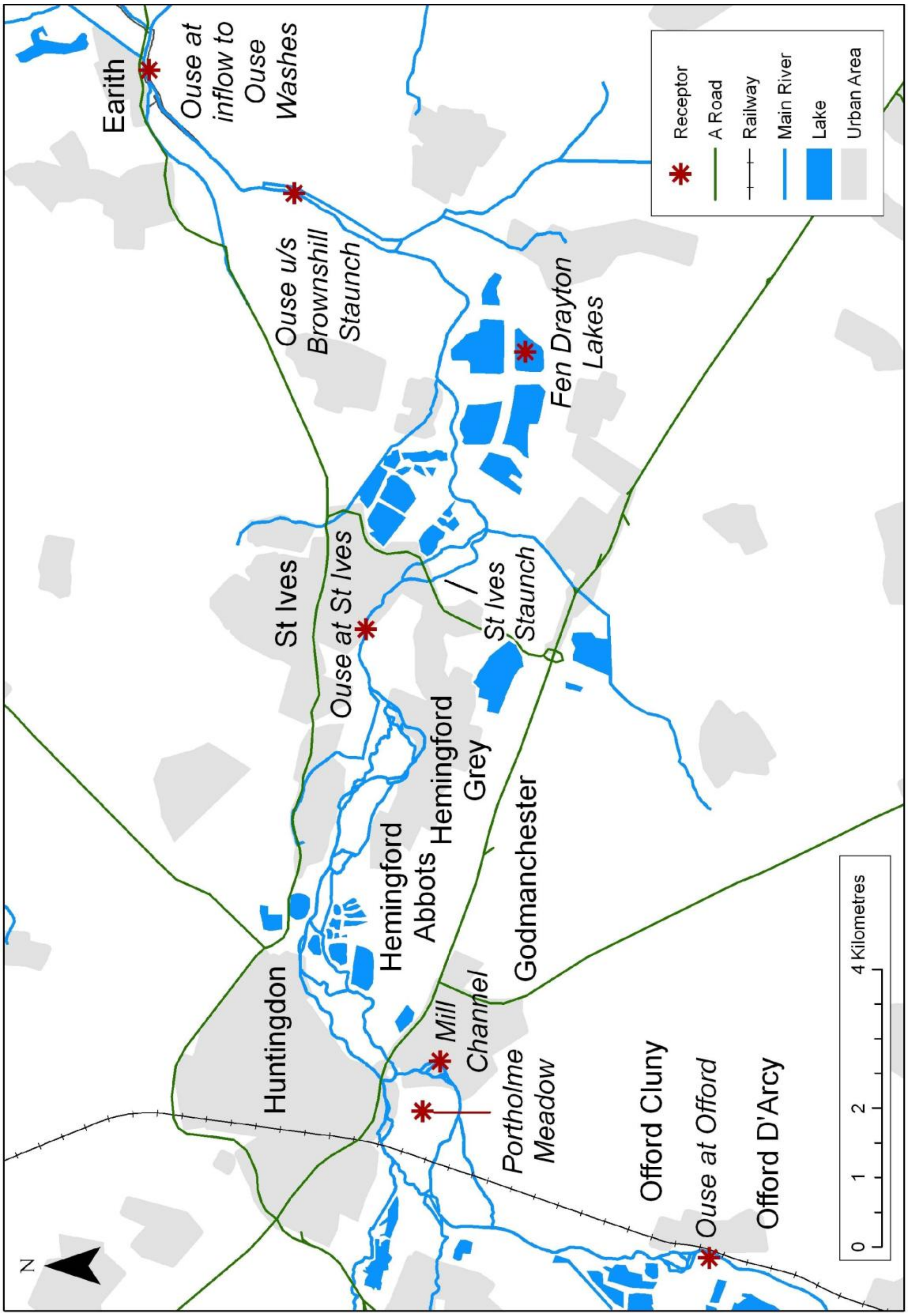
Table 5-6 Current responses to flood risk in the Bedford Ouse catchment

Response group*	S-P-R^ type	Evidence of use	Signifi-cance#
Rural infiltration	Pathway	Unknown, although afforestation in Marston Vale.	+
Catchment-wide storage	Pathway	Local storage e.g. upstream of Towcester; re-creation of wetlands along valley including former gravel pits; Ouse Washes downstream.	++
Rural conveyance	Pathway	Management of vegetation e.g. weed cutting and dredging (at least partly for navigation)	+
Urban storage	Pathway	Attenuation of runoff from Milton Keynes.	++
Urban infiltration	Pathway	Limited to new development.	+
Urban conveyance	Pathway	Generally concerned with rapid removal.	+
Pre-event measures	Pathway and Receptor	Environment Agency publicity; media coverage of events increases awareness.	+
Forecasting and warning	Pathway and Receptor	Environment Agency implementation of flood forecasting system, plus warning via Floodline (although benefits unknown as mediated by other responses).	+++
Flood fighting actions	Pathway and Receptor	Adjustment of control structures, including locks and closing of gates; emergency response.	++
Collective damage avoidance actions	Receptor	Limited.	+
Individual damage avoidance actions	Receptor	Unknown.	+
Land-use management	Receptor	No relocation.	+
Flood-proofing	Receptor	Unknown.	+
Land-use planning	Receptor	Implementation of PPG and PPS25.	+++
Building codes	Receptor	Flood resistance not a requirement in Schedule 1 of Building Regulations 2000 (ODPM, 2004), but advice exists on flood resistance and resilience (e.g. CLG, 2007)	+
Insurance, shared risk and compensation	Receptor	Reliance on private insurance; Bellwin Scheme payment to Huntingdonshire District Council in relation to Easter 1998 floods (DTLR, 2001b).	+++
Health and social measures	Receptor	Unknown.	+
River conveyance	Pathway	Limited; some improvement of floodplain conveyance around St Ives.	+
Engineered flood storage	Pathway	Local storage e.g. upstream of Towcester.	+
Floodwater transfer	Pathway	Limited e.g. pumped removal of flood-locked outfalls.	+
River defences	Pathway	Commonly used response for towns and villages.	+++

*From Foresight Future Flooding study (Evans *et al.*, 2004b). ^Source-Pathway-Receptor. #Significance: +++ = very significant; ++ moderately significant; + minor to insignificant.

Figure 5-7 Selected receptors in the lower part of the Bedford Ouse catchment

Original in colour.



5.2.3 Eden catchment

Current driving pressures of flood risk in the Eden catchment are described in Table 5-7. Evidence (third column) has been collated from catchment-related documents including: the CFMP Scoping Report (reviewed in Section 5.1.3); reviews of the January 2005 floods (Environment Agency, 2005b, 2006a; GONW, 2005); the *Water Framework Directive Characterisation Report* (SEPA and Environment Agency, 2005) and *Interim Overview of Significant Water Management Issues in the Solway–Tweed River Basin District* (SEPA and Environment Agency, 2007); the *Catchment Abstraction Management Strategy* (Environment Agency, 2006b); the *River Eden cSAC Conservation Strategy* (Locke and Robinson, 2003); and knowledge of the catchment gained through a field visit and various Atkins projects for the Environment Agency. Based on the evidence a subjective classification of significance (fourth column) has been made, with the most significant driving pressures of flood risk in the Eden catchment identified as:

- Climate change;
- Buildings and contents;
- Urban impacts;
- Infrastructure impacts;
- Social impacts.

Current responses to flood risk are summarised in Table 5-8 under the response groups used in the Foresight Future Flooding study (Evans *et al.*, 2004b). Evidence has been collated from the CFMP (Environment Agency, 2005f, 2008) and knowledge of the catchment. Based on this, a subjective classification of significance has been made, with the most significant current responses to flood risk in the Eden catchment identified as:

- Forecasting and warning (although the benefits are somewhat unknown given that they are mediated by other actions such as individual damage avoidance);
- Land-use planning;
- Insurance;
- River defences.

Table 5-7 Current driving pressures of flood risk in the Eden catchment

Scenario driver*	S-P-R^ type	Evidence for driving pressure	Significance#
Climate (change): precipitation and temperature	Source	Heavy rainfall initiated flood events such as January 2005.	+++
Catchment land use and management	Pathway	Rural and agricultural, with little natural attenuation of rainfall and high percentage of runoff; reservoirs and lakes can offer flood attenuation e.g. Haweswater in January 2005; policy to reverse gripping.	++
Floodplain land use and management	Pathway	Urbanisation and infrastructure, including flood defences, affect the pathway of floods, particularly in Carlisle where there is a strong interaction with surface water flooding.	++
Agricultural impacts	Receptor	AAD £0.3M (<2% of total AAD); agricultural land protected by 56 km of defences.	+
Environmental regulation	Pathway	Relatively low pressure, in an attempt to maintain river habitat integrity; wetland floodplain areas reduced by drainage, although some floodplain woodland designated as cSAC.	+
River morphology and sediment supply	Pathway	Relatively few morphological pressures realised; active channels; increasing use of more sympathetic erosion control measures; several actions aimed at silt control to ensure integrity of salmon habitat.	+
River vegetation and conveyance	Pathway	Weed cutting and tree management undertaken in some places; few in-channel structures; conveyance generally unaffected, except by some bridges e.g. Eamont Bridge and in Carlisle.	++
Stakeholder behaviour	Pathway / Receptor	Professionally led engineering-based approach demanded by public in response to floods; environmental agencies desire a more holistic approach.	++
Buildings and contents	Receptor	>3,000 properties at risk from 1% APE, including several related to healthcare, emergency services and schools. January 2005 event flooded 2,700 residential properties; police station, fire & rescue station and council properties in Carlisle flooded. Costs estimated at £0.45–0.50M.	+++
Urban impacts	Receptor	Urban areas at risk include historical city and town centres, retail, industrial and residential. In Carlisle the floodplains of the Caldew, Petteril and Eden are heavily developed.	+++
Infrastructure impacts	Receptor	Infrastructure at risk includes A roads, railways (including West Coast Mainline), power and waste water infrastructure. Evidence of flooding of railways, roads and power infrastructure.	+++
Social impacts	Receptor	High SFVI, particularly in Carlisle. January 2005 floods: two elderly residents died in their homes and there was long-term disruption to lives and health effects.	+++

*Scenario drivers adapted from Foresight Future Flooding study (Evans *et al.*, 2004a). ^Source-Pathway-Receptor. #Significance: +++ = very significant; ++ moderately significant; + minor to insignificant.

Table 5-8 Current responses to flood risk in the Eden catchment

Response group*	**S-P-R^ type**	**Evidence of use**	**Signifi-cance#**
Rural infiltration	Pathway	CFMP states need to use environmental stewardship schemes to help reduce runoff; cSAC Conservation Strategy action to reverse gripping.	+
Catchment-wide storage	Pathway	Preferred CFMP policy for rural Caldew and Petteril is to increase storage.	++
Rural conveyance	Pathway	River maintenance and bank stabilisation at some locations.	+
Urban storage	Pathway	None.	+
Urban infiltration	Pathway	Unknown.	+
Urban conveyance	Pathway	Generally concerned with rapid removal.	+
Pre-event measures	Pathway and Receptor	Environment Agency publicity; media coverage of events increases awareness.	++
Forecasting and warning	Pathway and Receptor	Environment Agency flood forecasting system; warning service covers nearly 2,000 properties with a good uptake.	+++
Flood fighting actions	Pathway and Receptor	Emergency response, including pumps, defence raising and closing flood gates.	++
Collective damage avoidance actions	Receptor	Evacuation in some areas in January 2005.	++
Individual damage avoidance actions	Receptor	Unknown.	+
Land-use management	Receptor	No relocation.	+
Flood-proofing	Receptor	Unknown.	+
Land-use planning	Receptor	Implementation of PPS25.	+++
Building codes	Receptor	Flood resistance not a requirement in Schedule 1 of Building Regulations 2000 (ODPM, 2004), but advice exists on flood resistance and resilience (e.g. CLG, 2007).	+
Insurance, shared risk and compensation	Receptor	Reliance on private insurance; Bellwin scheme payments to Cumbria County Council of £1.1M after January 2005 flood (Environment Agency, 2006a).	+++
Health and social measures	Receptor	Unknown.	+
River conveyance	Pathway	None.	+
Engineered flood storage	Pathway	Scheme being considered upstream of Penrith; setting back of defences on Petteril, but not formal storage.	+
Floodwater transfer	Pathway	Limited e.g. scheme to pump water from Little Caldew to River Caldew.	+
River defences	Pathway	63 km of river defences protecting urban (7 km) and agricultural areas (56 km).	+++

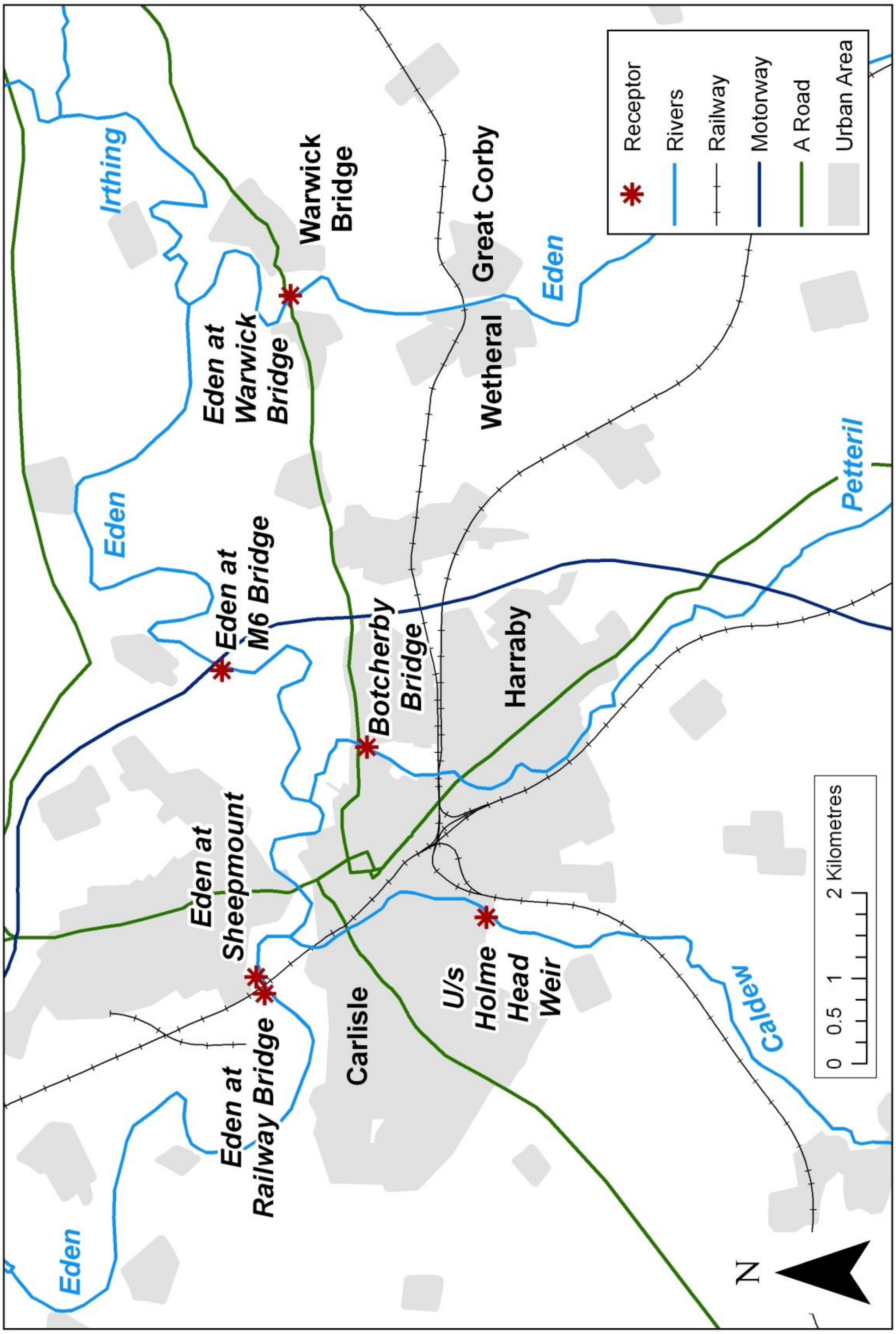
*From Foresight Future Flooding study (Evans *et al.*, 2004b). ^Source-Pathway-Receptor. #Significance: +++ = very significant; ++ moderately significant; + minor to insignificant.

There are a number of important receptors in the Eden catchment as described in Section 5.1.3. Rather than assessing flood risk across the entire floodplain, this research focuses on a number of exemplar receptors. These are focused in and around Carlisle (see Figure 5-8), which has experienced a number of serious floods, especially in January 2005. The following specific locations will be considered:

- Warwick Bridge (upstream of Carlisle and the Irthing confluence, but an historical gauging station);
- M6 Motorway Bridge;
- Botcherby Bridge (on the River Petteril);
- Holme Head Weir (at Denton Holme, the area of Carlisle through which the River Caldew passes);
- West Coast Mainline Railway Bridge;
- Sheepmount (downstream of the confluences, and an important gauging station adjacent to Carlisle’s city centre).

Figure 5-8 Selected receptors in the lower part of the Eden catchment

Original in colour.



6. Baseline climate

This chapter provides an assessment of baseline climate for both case study catchments introduced in Chapter 5. These form the baselines against which future climate change scenarios are assessed. This is preceded by a review of methods for producing baseline areal precipitation and PET, with particular reference to the Bedford Ouse catchment (the Eden catchment model does not require areal inputs, although areal data is used for bias correction; see Section 7.3).

6.1 Methods for producing baseline areal precipitation and PET

6.1.1 Introduction

The common baseline climate period used in recent climate change scenarios (e.g. Hulme *et al.*, 2002), and therefore impacts studies, is the World Meteorological Organization thirty year climate period 1961–1990. This period is considered to be suitably recent and reliable in terms of data coverage and quality. Climate change scenarios are typically presented *relative* to this period, and a future climate is therefore a combination of one of these scenarios and the baseline climate. (As noted in Chapter 3, there are reliability problems associated with the future climatology directly output by climate models.)

A variety of methods are used for deriving historical climate sequences. Of particular importance for rainfall–runoff modelling is the derivation of areal precipitation records; PET is conventionally computed in spatial (gridded) form, for example MORECS and MOSES (see below), and temperature (only significant for snowmelt) is generally less spatially variable and therefore can more adequately be represented by station data (and can be estimated from more distant sites).

6.1.2 Areal precipitation

This section begins with a brief comparison of methods for producing areal precipitation. Four datasets, representing three different methods, are then applied to the Bedford Ouse catchment to examine differences in areal precipitation at different temporal resolutions. The implications of these differences are assessed through a limited modelling exercise for the Bedford Ouse catchment. Finally, conclusions are drawn on which method to use in this thesis.

6.1.2.1 Comparison of methods

A comparison of different methods of producing areal precipitation series has been undertaken (Table 6-1). This excludes radar data, which is limited historically. The differences between approaches largely relate to the method of spatial interpolation between point (station) data. Further detail regarding each method is provided below.

The typical approach in preparing input data for rainfall–runoff modelling is to interpolate station data using Thiessen polygons (Thiessen, 1911), which weight the contribution of individual rainfall records to the catchment total by the Thiessen co-efficient, defined as the proportion of the catchment area represented by each gauge. The method is objective, but depends on a good network of representative gauges, does not take into account other spatial factors such as elevation, and is not a reliable method for calculating areal rainfall from intense local storms (Shaw, 1994).

Table 6-1 A comparison of methods for producing areal precipitation series and potential method of perturbation for use in climate change impact studies

Method of deriving (baseline) areal precipitation series	Application	Spatial unit	Timestep*	Potential method of climate change perturbation^
Gauge + Thiessen polygon (area only)	Rainfall–runoff modelling	Catchment	Any, subject to gauge data	CF approach based on statistical or dynamic downscaling
Gauge + inverse-distance weighted interpolation of regression residuals	Met Office records; baseline for use in climate change impact assessment.	5 km by 5 km grid	LTA (Perry and Hollis, 2005a), monthly (Perry and Hollis, 2005b), daily	CF approach based on dynamic downscaling; advanced CF approach plus stochastic weather generator included in EARWIG using UKCIP02 and PRUDENCE scenarios (Kilsby, 2006); bias correction of multiple GCMs (Vidal and Wade, 2008)
Met Office monthly 1 km by 1 km grid overlain by catchment	NRFA Catchment Annual Average Rainfall#; FEH Standard Average Annual Rainfall	Catchment	LTA only	CF approach based on dynamic downscaling

*LTA = long-term average; ^CF = change factor; #As quoted in the National River Flow Archive (NRFA) Gauging Station Summary Sheets.

More advanced interpolation typically combines information from secondary variables (or covariates) for example elevation and distance from coast, using cokriging or geostatistical methods. For example, Perry and Hollis (2005b) have generated monthly 5 km by 5 km gridded datasets for 36 climatic parameters over the UK. They used a Geographical Information System (GIS) in a two-stage process of multiple regression with geographic factors as the independent variables, followed by inverse-distance weighted interpolation of the model residuals, with the two resulting surfaces added. For precipitation, the regression was based on easting and northing only; additionally normalisation was used, with raw values divided by the long-term average (LTA), to remove long-term patterns including altitude dependency. The R squared statistic of the regression model was 0.44 for precipitation (based on the 1961–2000 average and for the whole of the UK) and it is likely that this was reduced by the normalisation process. Climate Memorandum 24 (Perry *et al.*, 2009) describes the method used to produce the most recent set of daily gridded data (which replaces the earlier output discussed below). For this, station data was normalised using monthly 1 km by 1 km gridded data (see below) and then interpolated using inverse-distance weighting.

The National River Flow Archive (NRFA) quotes catchment-average annual rainfall for most gauging stations. The averages are produced by the Centre for Ecology and Hydrology (CEH) by laying the catchment over a 1 km by 1 km grid of 1961–1990 annual average rainfall totals, which are constructed by the Met Office using monthly average rainfall grids for the UK (Terry Marsh, CEH, personal communication). This appears to be the same method as used to generate Standard Average Annual Rainfall (SAAR) in FEH (Bayliss, 1999), although there are some differences for the Eden catchments examined. The method used by the Met Office to construct the monthly 1 km by 1 km gridded rainfall dataset is unknown; although it is still too coarse temporally to be used as an input to flood modelling, it does provide a useful check for other methods.

6.1.2.2 Application of methods to the Bedford Ouse catchment

A detailed trial and comparison of four different datasets (representing three different methods) of areal precipitation series has been undertaken for the Bedford Ouse, for the whole catchment and for the upper catchment above Newport Pagnell. Areal series and long-term averages were produced using each method as follows:

- **Thiessen polygon**. These data were available for the 21 Bedford Ouse catchments from the Bedford Ouse model calibration and validation period of February 1993 to March 2002 at sub-daily level, although data was abstracted from MIKE11 for the nine complete input hydrological years of October 1992 to September 2001. Initially data was abstracted from MIKE11 using the time-interpolation function, which attempts to interpolate for missing values. However, this method led to an underestimation of total rainfall. Therefore the previously spatially interpolated tipping bucket rainfall (TBR) (catchment areal average) data was extracted, and then aggregated to the daily level and to an annual average.

- **UKMO gridded**. This data, consisting of text files of daily 5 km by 5 km gridded precipitation for the period 1958–2005, was made available[26] under licence from the Met Office. Data were extracted for the cells of interest using a VBA macro[27]. The cells of interest were identified by laying the 21 catchment boundaries over the 5 km by 5 km grid in ArcMap (see Figure 6-1); this process also identified the contribution of each square to each catchment[28]. The extracted values were checked using the GIS. The areal series for each catchment was computed by totalling the rainfall from the contributing areas and dividing by the total area; long-term averages were also calculated.
- **EARWIG**[29]. Areal series are computed automatically by the weather generator on a daily basis for the period 1961–1990. However, a set of checks were made on an area and AAR basis to verify the default choice of UKMO grid cell selection. The rule applied in EARWIG is that the cell is incorporated if the centroid is within the catchment. This was compared with three alternatives: an area-based method where the cell is incorporated if at least half of the cell is within the catchment; and two further methods based on visual inspection, which tried to balance residual areas. Overall the best method, based on area and baseline AAR (which may not be the same for flood-generating rainfall), was the area-based method, which matched the true catchment area and was marginally better than the UKMO rainfall in the EARWIG default area in replicating true AAR. The cells selected using this preferred method are shown in Figure 6-1. Note that the *actual* performance of EARWIG is discussed below.
- **NRFA**. The long-term (1961–1990) average annual rainfall was extracted from the National River Flow Archive.

Long-term annual averages for the baseline period of 1961–1990 are presented in Table 6-2. These show close agreement between the UKMO gridded data and NRFA averages for the whole catchment and that above Newport Pagnell. Comparisons have also been made for individual catchments and these also show a close similarity.

[26] To the University of East Anglia.
[27] Developed specifically for this thesis by Tom Rouse, Atkins.
[28] The GIS files were set up by Paul Morgalla, Atkins, who also calculated the contributions.
[29] EARWIG is the Environment Agency Rainfall and Weather Impacts Generator, designed by the Universities of Newcastle and East Anglia for use in climate change impacts assessments.

Box 6-1 EARWIG

EARWIG (Kilsby, 2006; Kilsby *et al.*, 2007) incorporates two stochastic models in series: a rainfall model and a weather generator. The rainfall model (run within the RainClim software package) is based on the Neyman-Scott Rectangular Pulses (NSRP) model. The NSRP model uses a clustering approach, which handles rainfall occurrence and amount in one process and has been shown to realistically reproduce extreme values (Kilsby *et al.*, 2007). The weather generator then uses precipitation occurrence on the preceding and current day (from the NSRP model) to determine other meteorological variables based on four different regression relationships, which also incorporate values of variables from the preceding day and a random element.

A major advantage of EARWIG is that spatial regression relationships for non-precipitation variables have been developed, based on 115 stations and geographical variables of elevation, easting, northing and distance from the coast; precipitation is based on the UKMO 5 km by 5 km gridded dataset. This means that areal weather sequences can be generated, although these must be interpreted as data for a site representative of an area, rather than an areal average (Kilsby, 2006). This is particularly pertinent where there are large local variations in variables (e.g. due to topography) and where true areal averages are required (Kilsby, 2006). In the latter case, while the representative long-term mean values from EARWIG will be the same as the areal average values, other statistics will not (Kilsby, 2006). This has particular implications for the modelling of flood events, starting with the use of rainfall–runoff models which rely on higher order (extreme) areal inputs. EARWIG has a working upper limit of 1,000 km^2 to restrict such errors. More generally it is important that areas are reasonably homogenous and avoid large differences in precipitation or temperature, for example due to elevation.

Table 6-2 A comparison of baseline areal annual average rainfall for the Bedford Ouse catchment produced using different methods

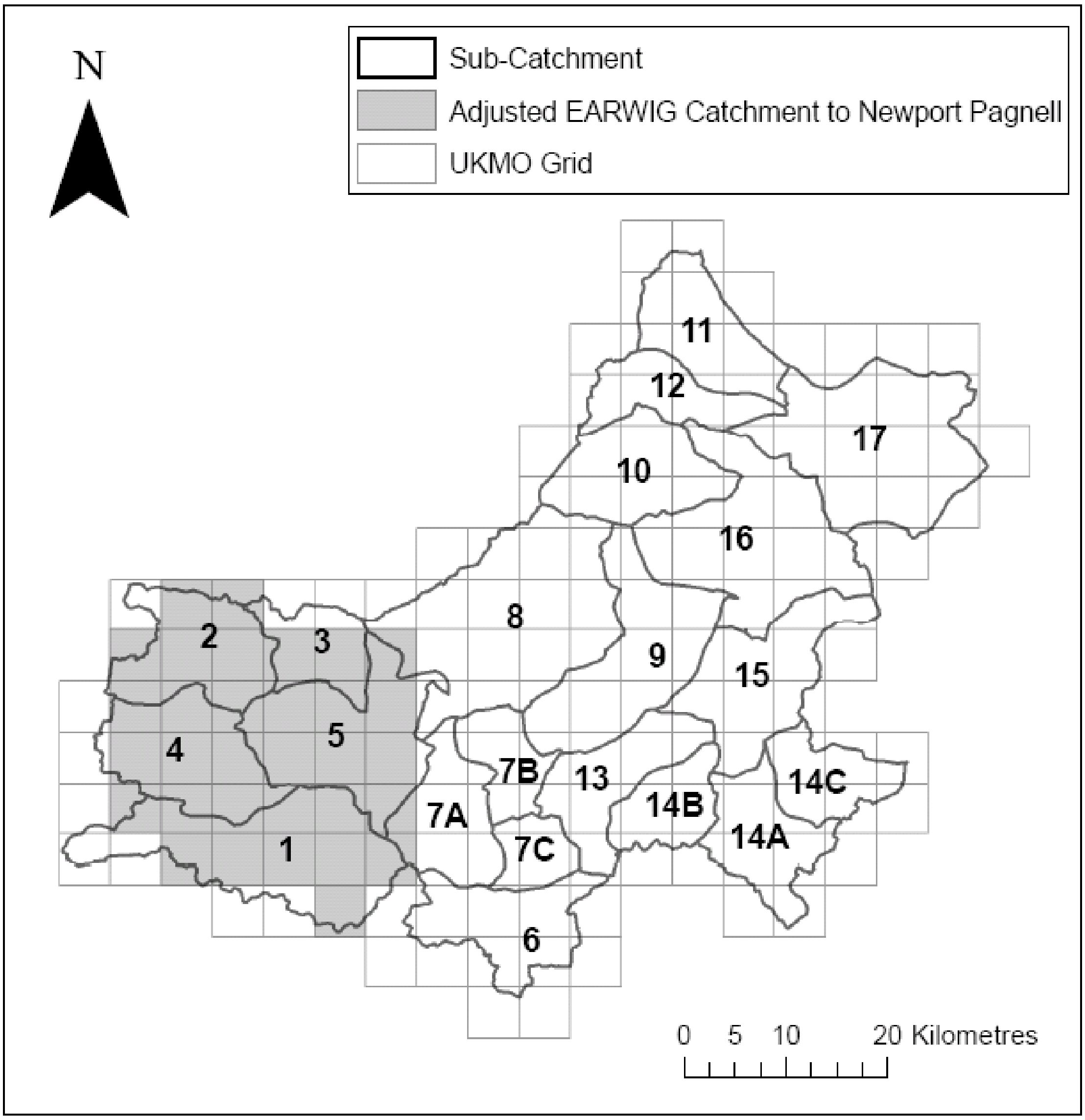
Method of deriving (baseline) areal rainfall series	Bedford Ouse above Newport Pagnell		Bedford Ouse above Brownshill Staunch	
	Area (km^2)	AAR (mm)	Area (km^2)	AAR (mm)
UKMO gridded	800.6	648	3039.2	599
EARWIG adjusted*	800.0	666	3100.0	n.a.#
NFRA^	800.0	648	3030.0	601

AAR = Annual Average Rainfall; NRFA = National River Flow Archive. *Adjusted as described above; AAR based on five simulations of 150 years in EARWIG v2.1. ^AAR corresponds to 1969–1990 average for Newport Pagnell. #Not available as EARWIG has a maximum limit of 1,000 km^2.

The EARWIG AAR for the area above Newport Pagnell[30] is just over 2.5% higher than the UKMO AAR (Table 6-2), with particularly large monthly deviations (Figure 6-2) in October, November, January (all positive) and March (negative). Intuitively, this would seem to relate to the imperfect representation of the catchment; however, a like-for-like comparison using the same UKMO grid cells revealed that this only accounts for around 0.9 mm of the 17.7 mm difference between EARWIG AAR and that for the true catchment based on the UKMO data. Therefore, although based on the same underlying data, EARWIG itself was found to slightly overestimate precipitation.

[30] Based on the area in Figure 6-1, and calculated from five simulations of 150 years in EARWIG v2.1.

Figure 6-1 Bedford Ouse catchments, UKMO rainfall grid and adjusted EARWIG catchment to Newport Pagnell



Annual averages for the period October 1992 to September 2001 are presented in Table 6-3. These show fairly large discrepancies between the Thiessen polygon method and the UKMO record. This is particularly surprising given the high proportion of missing data for the TBR records that underpin the Thiessen method. Closer inspection of the spatially interpolated TBR data revealed some suspect data, for example areal average values greater than 50 mm in 15 minutes. This highlights a recognised flaw in the use of the Thiessen method at short timescales (see above), where intense local rainfall events are extrapolated across a much larger area than the storm actually covered. For discrete design storms an areal reduction factor is applied to more realistically represent the spatial nature of rainfall and thus avoid such over estimation. The problem is accentuated where gauge coverage is sparse and although 23 TBR gauges were used, the mode for each catchment was three, with two catchments reliant on only one gauge. The high level of missing data also contributes to the problem, effectively reducing the number of available gauges. However, notwithstanding the suspect data, the lack of areal reduction should not affect the long-term averages, unless the gauges are located in wetter areas of the catchment. This is because a single gauge will under-record (relative to the catchment average) or miss storms that are more intense elsewhere in the catchment at other times. Another possible contributor to the problem could be systematic over-recording of rainfall by TBR gauges relative to storage gauges, although the discrepancies in Table 6-3 are larger than those resulting from application of the Environment Agency's quality control of TBR data, which is based on monthly totals. There is no system for flagging individual high 15-minute values; these should be picked up during the processing and adjusted, although there are some quality issues with TBR data greater than four years old (Jon Lampard, Environment Agency, personal communication).

Figure 6-2 A comparison of baseline areal monthly average rainfall for the Bedford Ouse above Newport Pagnell based on the UKMO grid and adjusted EARWIG

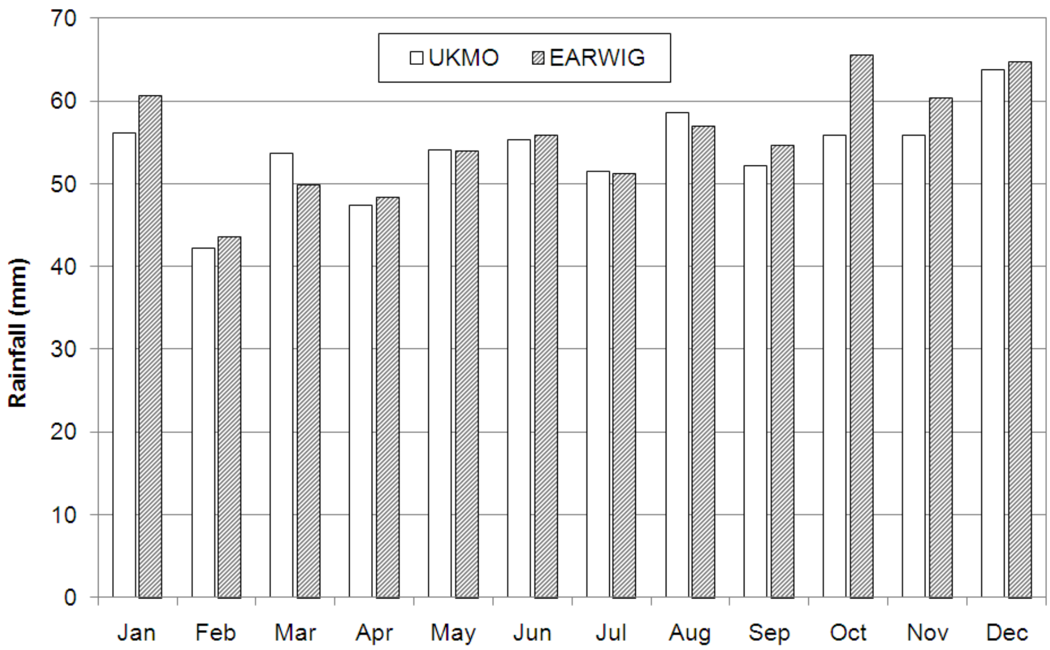
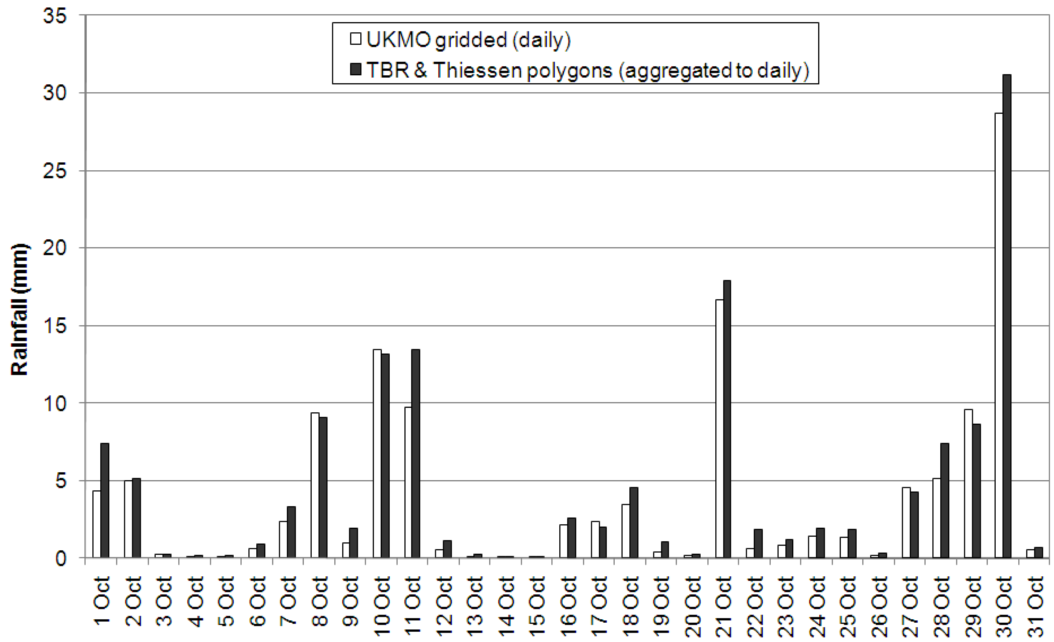


Table 6-3 A comparison of areal annual average rainfall for the Bedford Ouse catchment produced using Thiessen polygons and the UKMO gridded dataset for the Bedford Ouse model calibration and validation period

Method of deriving (baseline) areal rainfall series	**Bedford Ouse above Newport Pagnell**	**Bedford Ouse above Brownshill Staunch**
Thiessen polygon (Oct 1992 – Sept 2001)	834 mm	758 mm
UKMO gridded (Oct 1992 – Sept 2001)	699 mm	648 mm

In addition to long-term averages, it is also important to compare the different methods on a continuous basis, i.e. day-to-day, in particular to compare periods of extreme, flood-generating rainfall. The hyetographs for the methods based on Thiessen polygons and the UKMO grid are presented in Figure 6-3 for October 2000 for the whole Bedford Ouse catchment. In this very wet month, the summed TBR records are more than 15% greater than the UKMO series, which is based on daily gauge recordings.

Figure 6-3 A comparison of daily rainfall totals based on different recording and interpolation methods during October 2000 for the Bedford Ouse catchment



The rainfall totals relate to the 24 hours to 9am on the day against which they are plotted.

6.1.2.3 Implications for rainfall–runoff modelling in the Bedford Ouse catchment

The differences in the rainfall records may have important implications for the use of an alternative rainfall record to that used in calibration and validation of the rainfall–runoff model. Therefore a comparison was undertaken for the Twin catchment (see Figure 5-3 and Table 5-2). This explored the potential differences in rainfall data (see above) and rainfall timestep (the differences between the raw 15-minute and aggregated to daily TBR data). In addition, the influence of the rainfall–runoff model timestep was considered; this determines the frequency at which the water balances and movements are computed. Four separate runs were undertaken, as described in Table 6-4.

Table 6-4 Details of runs to compare influence of rainfall data, rainfall timestep and model timestep on river flows

Run reference (see Figure 6-4)	Rainfall data	Rainfall timestep	Model timestep
Black	TBR, Thiessen	15 minute (raw)	15 minute
Red	TBR, Thiessen	Daily (aggregated)	15 minute
Blue	UKMO	Daily	15 minute
Green	UKMO	Daily	Daily

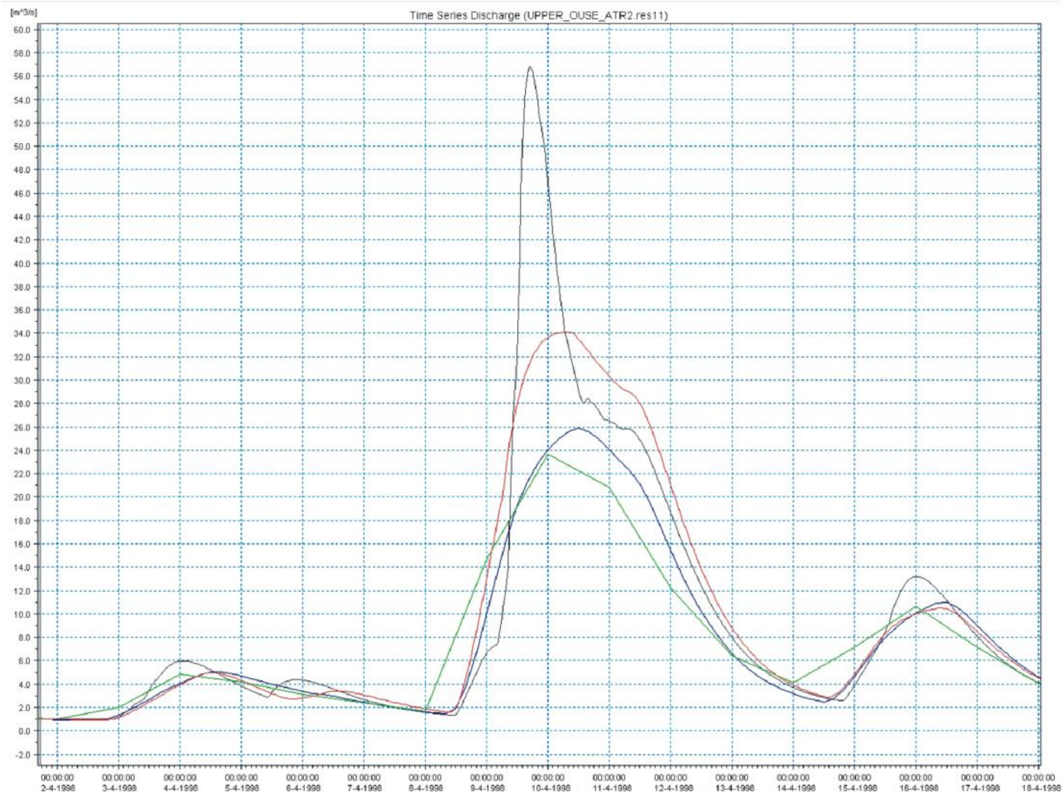
From the results (see Figure 6-4 for the Easter 1998 flood event) the following conclusions have been drawn:

- **Model timestep** (blue compared with green): the differences are small, and a model run timestep of 1 hour could be adopted as a compromise.
- **Rainfall timestep** (black compared with red): there are large differences on some, but not all, peaks. Disaggregation of the daily data could be considered, but it is not thought that such differences will be apparent downstream (especially as volume seems to be displaced rather than lost). However, this will be tested (see below).
- **Rainfall data** (red compared with blue): there are fairly large differences on some peaks (and at other times, not shown, there appears to be systematic differences). Such differences are a function of the records and without further checking will have to be accepted.

In order to test the influence of rainfall timestep on downstream flood peaks, the 'Red' run (but at a half-hourly timestep) was undertaken for all 21 catchments and routed using the hydraulic model[31]. This was compared with the original model run (the 'Black' run). The results (see Figure 6-5) show that there are fairly large differences in level for the Easter 1998 flood event: the peak is approximately 100 mm lower using the aggregated data. This compares to a value of 300–450 mm 'freeboard' typically allowed for in flood defence design for engineering and flood modelling uncertainties. However, the original model run has some error correction within it that will adjust values closer to actual values; this is based on upstream updating points at which modelled values were corrected using observed values (Tom Rouse, Atkins, personal communication). The calibration results for this location show that modelled peaks tend to be higher than observed peaks, with an amplitude error (RMSE) of 9 cm (suggesting a greater divergence between the two runs in Figure 6-5, but with the actual levels falling between them), although the opposite was true during autumn 2000 where the highest modelled value was about 2 cm less than that observed (Atkins, 2006b).

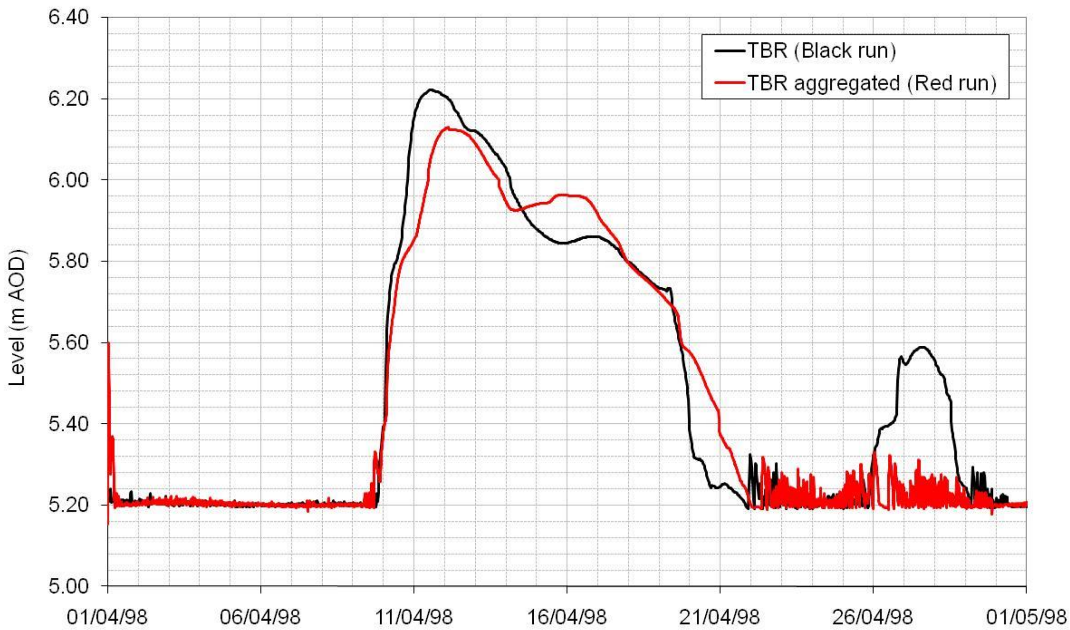
[31] The model runs were undertaken by Tom Rouse, Atkins.

Figure 6-4 Four hydrographs for the Easter 1998 event for the Twin catchment based on four different runs to compare rainfall data, rainfall timestep and model timestep



Original in colour.

Figure 6-5 Water levels for April 1998 at St Ives Staunch modelled using 15-minute and daily rainfall timesteps



Original in colour.

6.1.2.4 Conclusions

For this thesis, it was initially intended to replicate the conventional approach to rainfall–runoff modelling by producing a long-term sequence of areal rainfall based on local gauges and Thiessen co-efficients. Therefore, starting with the Bedford Ouse, rainfall data in and close to the catchment was collected from the Environment Agency's WISKI database. The NAM rainfall–runoff model was calibrated using sub-daily rainfall records (Atkins, 2004); similarly the Eden FEH rainfall–runoff model has inputs of sub-daily rainfall. However, for the Bedford Ouse the record length of sub-daily (TBR) gauges was found to be limited, with the earliest commencing in January 1988 and many not starting until the mid to late 1990s. The daily records extend further, with 16 of the 38 in use and relevant to the catchment commencing before 1990, of which five started at the beginning of or before January 1961. As noted above there are also significant quality issues with some of the sub-daily data.

Based on this review of the Bedford Ouse, it was decided to adopt the daily gridded rainfall data produced by the Met Office. This data provides a consistent record of areal rainfall extending back to 1958 which incorporates all available, quality-checked daily gauges relevant to each catchment. It also offers more flexibility in terms of climate change perturbation, as it has been incorporated into the EARWIG weather generator and can be simply perturbed using change factors from RCM gridded output.

However, there are issues with the use of this dataset for input into rainfall–runoff modelling (relevant to the Bedford Ouse modelling). In particular the absolute results for individual catchments will have to be treated with caution; higher confidence can be expected from the relative results i.e. those obtained by considering changes between the baseline and future runs, both of which will be based on the same daily data. Greater confidence can be placed on the downstream results, which are less sensitive to the rainfall timestep. An hourly model timestep will be used as a compromise between precision and efficiency.

6.1.3 Areal potential evapotranspiration

The longest record of areal PET is contained within the Met Office Rainfall and Evaporation Calculation System (MORECS). MORECS Version 2.0 (1995) is described in Hough *et al*. (1997) and the method of calculating PET is briefly summarised here. MORECS was designed to provide estimates of weekly and monthly evaporation and soil moisture deficits averaged over 40 km by 40 km squares, based on daily synoptic weather data. The weather data are normalised based on square averages and interpolated. PET is calculated using the Penman–Monteith equation which is slightly modified to use empirical formulae for net radiation. PET is produced for a range of surface land covers based on their values of albedo, soil heat flux, aerodynamic resistance and canopy resistance. Real land-use values of PET are calculated based on their contribution to each MORECS grid square.

More recently, MORECS has been replaced by the Met Office Surface Exchange Scheme (MOSES). MOSES was designed to better represent land surface schemes, in particular for use in the Hadley Centre's GCM. Version I is described in detail in Cox *at al*. (1999), whilst Version 2.2, which explicitly represents sub-grid land cover heterogeneity, is presented in Essery *et al*. (2001).

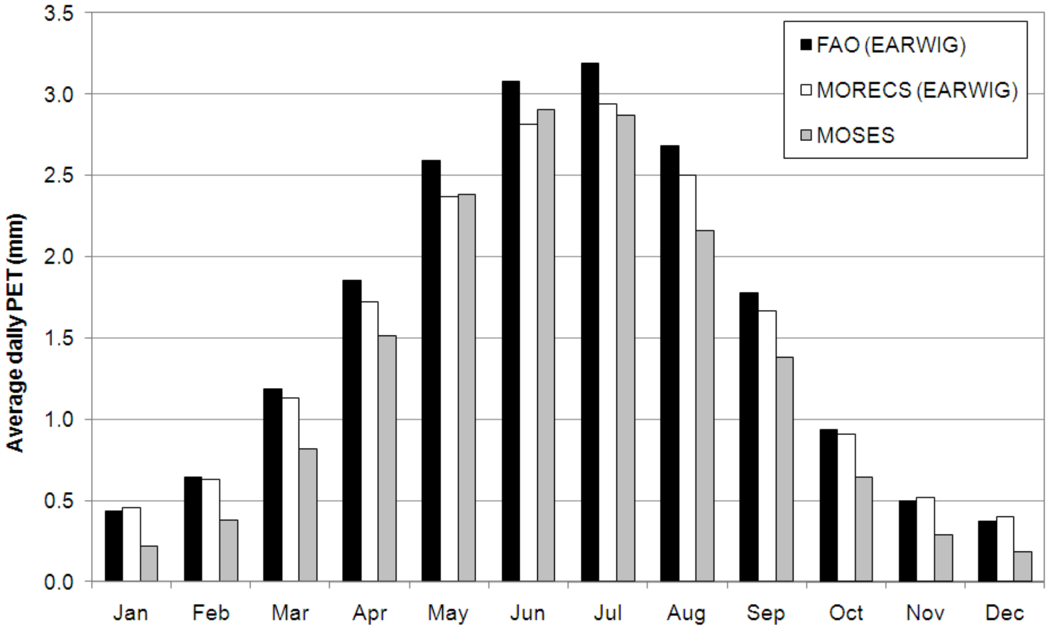
An important issue in hydrological modelling is that MORECS and MOSES produce different values of PET. A comparison between MORECS and MOSES (Entec, 2007) found large discrepancies in grass PET for three MORECS squares in Essex (140, 141 and 152). Over the period 1990–2004, for annual long-term averages MORECS was greater than MOSES by around 14%. For monthly long-term averages, MORECS was greater than MOSES by up to 15% between April and September (and less by around 1% in June for two squares), but MORECS was greater than MOSES by more than 25% between October and March, peaking at over 70% in December. Although this could be misleading given the low values of winter PET (Entec, 2007), it could be more important in relation to climate change, where significant increases in winter PET are projected. The discrepancies have been attributed to differences in the parameterisation of albedo, grass height and surface resistance for the reference surface (Holman *et al.*, 2005a; cited in Entec, 2007).

Another comparison was undertaken by Hough and Hood (2003) who compared four different squares (85, 105, 144, 152) on a monthly basis during the 1975–1976 drought and the 2000–2001 floods. This had similar results, although there was a much longer period in summer when MOSES exceeded MORECS, particularly in 2000–2001, when for square 152 (a mainly arable area of Essex) the annual total MOSES PET exceeded that of MORECS. The differences depended on the magnitude of PET, with a daily comparison for 1975–1976 showing that MOSES < MORECS PET below a MORECS PET of 1 mm per day (typical for winter) and MORECS > MOSES when MORECS PET is between 3 and 4 mm per day (typical of summer). Beyond this (and likely to represent the hottest conditions of 1976), MOSES PET tends to level off to between 3 and 5 mm per day, while MORECS PET increases. This happens because MOSES assumes an increase to crop canopy resistance on hot, sunny days with low humidity, whereas MORECS does not include this effect for grass (Hough and Hood, 2003).

A further comparison has been undertaken for this thesis, to evaluate the potential incompatibility of MOSES data used in the calibration of the Bedford Ouse rainfall–runoff model with PET calculated using MORECS and FAO-Penman (Allen *et al.*, 1994) formulae in EARWIG. The author and colleagues, in unpublished work, found that the East Kent

Groundwater Model, calibrated using MOSES, dried up in the upper part of the chalk when ran using MORECS data derived from EARWIG. Given that EARWIG is a stochastic weather generator, a timeseries comparison such as those described above was not possible. Instead, mean monthly average daily PET was calculated from the MOSES timeseries available, and from five simulations of 150 years of EARWIG (the same five simulations as for precipitation above). The results (Figure 6-6) show that the FAO formulation tends to exceed MORECS, especially in summer, and always exceeds MOSES. The comparison of MORECS and MOSES leads to similar conclusions to those reported above, although MORECS exceeds MOSES by 0.34mm per day on average in August.

Figure 6-6 A comparison of mean monthly average daily PET produced by EARWIG (FAO and MORECS) and MOSES for the Bedford Ouse catchment above Newport Pagnell for the baseline period (1961–1990)



In general, the accuracy of PET is less important for flood modelling than for low-flow and drought assessments, and the use of the same MOSES timeseries that calibrated the rainfall–runoff model will avoid the issues associated with the replacement rainfall timeseries. However, for the stochastic modelling the total and seasonal differences between MORECS and MOSES may affect the timing and magnitude of flood events; this will be considered further in Chapter 8.

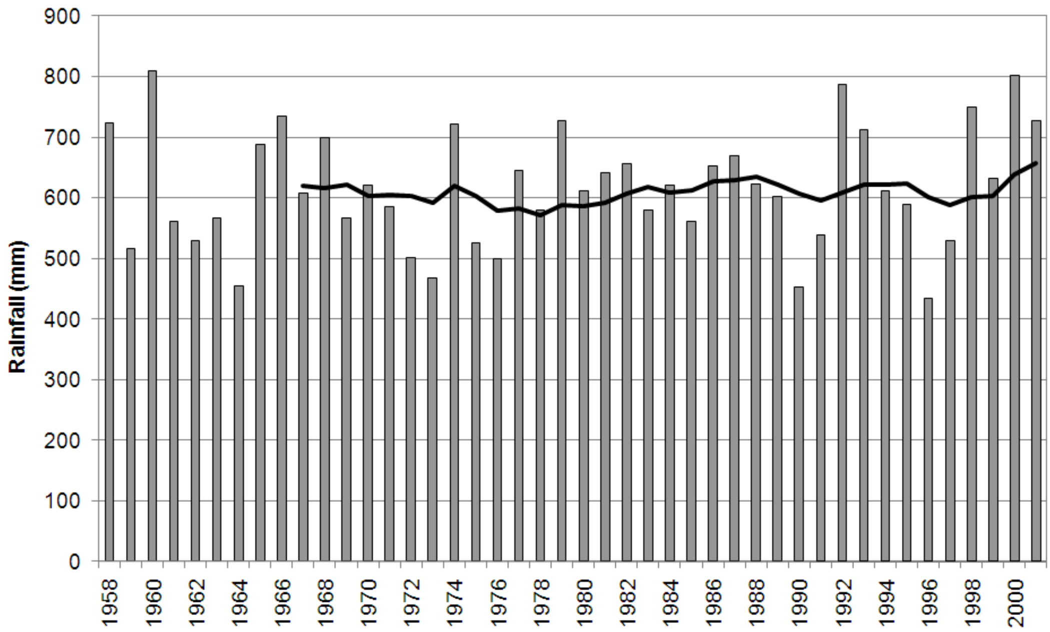
6.2 Baseline climate of the Bedford Ouse catchment

The Bedford Ouse catchment is isolated from marine influences and much of the catchment lies within the rain shadow of western England including the Chiltern Hills to the south and the Cotswolds and Northamptonshire Heights to the west, the latter where the river rises. The climate is therefore continental in nature, like much of eastern England (Mayes and Sutton, 1997), being dry (see below) with particularly warm and sometimes thundery summers and prone to frost in other seasons. Woburn in Bedfordshire (Figure 5-2) recorded an annual average 57.6 air frosts and 113.9 ground frosts during the period 1961–1990 (ibid.).

6.2.1 Precipitation

The UKMO gridded rainfall series (described in Section 6.1.2.2) has been analysed for the Bedford Ouse catchment in order to describe baseline rainfall. Annual average rainfall for the period 1961–1990 is 599 mm. Above Newport Pagnell this rises to 648 mm and the individual catchment averages range from 665 mm in the Upper Ouse to 542 mm in the downstream Ouse between Offord and Earith (see Table 5-2). Annual rainfall totals for the catchment vary greatly, from dry years such as 1996 with 435 mm to wet years such as 1960 and more recently 2000, both of which exceeded 800 mm (Figure 6-7). The decadal moving average shows that the ten years ending in 2002 were the wettest decade in the record and the period October 1992–September 2001 (which included a drought as well as floods) was 8% wetter than the baseline period 1961–1990.

Figure 6-7 Annual areal rainfall series for the Bedford Ouse catchment (1958–2001)



Thick black line = moving decadal average.

The monthly rainfall totals (Figure 6-8) range from 1.5 mm in February and September 1959 to 147.2 mm in October 1987. The months of notable floods (collated from various sources) are highlighted in Figure 6-8, which shows coincidence of the highest rainfall totals with flood events, although there are several very wet months where no widespread flooding has been noted, which probably relates to the nature of the rainfall, antecedent conditions and storage influences.

An areal monthly rainfall series for the larger Ely Ouse to Denver (see Figure 5-1) has been produced by Jones *et al*. (2006), extending back to 1800. This shows that there have been a series of wet years exceeding 750 mm of rainfall and several winters (DJF) with in excess of 200 mm of rainfall. Particularly wet periods – with the moving decadal annual average rainfall exceeding 700 mm – have occurred in the late 1870s and early 1880s, and briefly in the early 1990s, with the wettest during the late 1990s and early 2000s (to the end of the analysis in 2002).

Rainfall in the Bedford Ouse catchment is distributed fairly evenly throughout the year (Figure 6-9), with February notably drier than other months with an average of just 37.8 mm. Despite December being the wettest month (56.7 mm), winter (DJF) is the driest season (144.4 mm), closely followed by spring (144.8 mm). Summer is the wettest season (155.9 mm).

Figure 6-8 Monthly areal rainfall series and the months of notable floods for the Bedford Ouse catchment (1958–2001)

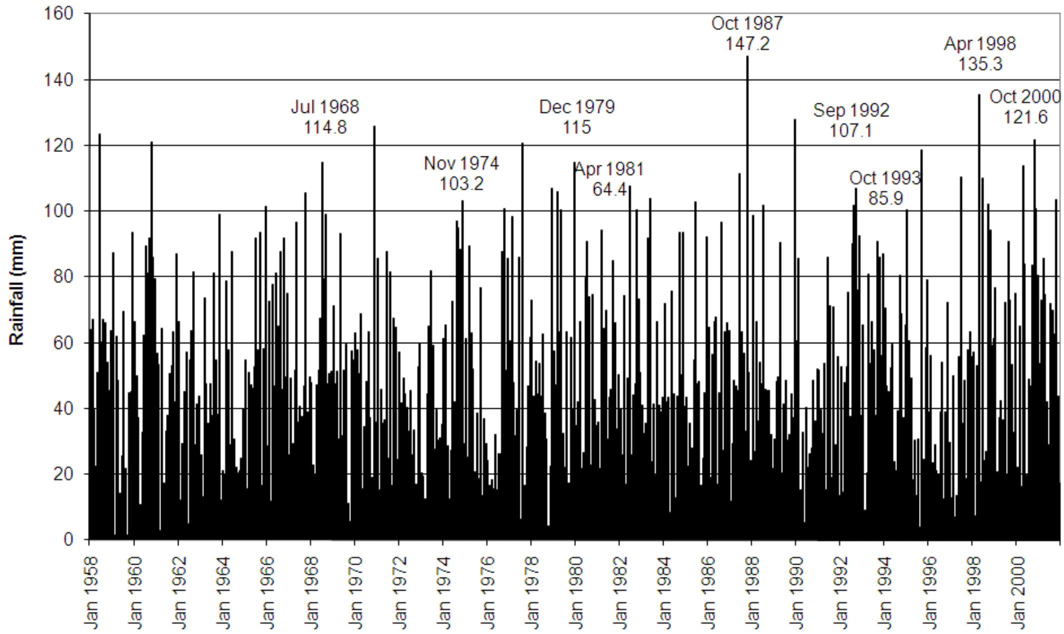
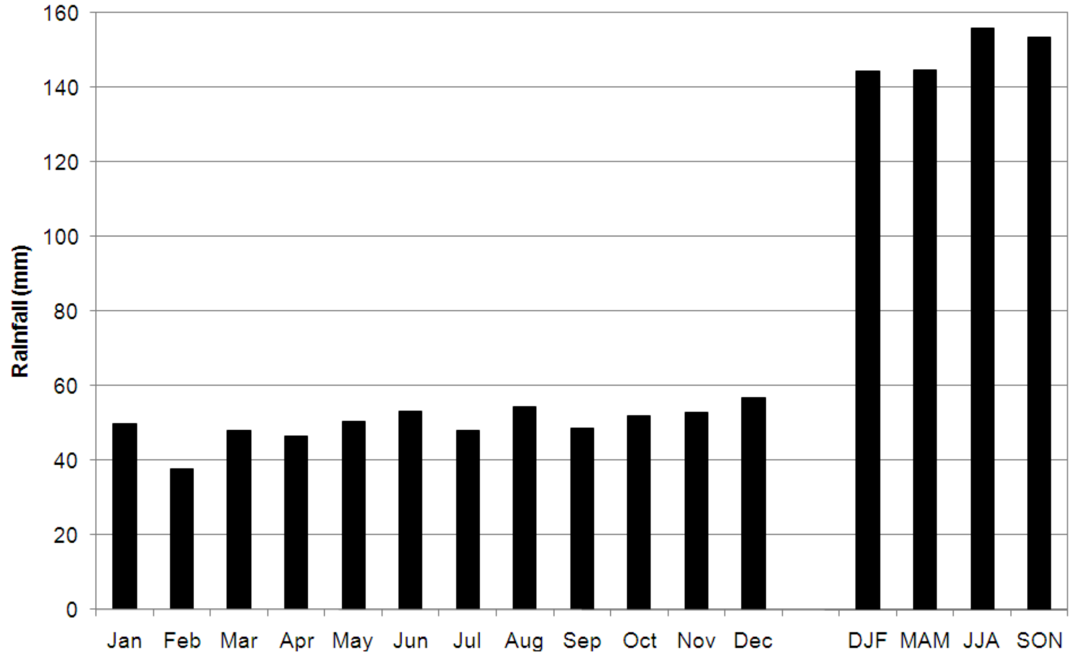
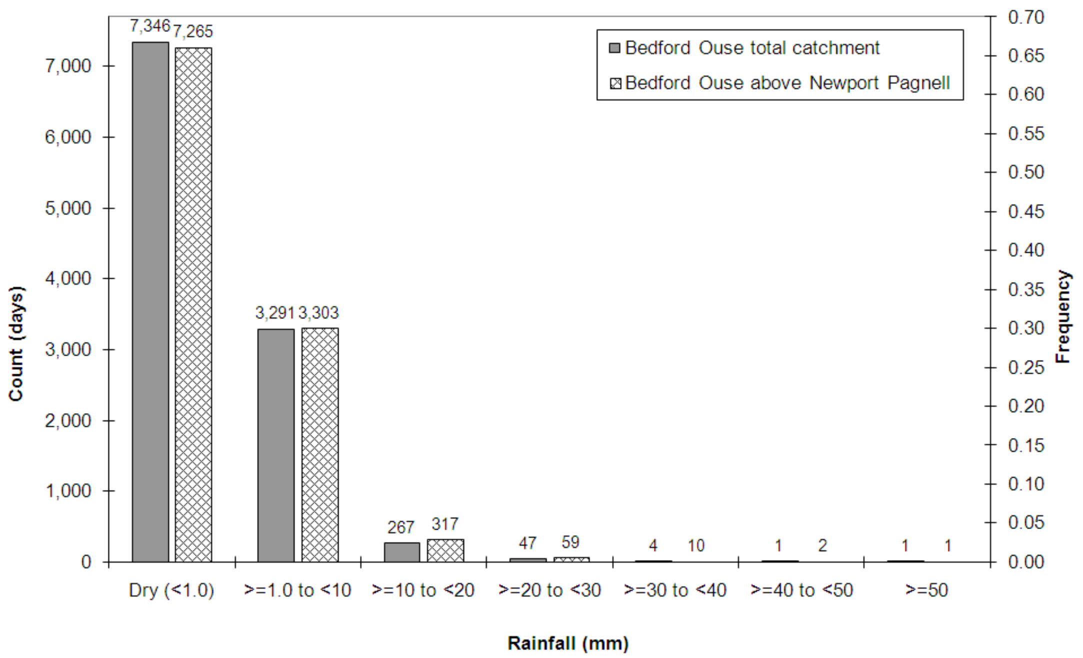


Figure 6-9 Monthly and seasonal areal average rainfall for the Bedford Ouse catchment (1961–1990)



Approximately two-thirds of all days are dry (less than 1.0 mm of rain) across the whole catchment, with only 3% of days experiencing more than 10 mm of rainfall (Figure 6-10). Days on which the catchment average rainfall is at least 30 mm are rare, only six being recorded over the 30-year baseline period. The upper catchment above Newport Pagnell (see Figure 5-1) receives more heavy rainfall days, with 13 equalling or exceeding 30 mm.

Figure 6-10 Daily rainfall histogram for the Bedford Ouse catchment (1961–1990)



6.2.2 Potential evapotranspiration

Baseline PET has been computed for each of the 21 catchments in the Bedford Ouse from 1961 to 2003 for use in the modelling work undertaken by Atkins for the Environment Agency. This baseline PET is based on the interpolation of MOSES data and has been corrected to remove negative values of PET for use in the modelling for this thesis. For the purposes of describing baseline PET, a catchment average PET has been calculated based on an area-weighted mean. PET is similar across the 21 catchments, although it is between 6% and 9% lower than the Bedford Ouse catchment average in the Flit and Hiz and their tributaries (see Figure 5-3 and Table 5-2). This is probably a function of the thin soils and exposed porous chalk geology dominant in this area, as well as the presence of urban areas.

Daily PET (Figure 6-11) follows a typical sine curve with values of between 0 and 5 mm per day. Daily average monthly PET (1961-1990) peaks in June at 2.88 mm, closely followed by July at 2.86 mm, and is least in December with 0.18 mm (Figure 6-12). Daily average PET was 1.31 mm between 1961 and 1990 and 5.6% higher at 1.38 mm between 1991 and 2001, which can be seen from the daily average annual PET series (Figure 6-13); a similar increase can be seen in the PET series for the Ouse computed by Jones *et al*. (2006) using the temperature-based Thornthwaite method. However, there appears to be no trend within the baseline period and therefore this can be used within the climate change assessment without the need for adjustment.

Figure 6-11 Daily PET series for the Bedford Ouse catchment (1961–2001)

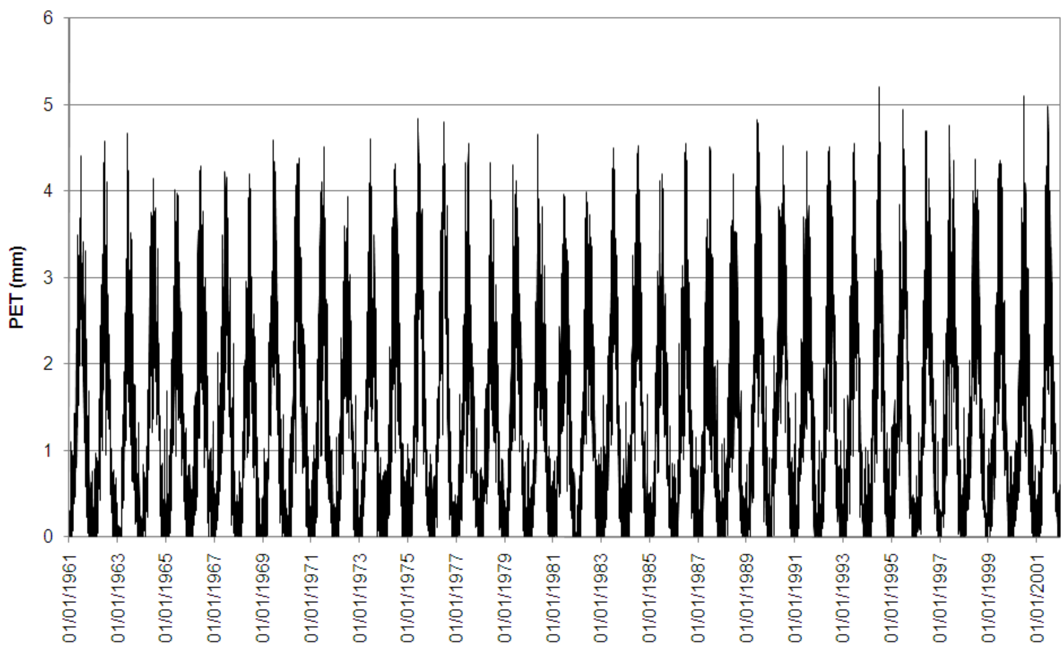


Figure 6-12 Daily average monthly PET for the Bedford Ouse catchment (1961–1990)

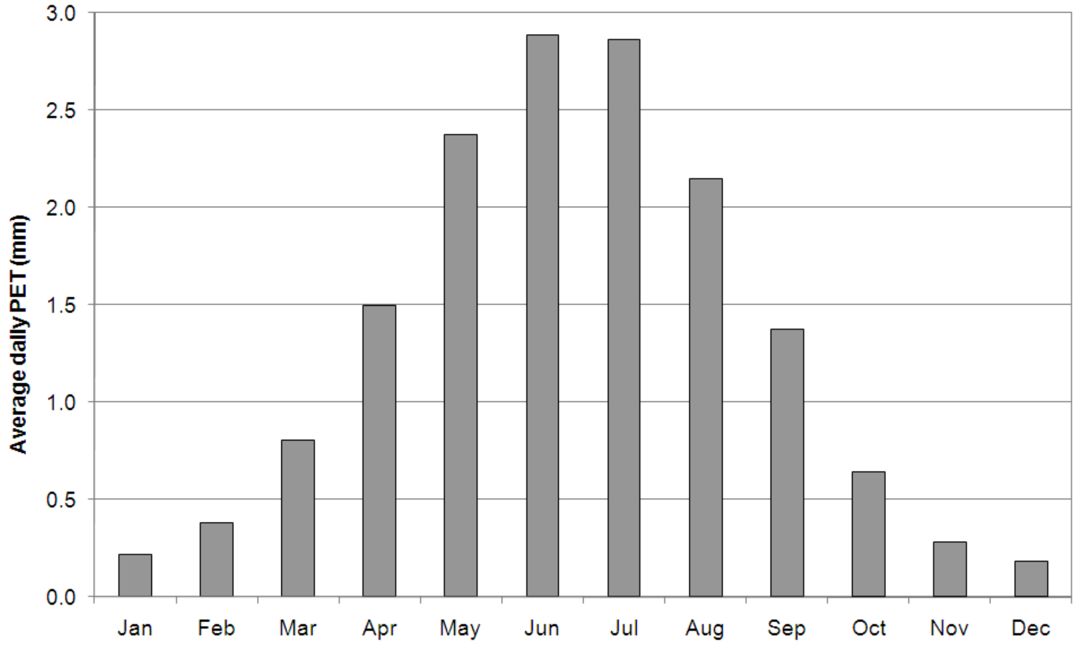
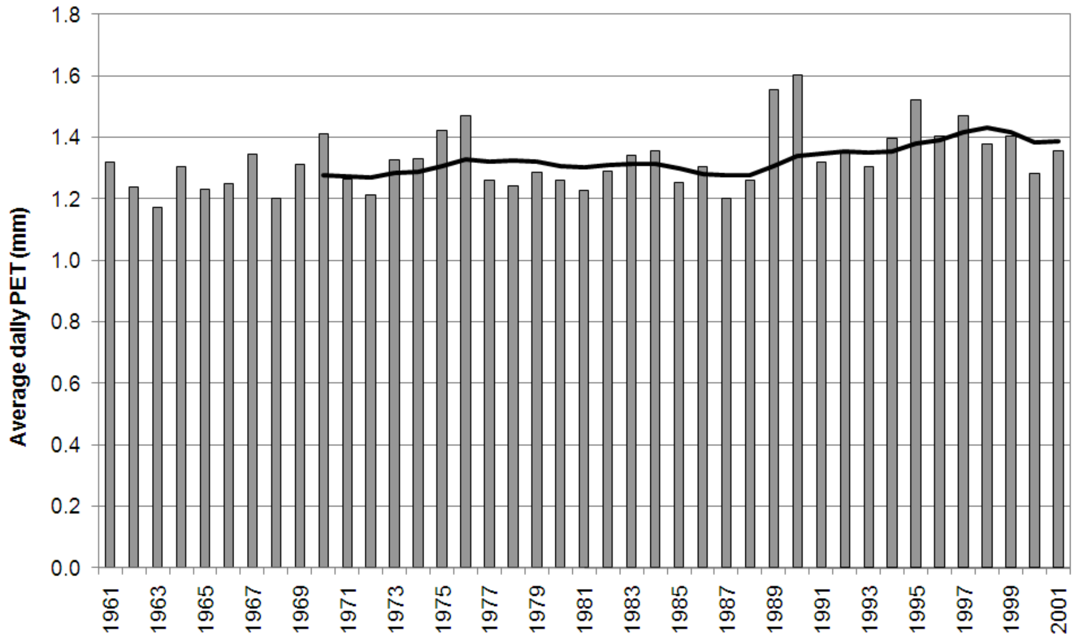


Figure 6-13 Daily average annual PET series for the Bedford Ouse catchment (1961–2001)

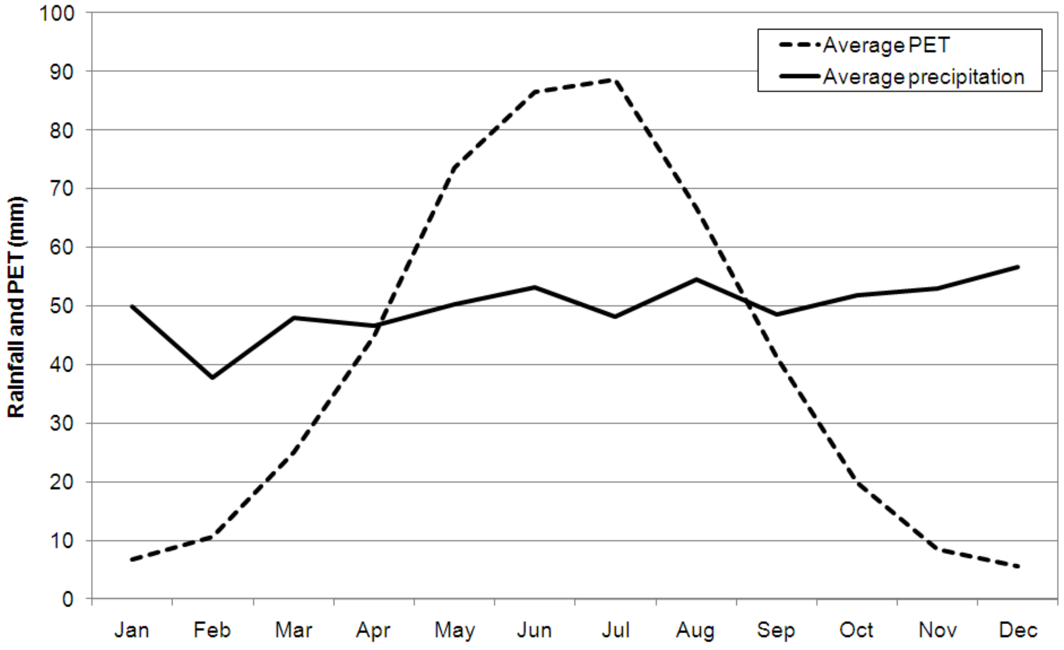


Thick black line = moving decadal average.

6.2.3 Moisture budget

A moisture budget, based on the difference between precipitation and PET (Figure 6-14), shows that precipitation exceeds PET from early September to mid-April, although field capacity will be reached later in the autumn.

Figure 6-14 Monthly average PET and precipitation for the Bedford Ouse catchment (1961–1990)



6.3 Baseline climate of the Eden catchment

The climate of the Eden catchment varies considerably between the upland headwaters and the lowland valleys towards Carlisle. Whilst rainfall totals exceed 1250 mm per year in the uplands and 1750 mm in the south-west (Environment Agency, 2005f), much of the Eden valley is in the rain shadow of the Lake District under the prevailing west and south-westerly airstreams (Tufnell, 1997). Autumn rainfall totals can be very high in Cumbria, especially when Atlantic fronts and depressions are persistent, which can also give rise to heavy daily falls, assisted by relatively high sea temperatures (ibid.). Snowfall in the Eden catchment is influenced by altitude and aspect, with greater falls on eastern-facing slopes (ibid.).

6.3.1 Precipitation

As discussed, the UKMO gridded rainfall series is not required for the Eden rainfall–runoff model (except for bias correction, see Section 7.3) and so the description of baseline precipitation is largely drawn from the work of Jones *et al*. (2006), including re-presentation and further analysis of the raw data[32]. Jones *et al*. produced areal monthly precipitation series for the Eden to Temple Sowerby and to Warwick Bridge (see Figure 5-4), extending back to 1800. The larger catchment to Warwick Bridge has a higher areal average precipitation than the upper catchment to Temple Sowerby. This unusual effect relates to the contribution from the very wet south-east section of the Cumbria High Fells, which drains via the Eamont and joins the Eden just downstream of Temple Sowerby (see Figures 5-4 and 5-5).

Annual average precipitation for the Eden to Warwick Bridge for the period 1961-1990 is 1309 mm, compared to 1346 mm over the period 1800-2002. Above Temple Sowerby these averages are 1170 mm and 1206 mm respectively, and the sub-catchment averages (from the National River Flow Archive) range from 945 mm in the Petteril (1968-1990) to 2429 mm in Haweswater Beck (1961-1990) (see Figure 5-5). Annual average precipitation for the full catchment (to Sheepmount) is 1183 mm (National River Flow Archive).

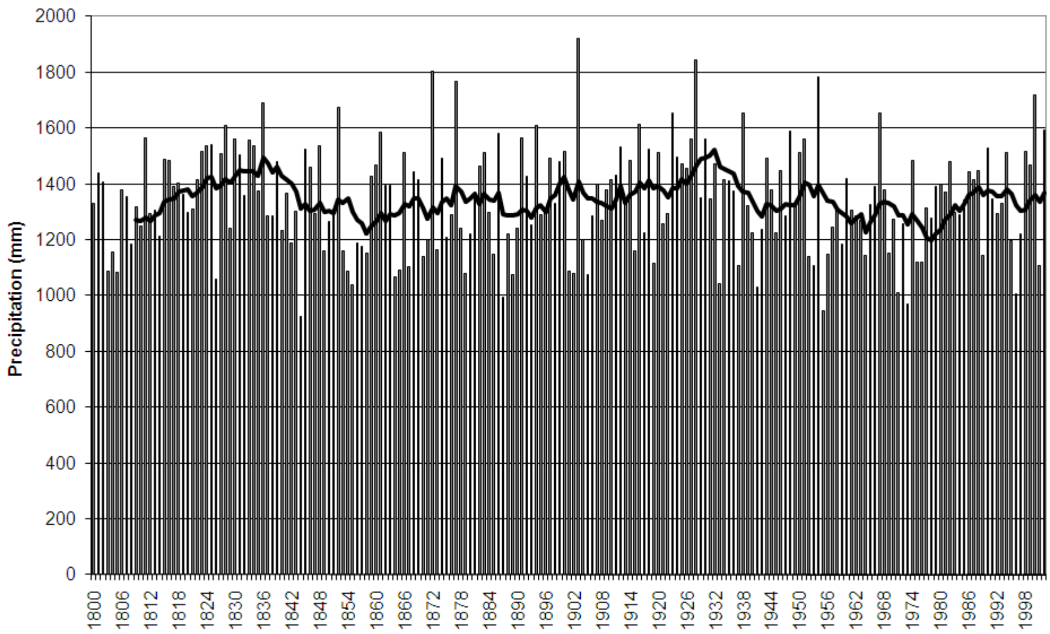
Annual precipitation totals (Figure 6-15) vary greatly, from dry years such as 1844 (927 mm), 1955 (945 mm) and 1973 (968 mm) to wet years such as 1903 (1923 mm) and others above 1700 mm (134% of the 1961-1990 annual average): 1928, 1872, 1954, 1877 and 2000 (in decreasing order; note 2004/05, incorporating the January 2005 flood event, was beyond the data range). The decadal moving average (Figure 6-15) shows distinct wet (e.g. mid to late 1920s) and dry (e.g. early to mid 1970s) periods, with no overall trend. Recent precipitation has been similar to the long-term average, although the annual averages mask seasonal changes: there has been a decline in summer (JJA) precipitation since the middle of the

[32] Provided by Prof. Phil Jones.

twenty-first century, which has been offset by a rise in winter (DJF) precipitation (Jones *et al*. 2006).

The monthly precipitation totals for the period 1900-2002 (Figure 6-16) range from 3.4 mm in August 1947 to 341.6 mm in October 1967. The years of notable floods (Environment Agency, 2005f) are highlighted in Figure 6-16. This shows some coincidence of the highest precipitation totals with flood events, including the 1984 event which followed a severe drought, although there are several very wet months (e.g. in the early 1950s) where no flooding has been noted, which probably relates mainly to the nature of the precipitation.

Figure 6-15 Annual areal precipitation series for the Eden catchment above Warwick Bridge (1800–2002)



Thick black line = moving decadal average.

Figure 6-16a Monthly areal precipitation series and the years of notable floods for the Eden catchment above Warwick Bridge (1900–1950)

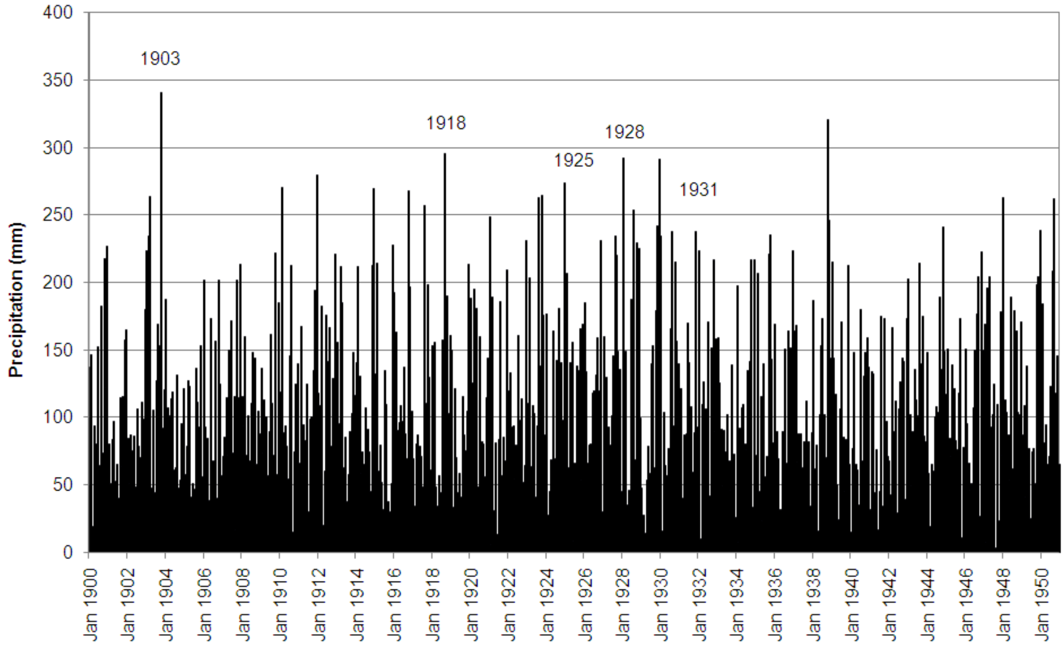
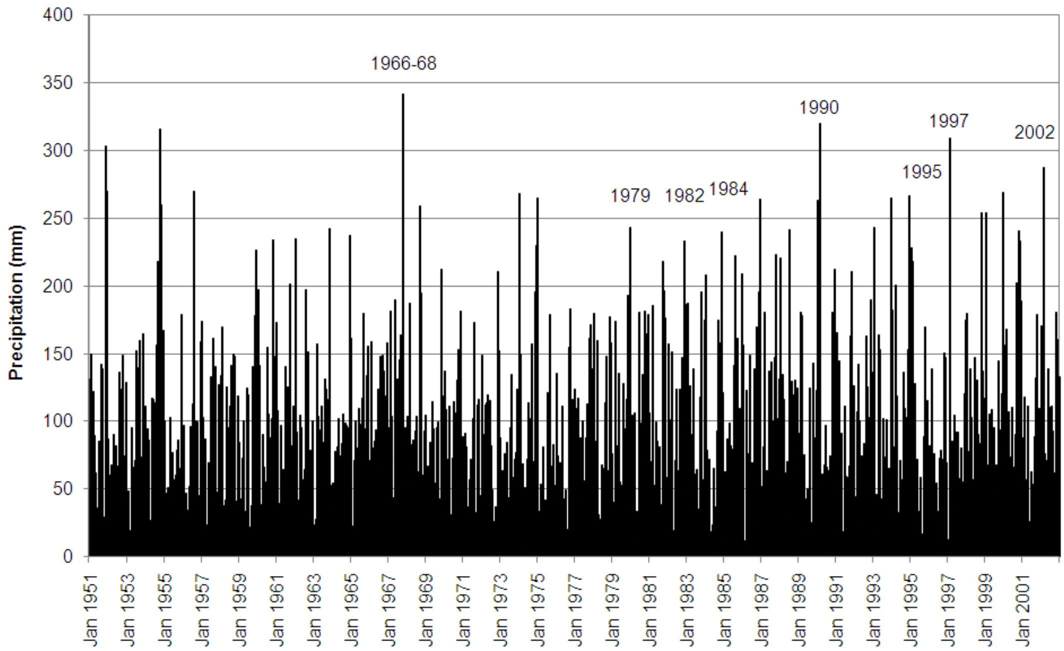
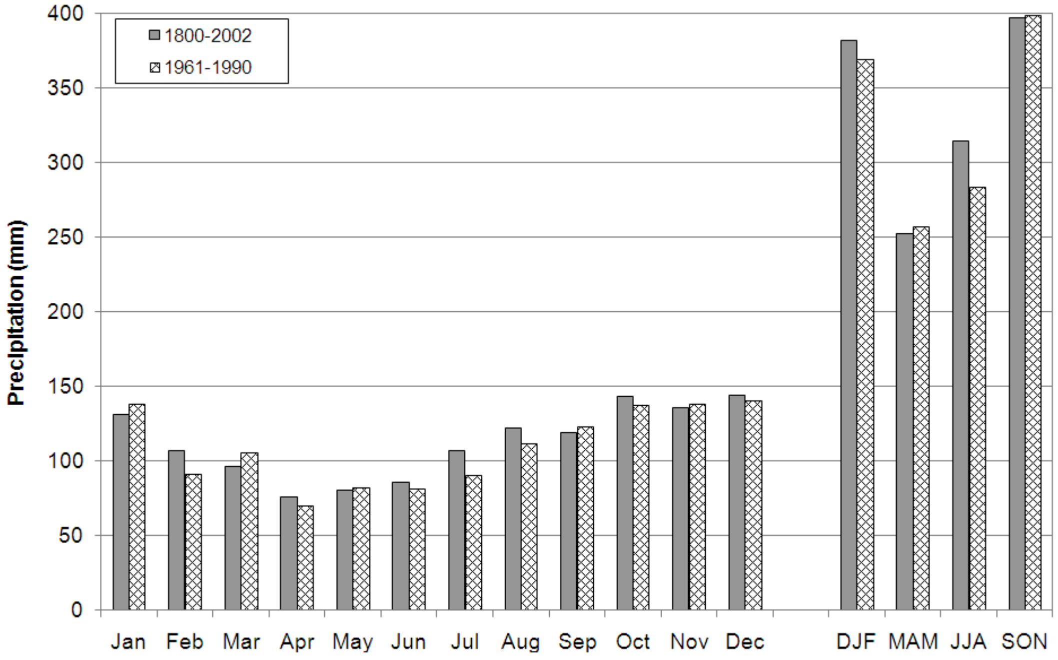


Figure 6-16b Monthly areal precipitation series and the years of notable floods for the Eden catchment above Warwick Bridge (1951–2002)



Precipitation is seasonal, with summer and particularly spring notably drier than winter and autumn (Figure 6-17). April is the driest month (75.4 mm average 1800-2002) whilst December is the wettest month receiving almost twice as much precipitation (144.3 mm).

Figure 6-17 Monthly and seasonal areal average precipitation for the Eden catchment above Warwick Bridge (1800–2002 and 1961–1990)



6.3.2 Potential evapotranspiration

The Eden rainfall–runoff model does not require areal PET (see Section 7.3) and so the description of baseline PET is drawn briefly from the computation of Jones *et al*. (2006). Jones *et al*. estimated monthly mean PET using the temperature-based method of Thornthwaite, which allowed relatively easy estimation back to the seventeenth century. Based on this formula PET for the Eden ranges from 530 mm to just over 610 mm per year, with the decadal mean fluctuating between approximately 550 mm and 600 mm per year. PET has risen sharply since about 1980, with the decadal average increasing from 580 mm to more than 610 mm per year by 2002, its highest value in more than 350 years, although the nature of the temperature-based formula may influence this.

7. Climate change scenarios

Climate change scenarios were introduced in Section 3.1.2, their uncertainties were discussed in Section 3.1.3 and their role in the assessing floodplain futures was outlined in Section 4.2. This chapter describes the potential and adopted methodologies used to create climate change scenarios, before presenting the resulting scenarios for the Bedford Ouse and Eden catchments.

7.1 Methods

As noted in Section 3.1.3, current climate change scenarios must be applied to a baseline climatic record to provide scenarios of future climate, which can be input into a rainfall–runoff model. This traditional method – application to a baseline climatic record – is termed the *change factor*, *delta change*, or *perturbation* method. It is reasonably quick to use, especially if change factors are readily available for example from dynamically downscaled RCM output, and allows the analysis of known events 'with climate change' for example how the (current or baseline) 100-year flood or 1998 flood event will alter. However, the latter advantage is also a disadvantage, as natural variability is inherited entirely from the historical record; other weather events, sequences or combinations are not realised.

The basic change factor method applies the mean proportional change i.e. the baseline record is perturbed only by the absolute (temperature) or percentage (other variables) difference between the means of variables from the climate model runs of the baseline and the future (typically on a monthly basis). For example, if mean January rainfall increases by 20% for the medium-high emissions scenarios for the 2080s, then every day in the baseline January series is uplifted by 20% (days with no rainfall remain dry). The main problem with this method is that it does not provide for a change in the variance (Xu, 1999b). Alternative methods can be invoked to do this. As discussed in Section 3.2.2.2, Reynard *et al*. (2005) developed a 'combined method' which closely matched the change in frequency of daily rainfall of the UKCIP02 scenarios. However, this method does not always better the proportional method, especially in winter, and is significantly more complicated to implement. More fundamentally, the variance, and therefore change in variance, produced by climate models may not be realistic.

Stochastic approaches, including weather generators and resampling, produce series of climate data for baseline and future periods and provide a simple and robust approach to incorporating natural variability. However, their ability to capture interannual and decadal scale variability may be limited. Very long synthetic weather records can be developed, which are useful in calculating robust return periods, although weather generators are typically conditioned on 30-year periods which limits the size of return period that can be reliably estimated (Jones *et al.*, 2009). Weather generators generally do not include change in variability itself as a result of climate change, although EARWIG (see Box 6-1) perturbs rainfall based on statistics other than the mean, and the UKCP09 weather generator (ibid.) also perturbs temperature variance. However, information from climate models is a constraint. There are also spatial constraints where the number of stations used in deriving the areal record are limited. This is a particular problem for use with rainfall–runoff models which require spatially variable areal inputs. Weather generators are particularly time consuming to develop, although can be used repeatedly.

In contrast to point or one-dimensional models such as EARWIG, two-dimensional or spatial–temporal models are being developed which explicitly incorporate spatial patterns, although these are often multi-site rather than areal and typically only focus on rainfall. Stochastic point (rainfall) models can and have been extended, but they have generally been inadequate in modelling extremes and persistence (Burton *et al.*, 2008), and are difficult to validate due to the length and quality of radar data (Wheater *et al.*, 2006). A variety of spatial–temporal approaches has been developed, most recently based on Generalised Linear Models (GLMs) (Yang *et al.*, 2005; Wheater *et al.*, 2006), extension of Poisson cluster models (Wheater *et al.*, 2006; Burton *et al.*, 2008), a Poisson cluster model conditioned by weather types (Fowler *et al.*, 2005), and conditional resampling of downscaled large-scale atmospheric predictor variables (Wilby *et al.*, 2003).

Spatial–temporal rainfall model parameters require perturbation to account for climate change, or climate model output can be used more directly (for predictor variables rather than rainfall itself); both methods involve statistical downscaling from GCM or RCM resolutions to a more local scale. Methods that use atmospheric predictor variables can utilise direct output from GCMs; Chandler *et al*. (2007) present a bespoke methodology for conditioning a GLM on large-scale atmospheric conditions – specifically temperature, sea level pressure and near-surface relative humidity – using the GLIMCLIM software. Methods using weather types can use processed GCM data. The method of Fowler *et al*. (2005) can also use changes in weather types and rainfall characteristics to re-fit the rainfall model. Similarly, RainSim v3 (Burton *et al.*, 2008) requires the perturbation of additional parameters to those already perturbed in EARWIG (which includes a point version of RainSim). Spatial–temporal rainfall models are difficult to perturb because parameters can be difficult to measure from GCMs and RCMs, and are areal, rather than representative of points. Furthermore, they still assume linearity; for example, spatial patterns do not change within each weather type, meaning that additional adjustment is required to allow for a greater water holding capacity in warmer conditions.

The advantages and disadvantages of a range of different methods for constructing climate scenarios are summarised in Table 7-1. These methods are not mutually exclusive, but are presented as typically used; other combinations are possible, for example proportional change factors applied to stochastic weather generator output. The enhanced change factor method is defined here as one which perturbs the baseline record using a method more sophisticated than a proportional change, for example the combined method of Reynard *et al*. (2005). The advanced change factor approach is defined as one which applies change factors to statistics in addition to the mean.

Table 7-1 Methods for constructing climate scenarios: advantages and disadvantages

Method	Examples	Advantages	Disadvantages
Proportional change factor	Widely used in practice	+ Reasonably quick + Allows analysis of known events 'with climate change'	- Natural variability inherited entirely from historical record (although better representation than in climate models)
Enhanced change factor	Reynard (2003); Reynard *et al*. (2005)	+ More realistic representation of changes in variability including extremes	- Time intensive - Based on historical record
Advanced change factor plus stochastic weather generation	Kilsby *et al.* (2007)	+ Incorporates baseline climate variability + Very long synthetic records can be developed	- Time intensive (unless weather generator already developed) - Change in variability (if simulated by climate model) not included for all variables - Spatial limitations
Use of climate model output as input to spatial–temporal rainfall model	Wilby *et al*. (2003); Chandler *et al*. (2007)	+ Spatial representation of rainfall + Incorporates baseline climate variability + Very long synthetic records can be developed	- Time intensive, particularly if weather-types needed - Limited to rainfall
Advanced parameter perturbation of spatial–temporal rainfall model	Fowler *et al*. (2005)	+ Spatial representation of rainfall + Incorporates baseline climate variability + Very long synthetic records can be developed	- Time intensive - Requires high-level understanding of particular model - Limited to rainfall
Direct (future climate) output from climate or earth system models	Not yet reliable	+ Optimal output for impact assessment (ensembles could represent uncertainties)	- Computationally prohibitively expensive at present

Initially it was intended that EARWIG would be used to generate the climate scenarios. However, the catchments being modelled are too large (see Chapter 5) and although the individual catchments are smaller, they cannot be simulated independently and then used together. Therefore spatial–temporal methods were investigated, particularly GLM which has a software application. However, there are similar catchment size issues with GLM, which has a cautionary limit of 2,000 km^2 (inter-site dependence may decline for very large areas) and would be complex to implement given the high number of gauges. Furthermore, although spatial representation of rainfall (and change in rainfall, see below) are important, the benefits of spatial–temporal modelling diminishes with catchment size, as response runoff distribution becomes the dominant factor governing runoff generation (Wheater *et al.*, 2006).

The detailed methods for each catchment are discussed further in the following two sections.

7.2 Bedford Ouse

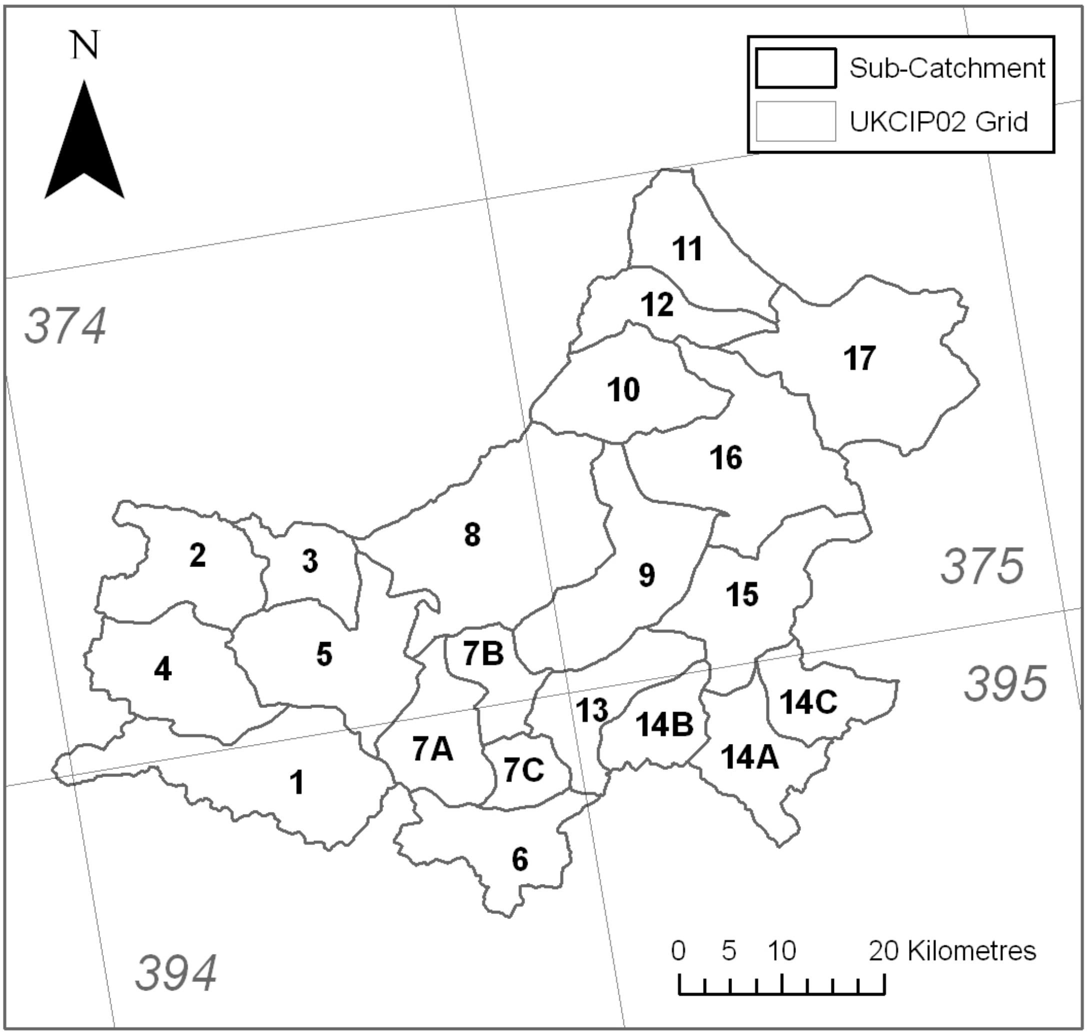
7.2.1 Precipitation

For the Bedford Ouse catchment, a proportional change factor approach will be used to generate a continuous series for input to the NAM rainfall–runoff model. This will allow the analysis of known events ‘with climate change’ and will be relatively quick to apply. However, a stochastic method will also be employed for the upper five catchments (see below). Although the individual catchments require a sub-daily input of rainfall, the selected receptors of interest (see Section 5.2.2) are in the lower catchment and therefore daily rainfall will be used as described in Section 6.1.2.

During initial investigations, it was found that care must be taken in computing perturbed areal rainfall in cases where spatial variability is high and where change factors are different. Specifically, when calculating total catchment areal rainfall from contributing sub-catchment areal rainfalls, and where the change factors being applied are different, then it is important not to average the change factor and apply that; rather, change factors should be applied to the areas they relate to and then the new areal rainfalls summed. Similarly, if areal rainfall totals are made up of areas of quite different baseline rainfall, as may occur over large catchments or where there are significant topographic variations, applying different change factors to averaged baseline rainfall could misrepresent the true areal rainfall under climate change. Therefore, if change factors are very different, it is important that areal rainfalls represent areas of homogeneous rainfall; if not, such areas should be identified and change factors applied to these. The split of the case study catchments into numerous smaller catchments should help in this respect, although the split was based on hydrological response rather than rainfall characteristics.

As discussed in Section 6.1.2, precipitation will be based on the daily 5 km by 5 km UKMO gridded baseline. UKCIP has produced a set of *climate* scenarios based on these data for a limited set of variables including precipitation and temperature. The climate scenarios have been produced by interpolating the climate changes projected by the RCM onto the same 5 km by 5 km grid[33]. However, precipitation is only available on a monthly basis. This thesis will therefore use the UKCIP02 change factors and apply these to the baseline rainfall series. For each catchment, change factors have been calculated based on a weighted average of the contributing HadRM3 grid squares (see Figure 7-1). Contributions of less than 5% have been re-allocated.

Figure 7-1 The UKCIP02 grid and the Bedford Ouse catchments

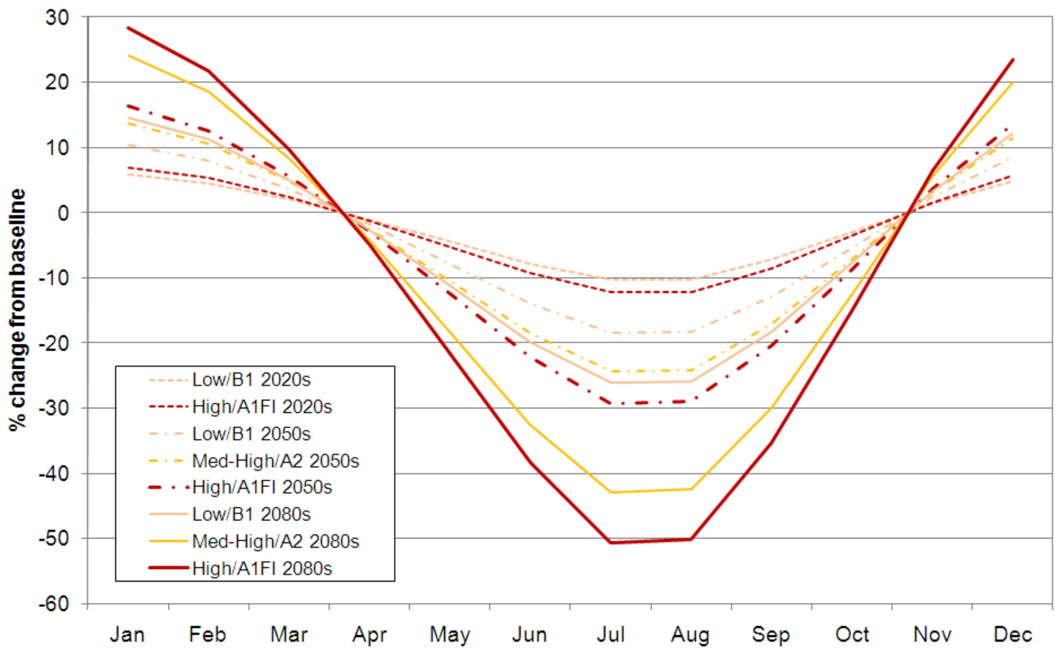


[33] See http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=349&Itemid=404#5km

As change factors are being produced for application to the observed 5 km by 5 km grid, there is no need for bias correction or spatial disaggregation. However, Kay and Davies (2008) point out that any bias in a climate model's ability to reproduce current climate does affect the confidence of its future simulations, even if it does not directly affect the water balance within the hydrological model. In any case, bias correction will only correct for baseline discrepancies. Of more importance to both bias correction and spatial interpolation is the use of appropriately downscaled data, and use of RCM data will be of benefit here. Spatial interpolation of some kind (e.g. bi-linear or geometric) could be used to smooth any discontinuities between RCM grid-box change factors. However, such discontinuities are small (see below and Figures 7-3 and 7-6); ignoring small contributions the catchments typically relate to one or two HadRM3 grid cells (Figure 7-1) and two to three quasi 0.25° CRU grid cells (see below including Figure 7-4). Therefore, no spatial interpolation will be used.

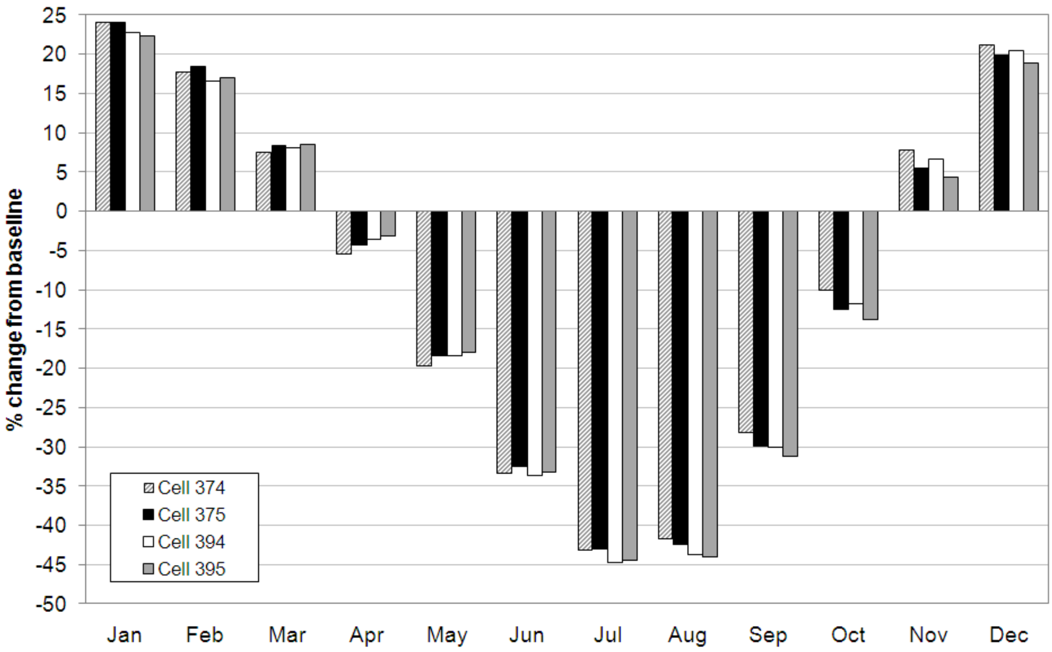
The UKCIP02 change factors for the most dominant HadRM3 grid cell (375) are illustrated in Figure 7-2. These project wetter winters (November to March) and drier summers (April to October). The factors are scaled from the IPCC SRES A2 emissions scenario for the 2080s (Hulme *et al.*, 2002), so other timeslices and emissions scenarios follow the same pattern, with later timeslices and higher emissions the most accentuated. The differences between the four grid cells of relevance (Figure 7-3) are generally small, with a slight north-west to south-east gradient.

Figure 7-2 Monthly precipitation change factors for HadRM3/UKCIP02 grid cell 375 under the UKCIP02 scenarios



Note that graph is based on monthly data: the lines are provided for ease of reference. For details of scenarios, see Hulme *et al*. (2002). Original in colour.

Figure 7-3 Monthly precipitation change factors for HadRM3/UKCIP02 grid cells 374, 375, 394 and 395 under the UKCIP02 Medium-High (SRES A2) emissions scenario for the 2080s



In addition to the UKCIP02 scenarios, produced using HadCM3-HadRM3, several alternative GCM–RCM combinations from the ENSEMBLES project will be used to investigate climate model uncertainty. From a large pool of GCM–RCM combinations, those taken forward[34] were those that provided different combinations, had runs from pre-1961 to c. 2100, provided precipitation, average daily near surface maximum and minimum temperatures (tasmax and tasmin), and provided outputs already converted from their native grid to a quasi 0.25° CRU grid. Those selected are described in Table 7-2; note that the first column provides the acronym with which the models are subsequently referred to in this thesis.

Table 7-2 Details of climate models used in scenarios

Acronym	Modelling centre	GCM	GCM grid size (R = regular; G = Gaussian)	GCM TCR*	RCM	RCM grid size (approx.)
DMI	DMI	ARPEGE	2.8125° (G)	unknown	HIRHAM	25x25 km
ETH	ETHZ	HadCM3Q0	1.25x1.875° (R)	2.0°C	CLM	25x25 km
KNMI	KNMI	ECHAM5	1.875° (G)	2.2°C	RACMO	25x25 km
MPI	MPI	ECHAM5	1.875° (G)	2.2°C	REMO	25x25 km
SMHI	SMHI	BCM	2.8125° (G)	unknown	RCA	25x25 km
UK02	METO-HC	HadCM3	1.25x1.875° (R)	2.0°C	HadRM3	50x50 km

ENSEMBLES information from ENSEMBLES project RT3 website[35] and UK02 information from Hulme *et al*. (2002) except for *(GCM transient climate responses) from Table 8.2 of Randall *et al*. (2007).

[34] Thanks to David Lister, CRU, for help with identifying problems with initially proposed combinations.
[35] http://ensemblesrt3.dmi.dk/

The raw model data (monthly precipitation totals and average daily monthly tasmax and tasmin) for the SRES A1B emissions scenario were extracted for the grid cells of interest by David Lister at the Climatic Research Unit, UEA, using the IDL code. Two further problems with the data were identified during this process. Firstly, the ETH files had a month missing, which was confirmed (by Daniel Luethi, ETH, through correspondence with David Lister) as December 2099 (the simulation for this model ends in 2099, rather than 2100). Secondly, the SMHI files had a year missing, which was confirmed as 2100 (Anders Ullerstig, SMHI, personal communication). Identifying these issues was important in correctly calculating the change factors described below.

Monthly change factors for the 2080s were produced for each GCM–RCM combination by comparing the mean monthly values for the period 2071–2100 with those of 1961–1990 (to provide a consistent baseline with UKCIP02). These were simply calculated as the future 30-year monthly mean average daily precipitation divided by that for the baseline.

Finally, the quasi 0.25° CRU grid change factors have been interpolated for each sub-catchment based on a weighted average of the contributing grid squares (see Figure 7-4). Contributions of less than 5% have been re-allocated (plus two slightly larger contributions that were of 1% or less of the whole catchment). A quasi 0.25° CRU grid (the common format for the ENSEMBLES data) was created in ArcMap[36] and the Bedford Ouse catchments were overlain[37]. Figure 7-4 is based on the geographic coordinate system used in creating the quasi 0.25° CRU grid, which is known as 'WGS 1984'[38]. This stretches the Bedford Ouse catchments when compared with the projected coordinate system more traditionally used in maps (see Figure 7-1). Overlapping areas were calculated in ArcMap 'on the fly' based on a projected system, thus preserving true areas.

The change factors derived from each GCM–RCM for the whole of the Bedford Ouse catchment have also been calculated (using an area-weighted mean) and are illustrated in Figure 7-5, which includes the change factors from the UKCIP02 2080s Medium-High (SRES A2) emissions scenario. These project wetter winters (November to March) and drier summers (April to October), although there is significant variability between GCM–RCM combinations. The differences between the grid cells of relevance are generally small, although can be large in summer, and are larger than those in UKCIP02 (Figure 7-3).

[36] Thanks to Paul Morgalla, Atkins, for creating the ArcMap Shapefile from the author's database.
[37] Thanks to Paul Morgalla, Atkins, for help with setting projections in ArcMap.
[38] World Geodetic System 1984 datum is a set of conventions, adopted constants and formulae used for Global Positioning Systems (OS, 2008).

Figure 7-4 The quasi 0.25° CRU grid used in ENSEMBLES and the Bedford Ouse catchments

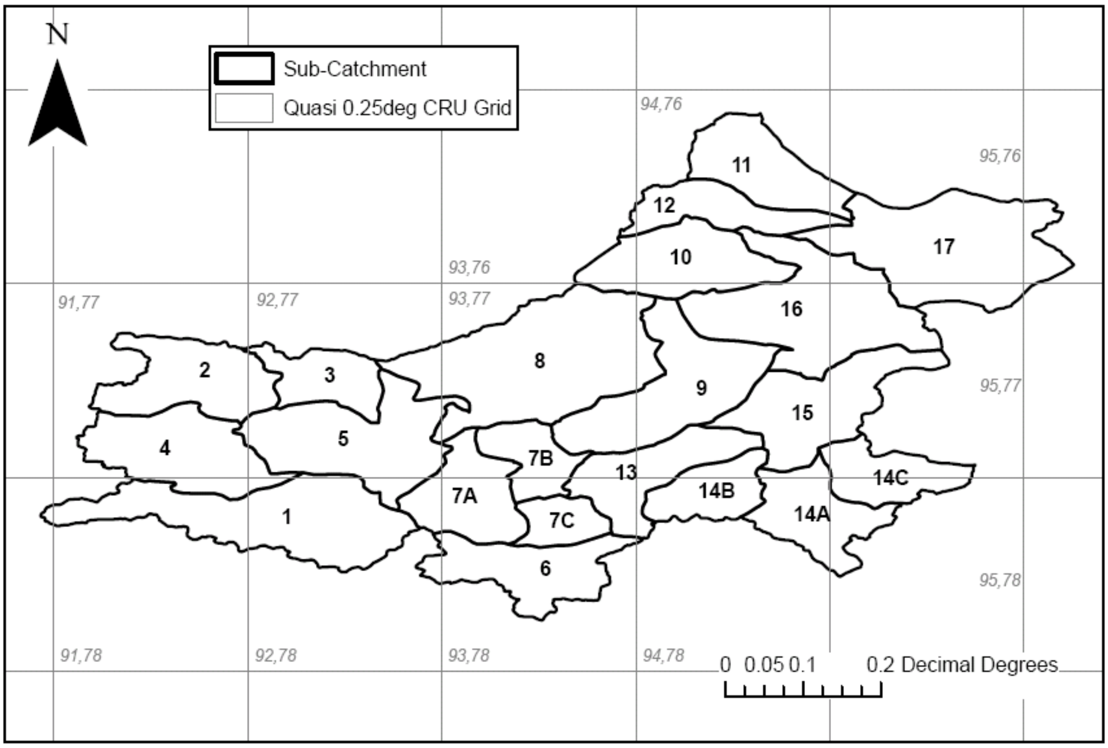
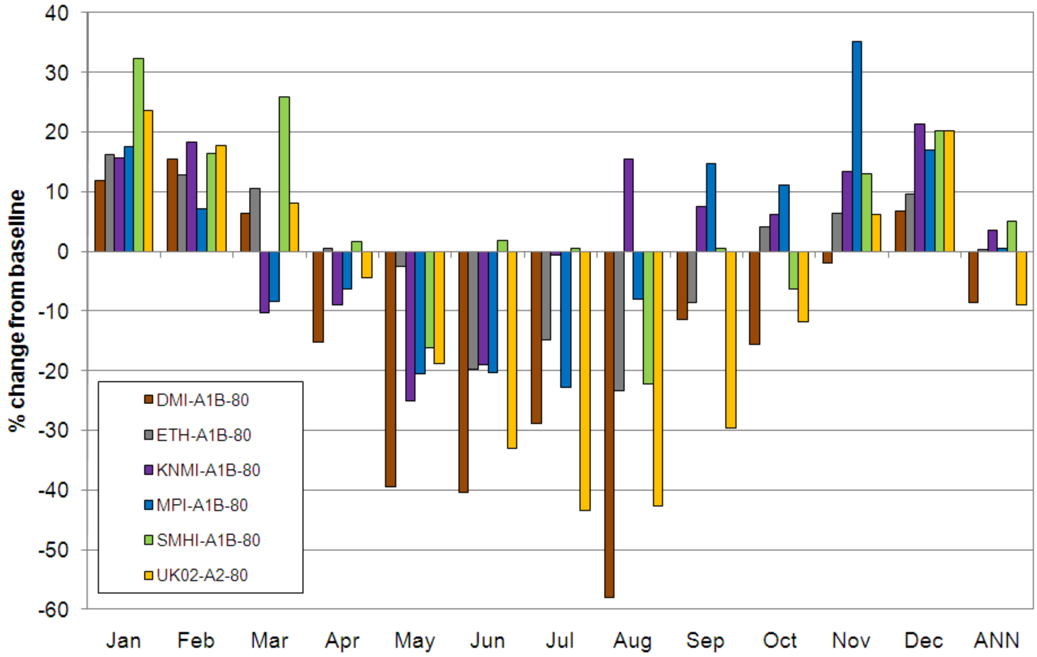


Figure 7-5 Monthly precipitation 2080s change factors for the Bedford Ouse catchment under different GCM–RCM combinations for the SRES A1B emissions scenario



Note that the UKCIP02 2080s Medium-High scenario relates to the A2 SRES emissions scenario. Original in colour.

7.2.2 Potential evapotranspiration

There are no readily available change factors for PET, so these have been calculated for each month using variables drawn from the UKCIP02 and ENSEMBLES scenario data. Kay and Davies (2008) compared the monthly mean performance of the Penman–Monteith equation of PET (Monteith, 1965) with a simpler temperature-based formula of PET (Oudin *et al.*, 2005) using variables drawn from climate models (GCMs and RCMs driven generally by HadAM3H). Kay and Davies (2008) found that the simpler temperature-based formula of PET matched MORECS PET more closely for the baseline period than the Penman–Monteith equation, with the RCM data in particular providing a better representation of the north-west to south-east gradient of annual PET, although this was largely due to an accentuation of the seasonal PET cycle. For some RCMs the Penman–Monteith formula provided the greater spatial variability seen in the MORECS baseline, which was attributed to the additional variables. In terms of changes in PET (and focusing here on the GCMs, which drive the changes), there were large differences between the two formulae geographically, seasonally and between climate models. For example, the changes projected by ECHAM4 using the Penman–Monteith equation were, in 'North Britain', close to zero in summer, around 80% in September and 20% in October. When applied to hydrological models of three contrasting catchments, differences were evident in the modelled flows. This was particularly the case for the southern catchment (high Base Flow Index, BFI) under the HadCM3 and ECHAM4 models where the impact of the temperature-based formula was much greater, although in general the differences for high flows were lower than for average and low flows.

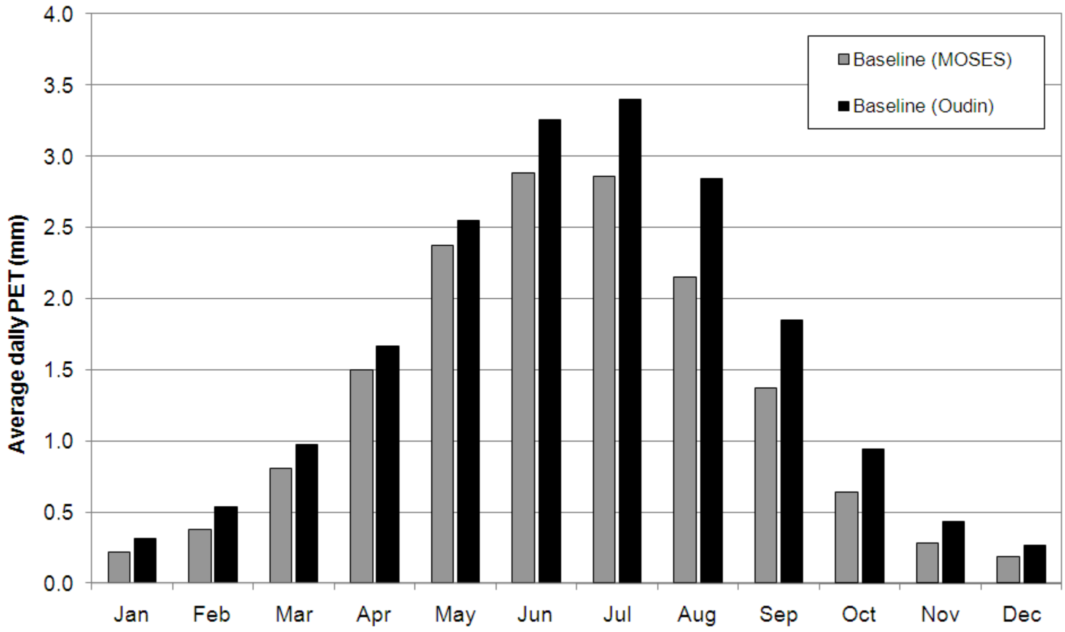
A variety of alternative equations exist for PET, for example Thornthwaite (1948) and Blaney–Criddle (1950), but this thesis will utilise that proposed by Oudin *et al*. (2005). Oudin *et al*. examined 27 PET models to identify the most relevant for use at the basin scale in a daily lumped conceptual rainfall–runoff model (like NAM) based on available atmospheric variables; rather than attempting to use the best replication of PET at a small scale, the objective was to identify that which facilitated better prediction and, where efficiency was similar, to identify a formula on the basis of simplicity. The first conclusion was that time-varying PET is only very marginally better than mean PET. The second was that energy based parameters are much more efficient than aerodynamic parameters, and that temperature-only based models can improve rainfall–runoff model efficiency.

On this basis Oudin *et al*. (2005) present a simple, common formula for computing PET, which is adopted here. Although the adjustment factors could change depending on the rainfall–runoff model, this is not an issue when producing proportional change factors. This method performs well for high-flow applications, and avoids problems associated with non-temperature Penman variables, such as bias and the need for substitution (see Kay and

Davies, 2008). It will also avoid the problems associated with high vapour pressure deficit in HadRM3H (Ekström *et al.*, 2007b) which can lead to very high estimates of PET using the Penman-Monteith equation and variants (as exemplified in Ekström *et al.*, 2007b; and Kay and Davies, 2008).

A comparison of PET produced by MOSES and the formula of Oudin *et al*. (see Figure 7-6) shows that the latter produces higher monthly average daily values of PET: the biggest absolute differences are in summer and early autumn, although the largest proportional changes occur in autumn and winter. The timing of the absolute differences, and the later maximum in the Oudin *et al*. formula, demonstrates the greater relative reliance on temperature. The PET factors will be applied to baseline PET based on MOSES, which is what the hydrological model is calibrated using, and therefore the baseline differences are not particularly important.

Figure 7-6 A comparison of monthly average daily PET based on MOSES and Oudin *et al*. (2005)



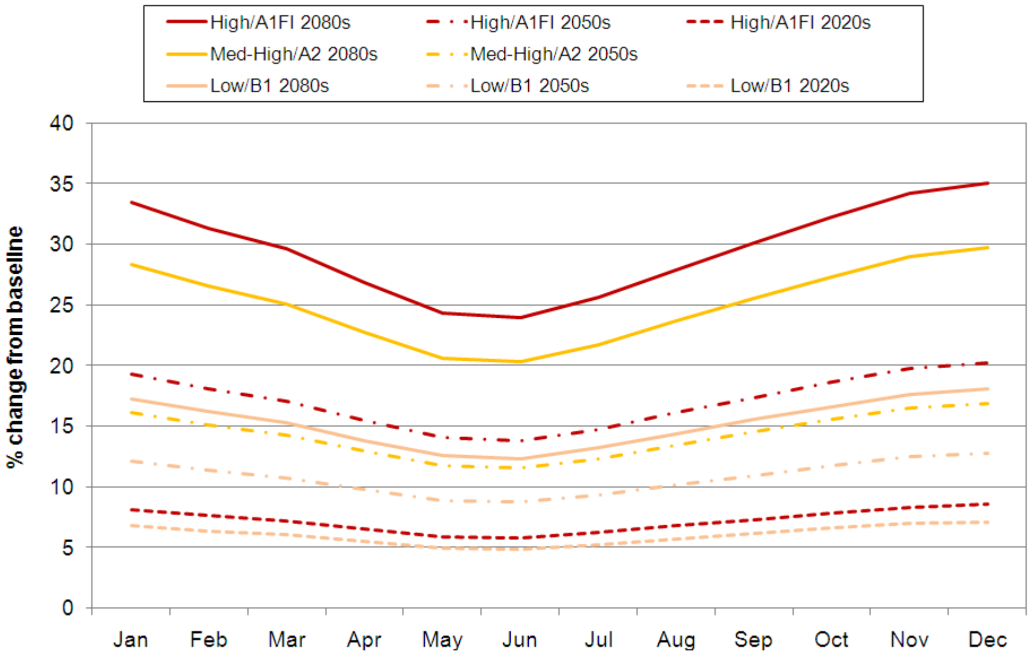
Future mean daily PET was calculated using the following steps:

1. Calculate the conventional mean daily temperature for each (average) month of the baseline period by averaging TMAX and TMIN from the climate model.
2. Calculate daily PET for the average year of the baseline period using the formula of Oudin *et al*. (2005) based on average monthly temperature (from Step 1) and average for each month.
3. Calculate actual TMAX and TMIN for future timeslices by adding the change factors to the baseline TMAX and TMIN values.
4. Calculate the conventional mean daily temperature for each (average) month of the future timeslice by averaging future TMAX and TMIN (from Step 3).
5. Calculate daily PET for the average year of the future timeslice using the formula of Oudin *et al*. (2005) based on average monthly temperature (from Step 4) and average for each month.
6. Calculate the change in mean daily PET by dividing the value for the future timeslice (from Step 5) by that for the baseline (from Step 2).
7. Apply the monthly change factors (from Step 6) to the baseline (MOSES) PET data.

For the ENSEMBLES data, the method was slightly adjusted: the baseline monthly mean tasmax and tasmin values were input into Step 1, the 2080s values were input into Step 4, with Step 3 superfluous where climate model temperature data are used directly.

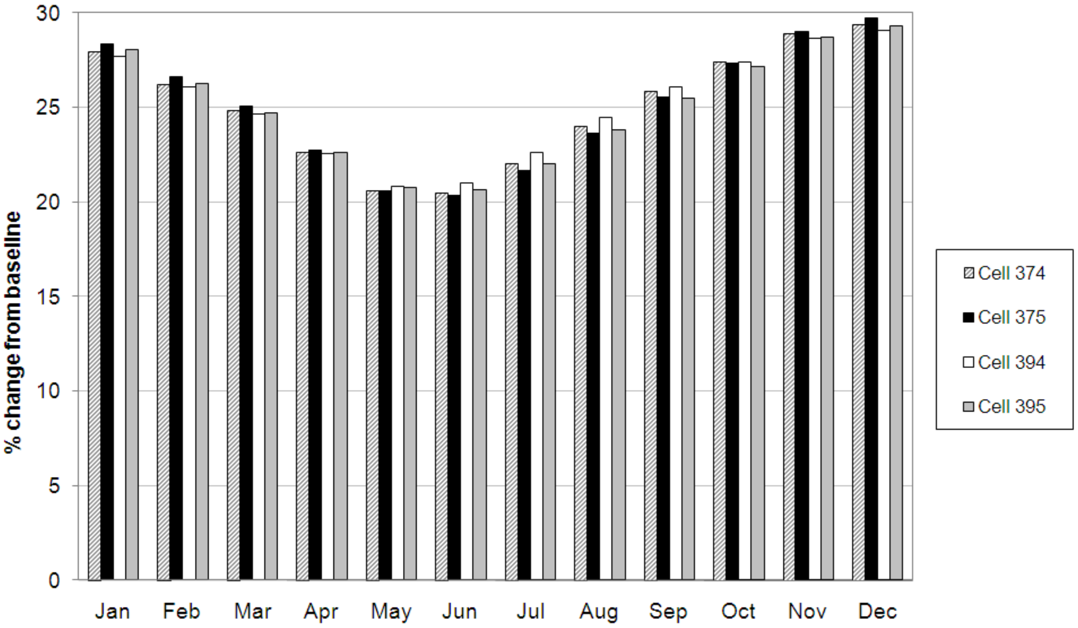
The UKCIP02 change factors for the most dominant HadRM3 grid cell (375) are illustrated in Figure 7-7. These project increases in PET throughout the year, with the biggest proportional changes occurring in winter, although the biggest absolute changes will be in summer. The factors are scaled from the SRES A2 emissions scenario for the 2080s (Hulme *et al.*, 2002), so other timeslices and emissions scenarios follow the same pattern, with later timeslices and higher emissions showing larger increases. The differences between the four grid cells of relevance are generally small (Figure 7-8).

Figure 7-7 Monthly PET change factors for HadRM3/UKCIP02 grid cell 375 under various emissions scenarios and timeslices



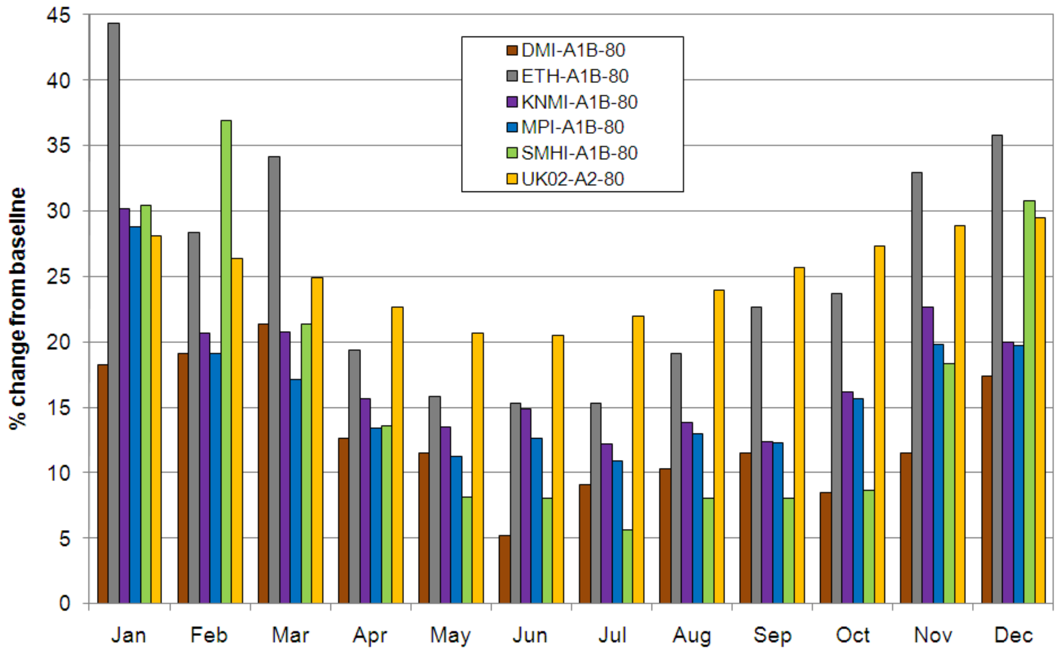
Note that graph is based on monthly data: the lines are provided for ease of reference. For details of scenarios, see Hulme *et al*. (2002). Original in colour.

Figure 7-8 Monthly PET change factors for HadRM3/UKCIP02 grid cells 374, 375, 394 and 395 under the SRES A2 emissions scenario for the 2080s



The change factors derived from each of the selected ENSEMBLES GCM–RCM combinations have been calculated (using an area-weighted mean) for the whole of the Bedford Ouse catchment (see Figure 7-9). The change factors from the UKCIP02 2080s Medium-High (A2 SRES) emissions scenario have also been calculated for the whole of the Bedford Ouse and are shown for comparison in Figure 7-9 (labelled as 'UK02-A2-80'). The differences in the change factors between contributing quasi 0.25° CRU grid cells are negligible, which is expected given the small spatial variation of temperature and latitude.

Figure 7-9 Monthly PET 2080s change factors for the Bedford Ouse catchment under different GCM–RCM combinations for the SRES A1B emissions scenario



Note that the UKCIP02 2080s Medium-High scenario relates to the SRES A2 emissions scenario. Original in colour.

7.2.3 Stochastic approach

A second modelling approach will be used to investigate the effect of using a stochastic weather generator. This approach will use EARWIG and therefore will be limited to the upper catchment (the 800 km^2 above Newport Pagnell). Five alternative model scenarios from PRUDENCE (embedded in EARWIG v2.1) will be run for the 2080s, all based on the SRES A2 emissions scenario.

7.2.4 Summary

The methods proposed range from simplistic change factors to the use of a stochastic weather generator for the upper catchment. They will demonstrate the use of reasonably simple techniques for climate change impact assessment suitable for input into rainfall–runoff models used in practice. A range of emissions scenarios and GCMs will be considered. Downscaling will be dynamic to the RCM level with a simple form of statistical downscaling to the 5 km by 5 km grid level. Overall, two climate change scenarios will be modelled for the 2020s, two for the 2050s and nine for the 2080s, plus a further five for the 2080s using the weather generator (see Table 7-3).

Table 7-3 Summary of methods and scenarios for the Bedford Ouse catchment

Details	**Main modelling**	**Stochastic modelling (upper catchment only)**
Approach	Proportional change factor	Advanced change factor, plus stochastic weather generator
Rainfall–runoff model	NAM (continuous, lumped, conceptual)	NAM (continuous, lumped, conceptual)
Baseline precipitation	UKMO gridded daily: 1958–1990	(UKMO gridded daily: 1961–1990); 300 years
Baseline PET	MOSES	(MORECS); 300 years
Climate change precipitation factor	UKCIP02 (B1, A2*, A1FI; 3 timeslices), ENSEMBLES x5 (A1B 2080s only)	EARWIG x5, driven by UKCIP02 & PRUDENCE x4 (A2 2080s only)
Climate change PET factor	Calculated from UKCIP02 (B1, A2*, A1FI; 3 timeslices), ENSEMBLES x5 (A1B 2080s only)	EARWIG x5, driven by UKCIP02 & PRUDENCE x4 (A2 2080s only)
Other inputs and assumptions	Assume other parameters remain the same	Assume other parameters remain the same

*This will not be modelled for the 2020s.

7.3 Eden catchment

7.3.1 A method for perturbing the FEH rainfall–runoff model

There are no continuous rainfall–runoff models available for the Eden catchment, although a real-time flood forecasting model has been developed. Recent flood risk mapping and design studies have used FEH or event-based hydrographs as input into hydraulic models. It is possible to develop continuous models based on the data available, but this research is seeking to use existing models that are used in current decision making. The unit hydrograph method provides a contrast with NAM used for the Bedford Ouse.

There is no simple or conceptually satisfying way to perturb a hydrograph, or a discrete event rainfall–runoff model. This is because change in climate is dynamic over time and through space, and it is hard to integrate such complexity in one or even a few parameters. However, given that baseline estimates of design floods are made using this approach, it is nonetheless possible.

Direct perturbation of a hydrograph, or specifically the peak flow, is the most reductionist and least satisfactory method. It can only be achieved by using an assumption regarding the response to rainfall, which is only likely to be reliable in small and simple catchments, or where knowledge can be applied from donor catchments based on similarity. Original guidance from Defra (2003b) recommended a sensitivity test of an additional 20% in peak *river flow or volume* over 50 years. As described in Section 3.2.2.2, this was based on research in the Thames and Severn catchments (Reynard *et al.*, 1998; Reynard *et al.*, 2001), which has been subsequently applied with little consideration of catchment similarity. This sensitivity figure still exists and is recommended for application to larger catchments (Defra, 2006).

A better approach is to perturb a rainfall–runoff model, which has a number of parameters describing the event and antecedent conditions. The rainfall–runoff model included in FEH (Houghton-Carr, 1999), a restatement of the FSR rainfall–runoff method, is widely used in design studies. At its core is a three-component unit hydrograph and losses model: the unit hydrograph (parameterised by the time to peak, *Tp*), the percentage runoff (*PR*) and the baseflow (*BF*). The parameters are ideally derived from rainfall and runoff records, although they can be estimated, via multiple regression equations, from catchment descriptors enabling estimates to be made at ungauged locations (ibid.). There are four model inputs: storm duration (*D*), storm depth (*P*), storm profile and antecedent catchment wetness (*CWI*). The first three define the total rainfall hyetograph of the event; these can be gained from observations or can be estimated for an event of a design return period using the FEH depth-duration-frequency (DDF) model. Catchment wetness is used in calculations of percentage runoff (which computes the effective rainfall hyetograph) and baseflow (which is added to the rapid response runoff hydrograph to give the total runoff hydrograph). Detailed formulae for the calculation of inputs and parameters are set out in Box 7-1.

Perturbation of the FSR/FEH rainfall–runoff model can be achieved, albeit rather crudely, by adjusting the inputs and parameters. This assumes that the regression relationships are robust and perform reliably when adjustments are made. The only example found of a climate change impact study using the FEH rainfall–runoff model was that of Lane *et al*. (2007), who only perturbed rainfall. HR Wallingford (2003) outlines a potential method based on storm profiles from RCM rainfall statistics and changes to baseflow calculated indirectly by applying changes to antecedent precipitation, soil moisture deficit and annual average rainfall. This has been developed further here and is summarised in Table 7-4. The method presumes that sites of interest are gauged and that upstream catchment rainfall records exist; it therefore assumes that inputs and parameters have already been computed based on flood events; there is more certainty with calibrated events and use of depth-duration rainfall statistics for low-frequency events may be problematic given the uncertainties in changes to rainfall (see below), although this also applies to rare observed events.

Table 7-4 Potential method for a climate change perturbation of FSR/FEH rainfall–runoff model inputs and parameters at gauged sites

Root input, parameter or constant	Sensitivity to climate change	Potential perturbation method
Time to peak (*Tp*)	Indirect via land-use change	None: effect of land-use impacts and autonomous land-use adaptation ignored
Standard percentage runoff (*SPR*)	Indirect via land-use change	None: effect of land-use impacts and autonomous land-use adaptation ignored
Percentage runoff from impervious urban areas (currently 70%)	Direct, moderate	Could be inferred from change in rainfall intensity
Standard annual average rainfall (*SAAR*)	Direct, high*	Re-calculate for future 30-year timeslice
Antecedent precipitation (*API*5)	Direct, high*	Change factor method or stochastic weather generation
Soil moisture deficit (*SMD*)	Direct, high (but low where *SMD* at or close to zero)	Change factor method applied directly to *SMD* or indirectly with use of soil moisture accounting model and inputs of rainfall and PET (but *SMD* often zero)
Storm duration (*D*), depth (*P*) and profile	Direct, high*	Change factor method (to retain duration and profile of known event); or stochastic weather generation (new duration, depth and profile)

*Based on the results (see in particular page 259), future peak flows are most sensitive to changes in storm depth (*P*) compared with average rainfall and event antecedent precipitation.

Box 7-1 Detailed calculations of inputs and parameters for the FSR/FEH rainfall–runoff model

The catchment wetness index, *CWI*, is calculated as:

$$CWI = 125 + API5 - SMD \qquad \text{(Eqn. 7.1)}$$

Where *SMD* is soil moisture deficit and *API*5 is the catchment average daily rainfall on the five days prior to the first day of the event. The *CWI* value is then adjusted to account for changes between 09:00 and the start of the event.

Time to peak, *Tp*, is the sole parameter for describing the unit hydrograph, which is a simple triangle of fixed shape. *Tp* is initially estimated for the equivalent instantaneous unit hydrograph (IUH), referred to as *Tp*(0), and then adjusted depending on the chosen time interval. The unit hydrograph is then computed, with *AREA* of the catchment being used to calculate peak flow (volume). When the site of interest is gauged, the preferred method for calculating *Tp*(0) is through the analysis of observed flood events. Alternatively, *Tp*(0) can be estimated, in order of preference, from catchment lag, catchment descriptors or by transfer from a donor catchment.

Percentage runoff from the natural part of the catchment, PR_{RURAL}, is calculated as:

$$PR_{RURAL} = SPR + DPR_{CWI} + DPR_{RAIN} \qquad \text{(Eqn. 7.2)}$$

SPR is a standard component which represents normal runoff generation. When the site of interest is gauged, *SPR* can be calculated as the mean catchment average *SPR* from observed events. Alternatively, *SPR* can be estimated, in order of preference, from the baseflow index, catchment descriptors (the hydrology of soil types, *HOST*, is currently used) or by transfer from a donor catchment.

DPR_{CWI} represents the variation in response due to the state of the catchment prior to the event:

$$DPR_{CWI} = 0.25\ (\mathrm{CWI} - 125) \qquad \text{(Eqn. 7.3)}$$

DPR_{RAIN} represents the variation due to the event itself:

$$DPR_{RAIN} = \begin{cases} 0 & \text{for } P \le 40 \text{ mm} \\ 0.45\ (P - 40)^{0.7} & \text{for } P > 40 \text{ mm} \end{cases} \qquad \text{(Eqn. 7.4)}$$

where *P* is the event precipitation. Total percentage runoff, *PR*, is estimated by adjusting PR_{RURAL} for the effects of urbanisation:

$$PR = PR_{RURAL}\ (1.0 - 0.615\ URBEXT) + 70\ (0.615\ URBEXT) \qquad \text{(Eqn. 7.5)}$$

where *URBEXT* is the urban extent. The adjustment assumes that 61.5% of the urban area is impervious and has a percentage runoff of 70%, whilst the remaining area has the same percentage runoff as the rural area.

If the site of interest is gauged the preferred method for estimating baseflow, *BF*, is by the analysis of observed events, calculated as the geometric mean. Alternatively, *BF* can be estimated from catchment descriptors (see Eqn. 7.6) or by transfer from a donor catchment.

$$BF = \{33\ (CWI - 125) + 3.0\ SAAR + 5.5\}\ 10^{-5}\ AREA \qquad \text{(Eqn. 7.6)}$$

where *SAAR* is standard average annual rainfall. Note that *BF* should be ≥ 0.

Source: Houghton-Carr (1999)

Tp and *SPR* are not directly affected by climate change. *Tp*(0) (see Box 7-1) depends only on catchment properties; climate change will only have an indirect effect via land-use change. Given that socio-economic changes are likely to dominate land use, this indirect effect is not considered further. *Tp* will also depend on the distribution of rainfall within a storm, for example whether storms are even or peaked, and when peaks occur; storm profiles are discussed further below. *SPR* will also only be affected indirectly via land-use change and is not considered further. For both parameters, it is important that a wide variety of historical events have been used to ensure that the values remain robust when used in climate change perturbations. The dynamic elements of *PR* are affected by changes to the inputs *P* and *CWI* (see below). *URBEXT* and the proportion of impermeable surface within urban areas are socio-economically determined. However, the constant that describes percentage runoff within urban areas may increase with climate change due to increased rainfall intensities, although this is complicated by drainage capacities and methods.

BF will be directly affected by climate change. Even when good records of baseflow exist, it will be necessary to use the catchment descriptors because perturbation of a hydrograph is problematic, as discussed above. Changes to *BF* will be determined by changes to *CWI* (see below) and *SAAR*. *SAAR* is simply the annual average rainfall for the 30-year timeslice in question. Given the preference for use of observed records, a proportional change calculated using the catchment descriptors can be applied to the observed values of *BF* where they exist.

CWI, which is an input as well as being used in the calculation of *PR* and *BF*, is itself calculated from *API*5 (five day antecedent rainfall) and *SMD* (see Box 7-1). *API*5 can be perturbed using a change factor method, which will retain the original event profile, or gained from a stochastic approach, which will generate a new profile. *SMD* can also be perturbed using a change factor method. This can be undertaken either directly, or indirectly with inputs of rainfall and PET using a soil moisture accounting model (e.g. Grindley, 1967), or more advanced model such as that incorporated into MORECS. It would also be possible to use a stochastic approach, although such time investment is unlikely to be warranted given that *SMD* is likely to be zero at the time of most major flood events.

Future storm events are likely to be sensitive to climate change. Winters are likely to be wetter, with an increase in precipitation intensity. The latter was assigned a high confidence in Hulme *et al*. (2002), who found an increase in 1-day, 2-year return period precipitation for the two grid boxes corresponding approximately to Cumbria for the 2080s under all emissions scenarios. Buonomo *et al*. (2007) also found an increase (in 1-day, 5-year return period precipitation) for HadRM3 boxes covering a similar area. Ekström *et al*. (2005), using the HadRM3H model, produced a decrease, although an increase was found for north-west England using a regional frequency approach (except for the 1 day event at the 25 and

50 year return periods). Fowler and Ekström (2009) found increases in 1-day, 5-year return period precipitation for a range of RCMs using a regional frequency approach, with large differences between RCMs.

In the context of the rainfall–runoff model, an increase in *P* can be assumed. However, there are large variations in estimates of short-duration precipitation extremes, even using the same climate model, which relates to the methods used. Therefore, and given that a perturbation approach is being used, a simple proportional change factor will be applied based on the corresponding change in monthly precipitation. Thus the baseline storm duration and profile will be retained; there is little evidence on which to base a change in these aspects, particularly as they are sub daily.

An alternative approach would be to use a stochastic method. This would involve extracting storm hyetographs from synthetic rainfall series, for example one produced by a weather generator such as EARWIG. However, although EARWIG would facilitate a better understanding of variability, it cannot define the duration and profile of sub-daily rainfall; furthermore the value of using it in isolation, compared to the perturbation of hourly data, is unclear. Nonetheless EARWIG could be used with a stochastic disaggregator to provide hourly data (now available in the UKCP09 weather generator). Another use would be to compare the difference in rainfall totals between baseline and future events of various durations and return periods, which has been adopted in UKWIR (2010 forthcoming).

A revitalised FSR/FEH rainfall–runoff method was published in 2005 (Kjeldsen *et al.*, 2005; Kjeldsen, 2007). This replaces the FSR/FEH rainfall–runoff model with the more sophisticated Revitalised Flood Hydrograph (ReFH) model and it was hoped to use this model in this thesis. However, although it is possible to simulate an event, estimating the parameters is time and data intensive (Kjeldsen, 2007) and the available spreadsheet model is only a design model with no option to simulate an observed or synthetically derived event. Furthermore, current hydrological inputs to the Eden models are based on and calibrated using FEH, with the hydraulic models calibrated accordingly. It was therefore decided not to use the revitalised method.

7.3.2 Precipitation scenarios

As discussed a proportional change factor approach will be used to estimate the uplift due to climate change to historical events and related antecedent conditions. This will be based on three event-based models which have been calibrated on discharges at times of flood.

Change factors (precipitation only) have been derived directly from the UKCIP02 scenarios and the ENSEMBLES project as described in Section 7.2.1 above. The position of the Eden catchment in relation to the UKCIP02 and quasi 0.25° CRU grids is illustrated in Figures 7-10 and 7-11 respectively. The UKCIP02 change factors for grid cell 255 (Figure 7-10), which covers the eastern side of the Cumbria High Fells, an area generating much rainfall at present, are illustrated in Figure 7-12. These show a decrease in summer precipitation (May to September) and an increase in winter precipitation (November to March). The changes are reasonably consistent between all of the contributing UKCIP02 grid cells (Figure 7-13), although the western catchment cells 236 and in particular 255 have a greater winter uplift and cell 255 has a notably lower decrease in summer. The increase in winter rainfall in the wettest parts of the catchment is likely to have a significant influence on flooding. The change factors derived from the ENSEMBLES GCM–RCM combinations (for the 2080s, SRES A1B emissions scenario only) have been calculated (based on an area-weighted mean) for the whole Eden catchment and are illustrated in Figure 7-14. These show a greater spread of potential changes (which are more extreme for individual cells), and large variation between climate models, although there is general agreement that winters will be wetter.

Figure 7-10 The UKCIP02 grid and the Eden catchments

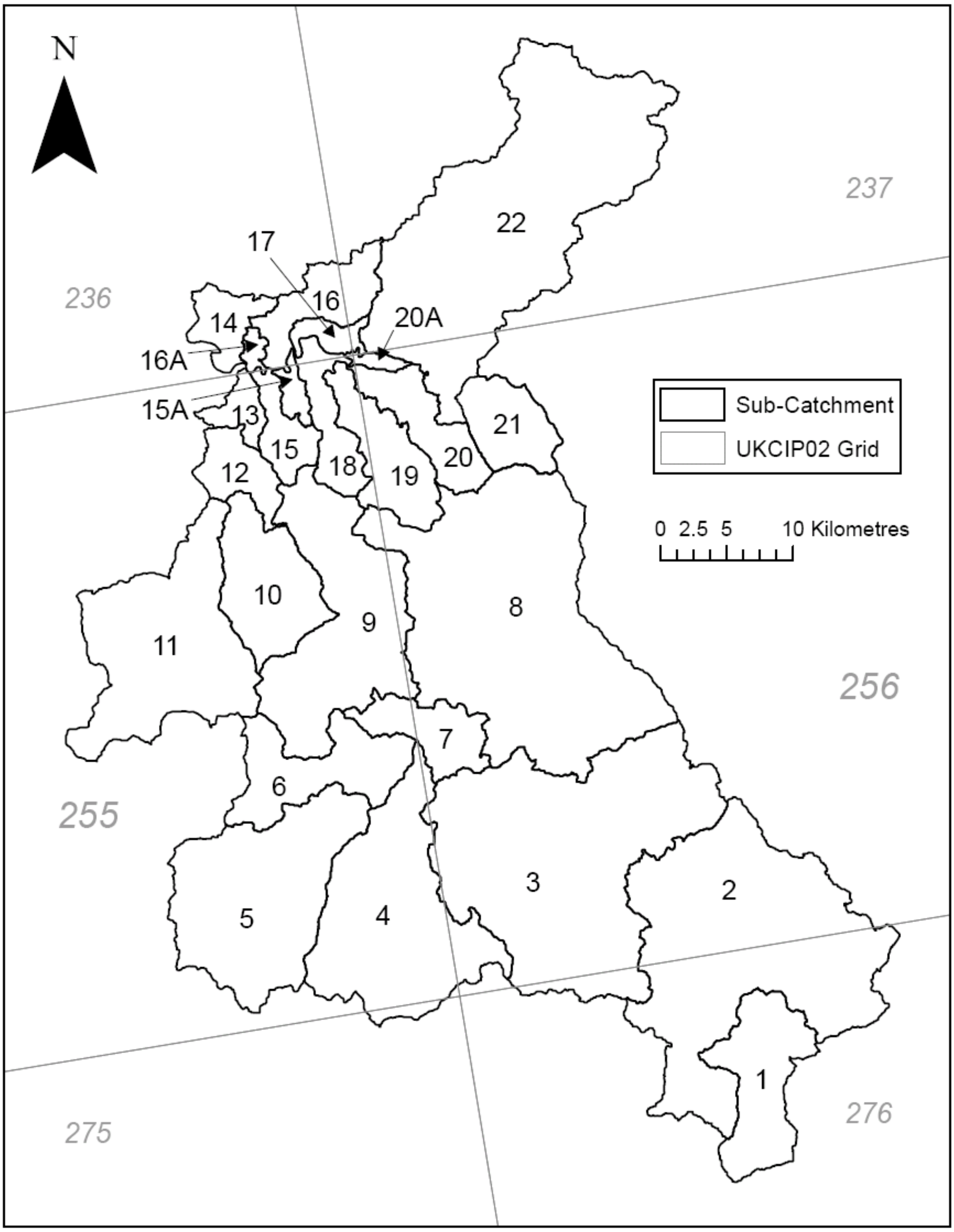


Figure 7-11 The quasi 0.25° CRU grid used in ENSEMBLES and the Eden catchments

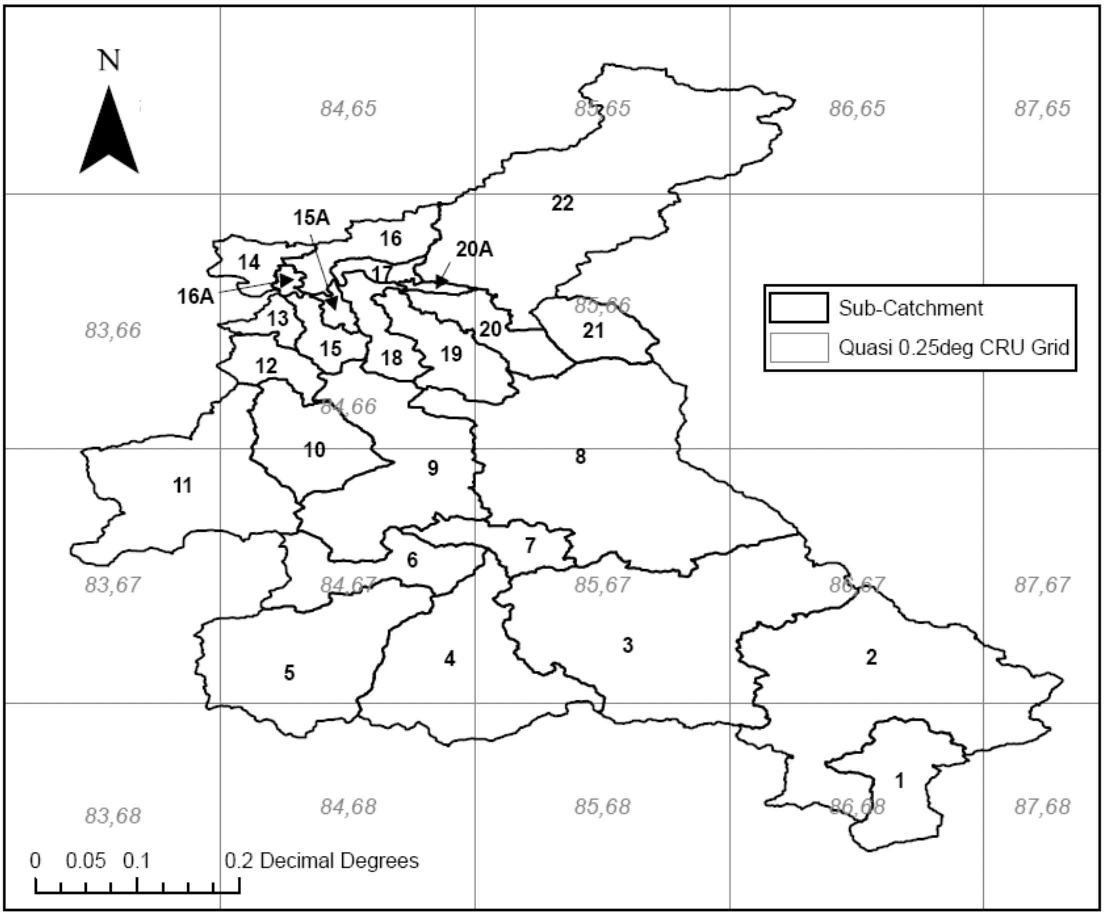
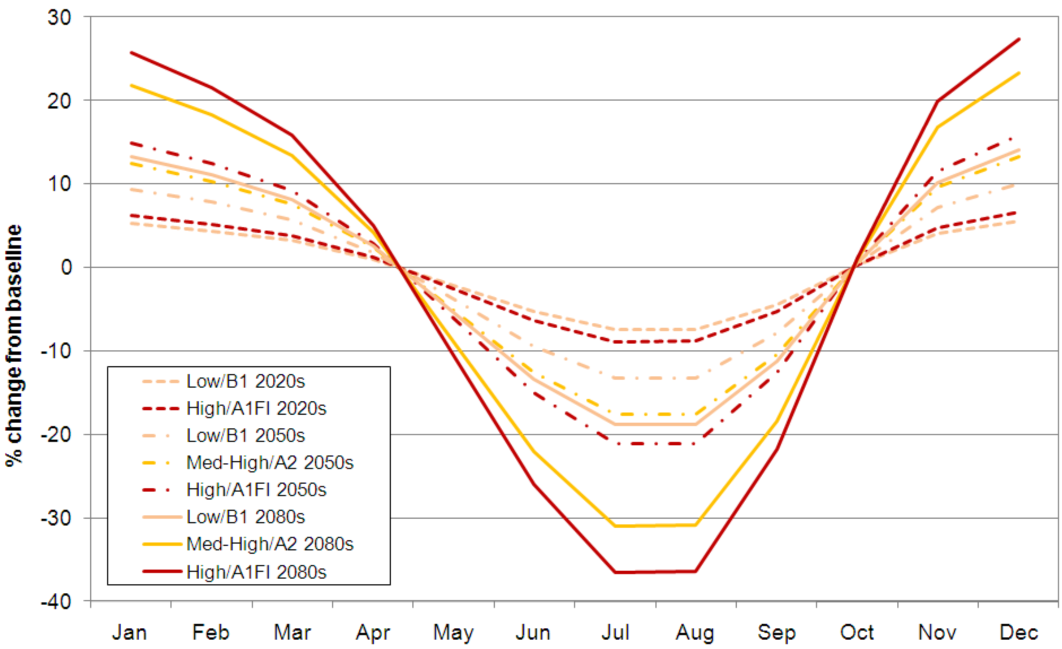
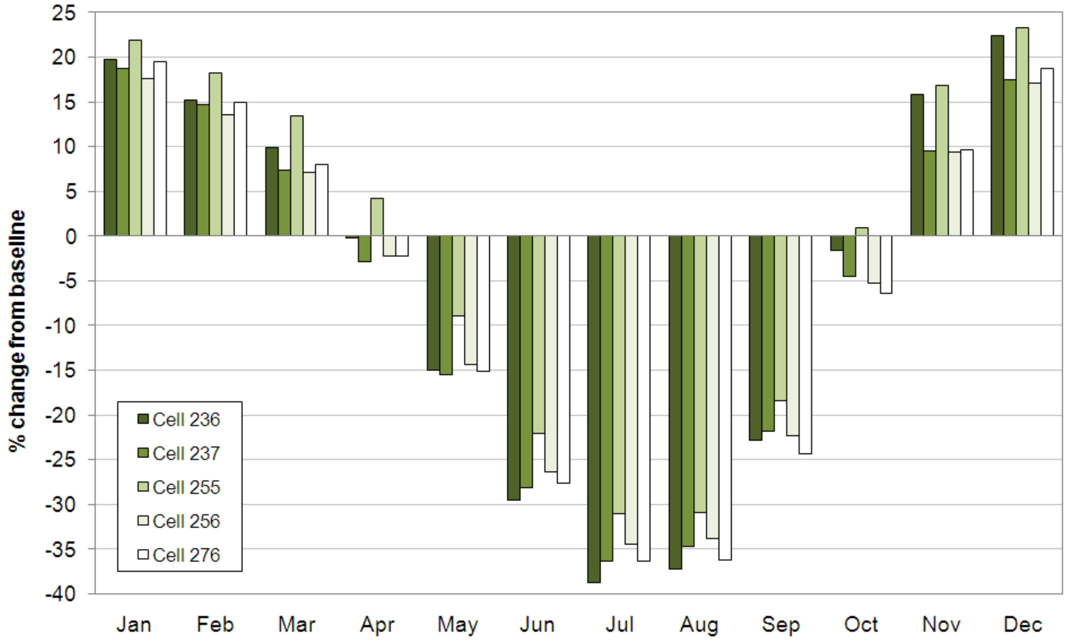


Figure 7-12 Monthly precipitation change factors for HadRM3/UKCIP02 grid cell 255 under the UKCIP02 scenarios



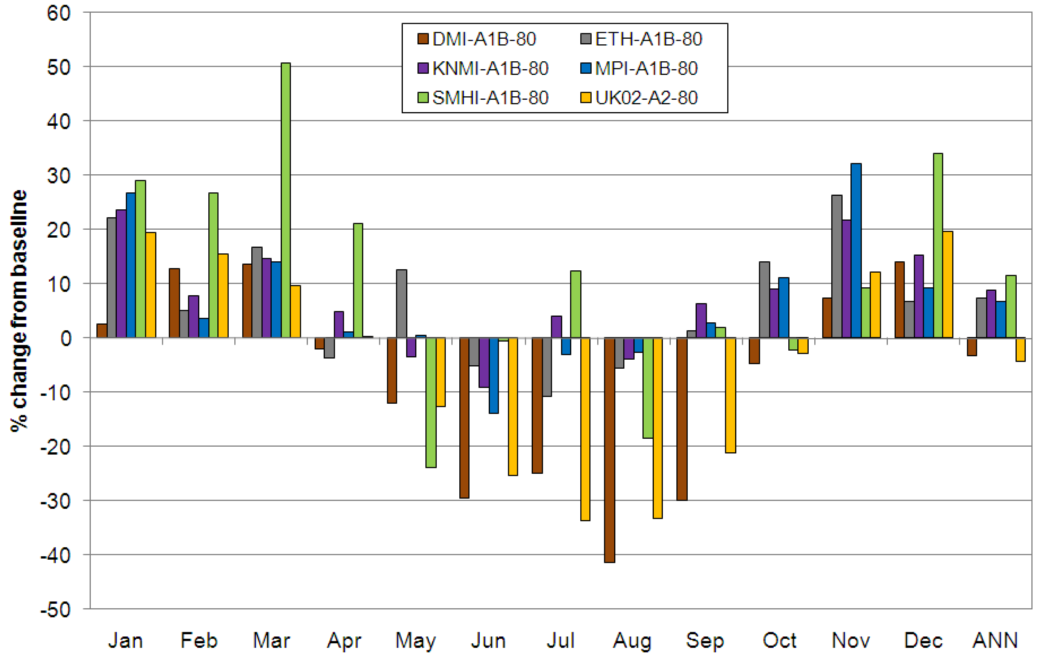
Note that graph is based on monthly data: the lines are provided for ease of reference. For details of scenarios, see Hulme *et al*. (2002). Original in colour.

Figure 7-13 Monthly precipitation change factors for HadRM3/UKCIP02 grid cells 236, 237, 255, 256 and 276 under the UKCIP02 Medium-High (SRES A2) emissions scenario for the 2080s



Original in colour.

Figure 7-14 Monthly precipitation 2080s change factors for the Eden catchment under different GCM–RCM combinations for the SRES A1B emissions scenario



Note that the UKCIP02 2080s Medium-High scenario relates to the SRES A2 emissions scenario. Original in colour.

7.3.3 Summary

The method proposed for the Eden catchment provides a simple approach to test the perturbation of the event-based FEH rainfall–runoff model (from which more complex methods of perturbation could be invoked in future). A range of emissions scenarios and GCMs will be considered. Downscaling will be dynamic via the RCMs only. Two climate change scenarios have been produced for the 2020s, three for the 2050s and eight for the 2080s (see Table 7-5).

Table 7-5 Summary of methods and scenarios for the Eden catchment

Details	Eden
Approach	Proportional change factor (applied to hyetographs and antecedent conditions)
Rainfall–runoff model	FEH (discrete, lumped, empirical)
Baseline precipitation	Event-based models
Baseline PET	Not required
Climate change precipitation factor	UKCIP02 (B1, A2*, A1FI; 3 timeslices), ENSEMBLES x5 (A1B 2080s only)
Climate change PET factor	Not required
Other inputs and assumptions	Assume regression relationships hold in future

*This will not be produced for the 2020s.

8. Future flooding: the Bedford Ouse

This chapter details the hydrological and hydraulic model runs undertaken, and describes the effect of the scenarios developed in Chapter 7 on future flooding in the Bedford Ouse catchment, introduced in Chapter 5. The first part summarises the model runs, model processes, assumptions, and how issues with model runs were resolved. The second part summarises the modelled baseline runs, the results of which are presented in the third and fourth parts, which detail the results of the perturbation and stochastic scenarios respectively. Results for the Eden catchment are presented in the next chapter. The concluding chapter presents a summary and comparison of the relative strengths and limitations of the approaches used in each catchment.

8.1 Model runs

The full model runs undertaken are summarised in Table 8-1. The rainfall–runoff and hydraulic models (for the 21 catchments) were run for the baseline and each of the 13 perturbations.

Table 8-1 Full model run schedule (baseline and 13 perturbed runs)

Reference	GCM–RCM	Emissions scenario^	Time period	Rainfall	PET
Base	n/a	n/a	1961–2001	UKMO gridded	MOSES corrected
UK02-B1-20	HadCM3-HadRM3*	B1	2020s	Base perturbed	Base perturbed
UK02-A1-20	HadCM3-HadRM3*	A1FI	2020s	Base perturbed	Base perturbed
UK02-B1-50	HadCM3-HadRM3*	B1	2050s	Base perturbed	Base perturbed
UK02-A2-50	HadCM3-HadRM3*	A2	2050s	Base perturbed	Base perturbed
UK02-A1-50	HadCM3-HadRM3*	A1FI	2050s	Base perturbed	Base perturbed
UK02-B1-80	HadCM3-HadRM3*	B1	2080s	Base perturbed	Base perturbed
UK02-A2-80	HadCM3-HadRM3*	A2	2080s	Base perturbed	Base perturbed
UK02-A1-80	HadCM3-HadRM3*	A1FI	2080s	Base perturbed	Base perturbed
KNMI-A1B-80	ECHAM5-RACMO**	A1B	2080s	Base perturbed	Base perturbed
SMHI-A1B-80	BCM-RCA**	A1B	2080s	Base perturbed	Base perturbed
MPI-A1B-80	ECHAM5-REMO**	A1B	2080s	Base perturbed	Base perturbed
ETH-A1B-80	HadCM3Q0-CLM**	A1B	2080s	Base perturbed	Base perturbed
DMI-A1B-80	ARPEGE-HIRHAM**	A1B	2080s	Base perturbed	Base perturbed

GCM–RCM output from *UKCIP02, **ENSEMBLES. ^IPCC SRES.

The NAM climate data specification and the MIKE11 modelling process are summarised in Box 8-1 (see Section 5.1.2.6 for a description Bedford Ouse model). The modelling process was very time and data intensive, requiring the creation and processing of more than 3,000 model files. Several assumptions were made regarding the models:

- Within the rainfall–runoff models, the groundwater abstractions (which vary on a monthly basis and are the same for each scenario) were used in every year of the model run; although such abstractions will have changed with time and may change in future, the models were calibrated with these present.

- Within the hydraulic model, surface abstractions and discharges (some constant, some with a monthly profile) were also used in every year of the model run. Other extensions required for retention levels and inflows are described in Box 8-1.
- The two hydraulic sub-catchments with 'hotstarts' (initial conditions set by timeseries data rather than parameters) were left as calibrated because the periods referred to were typical of general flow conditions and the influence of the initial conditions reduces rapidly and well before the flood events.

Two minor changes were required in the hydraulic models to remove instability problems; these are discussed in Box 8-2. Although the models were not calibrated with these changes, they are minor, and were used for both the baseline and climate change scenarios.

The hydraulic model, which routes the runoff through the catchment, is computationally expensive (taking one hour to run two months for each scenario for the most time-consuming model[39]), and given the focus on flooding, the model was run just for four flood events (per scenario). The selection of the flood events is discussed in Section 8.2.1.

The stochastic runs are summarised in Table 8-2. The use of the stochastic approach was limited to the upper rainfall–runoff model catchment group (five catchments; see Figure 6-1) given the spatial restrictions of the input data. The selection of stochastic data to run through the rainfall–runoff and hydraulic models is discussed in Section 8.2.2 below.

Table 8-2 Upper catchment model run schedule

Reference	GCM–RCM	Emissions scenario^	Time period	Rainfall	PET
Base	n/a	n/a	1961-1990	EARWIG	EARWIG
UK02-A2-80	HadCM3-HadRM3*	A2	2080s	EARWIG	EARWIG
EH-A2-80	ECHAM4-HIRHAM***	A2	2080s	EARWIG	EARWIG
HH-A2-80	HadAM3H-HIRHAM***	A2	2080s	EARWIG	EARWIG
ER-A2-80	ECHAM4-RCAO***	A2	2080s	EARWIG	EARWIG
HR-A2-80	HadAM3H-RCAO***	A2	2080s	EARWIG	EARWIG

GCM–RCM output from *UKCIP02, ***PRUDENCE. ^IPCC SRES.

[39] Using a computer with a processor speed of 1.8GHz and 1.0GB of RAM.

Box 8-1 Bedford Ouse model inputs and modelling process

The meteorological data were perturbed using MS Excel and converted into MIKE11 Timeseries files (*dfs0) via text files (with 14 scenarios, including the baseline, and 21 catchments (see Figure 5-3 and Table 5-2) this gave 294 files for rainfall and 294 files for PET). Rainfall was input as 'rainfall', 'millimetres', 'step accumulated'. PET was input as 'evaporation' (note that NAM then uses this as potential evaporation^) 'millimetres', 'step accumulated'. NAM treats 'step accumulated' linearly i.e. an even amount of rainfall and evaporation is assumed to accumulate over each day.

Each group of rainfall-runoff models (seven groups in total, ranging from one to five catchments in each) were set up with a MIKE11 rainfall-runoff (*.RR11) parameters file, which holds the rainfall-runoff model parameters (held constant), abstractions (annual profile held constant) and input meteorological data (which varied according to scenario; with 14 scenarios this gave 98 files in total); note that the Flit catchment had a hotstart, which was retained for all scenarios. Then 98 MIKE11 simulation (*.sim11) files were set up to run each of the rainfall–runoff files. These simulation files read the rainfall–runoff files, set the model timestep and model output timestep (both set to 1 hour), and specify the output file name and location. After initial testing on the Alconbury catchment, the simulation files were run using a text batch file (*.bat) and the MIKE11 application MzLaunch*. Results (*.res11) from each simulation were extracted by catchment for analysis.

There were ten groups of hydraulic models (three of the seven rainfall-runoff model groups are split). The MIKE11 hydraulic model is based on inputs describing the river network, cross-sections, parameters (all held constant) and boundary data. The latter includes stage–discharge relationships (held constant) and inflows. Furthermore, a tidal water level is required at Earith; the existing dataset (based on adjusted tidal data from the CS3 package of the Proudman Oceanographic Laboratory for a site in the Wash) was extended using TIDSIM[†], a tool for simulating tidal timeseries, with tidal data from the 2006 Admiralty Harmonic Tables. Inflows include discharges and abstractions (which were extended and held constant or with a constant profile) and the upstream catchment groups. The upstream inputs were the discharge results of the upstream hydraulic model runs. Note that for the Roxton to Earith model, three downstream flow records were also included, although flow above Earith is not particularly sensitive to these: for the Ely Ouse at Denver and St Germans flows, the recorded data were extended prior to 1992 (i.e. for the 1979 event; see Section 8.2.2) based on the daily average flow; for Welches Dam a constant average value prior to 1993 (i.e. for the 1979 and 1992 events) was used. The hydraulic model also contains inputs for retention levels at three structures: within the Newport Pagnell to Roxton model, the two constant retention levels at Castle Mills and Olney (structures) were extended; for the Roxton to Earith model, the seasonal retention level at Earith was extended.

The rainfall–runoff results files (*.res11) were converted into timeseries files (*.dfs0) and then imported into the hydraulic model boundary files (*.bnd11) for the relevant model run. There were 560 results files (14 scenarios, four events, ten groups) of which all but those for the final catchment require converting and importing, giving 504 timeseries files which were imported into 280 boundary files. Initial conditions were set by a parameter file except for two catchments set by a hotstart file based on typical flow. The simulation was based on a fixed timestep of 1 minute, with results stored every 15 minutes. Overall, 560 simulation files were required and these were run in four batches corresponding to the stream order i.e. the first batch had no upstream inputs, the second had upstream inputs, the third had upstream inputs from at least a second-order stream and so on.

^Tom Rouse, Atkins, personal communication.
*Note that the MIKE11 Batch Simulation malfunctions in the 2007 and 2008 versions, and therefore a DOS text batch file was required.
[†]Tidal Prediction Program 5.06 (23-Feb-2006) developed by George Mitchell, Atkins

Box 8-2 Minor changes to the Bedford Ouse hydraulic models

Firstly, in the Upper Ouse model, initial conditions appeared to perpetuate and influence the events of interest. The initial conditions derived from the parameter file were contrasted with a 'wetter' hotstart file, and both were examined under the driest (UK02-A1-80) and wettest (MPI-A1B-80) of the model scenarios. Large differences in flow were observed between the two sets of initial conditions, particularly downstream, and this appeared to be exacerbated in the wettest climate change scenario. Also apparent were instabilities in the flow (sudden large changes). Model author and Atkins colleague Tom Rouse suggested that stability could be restored by removing a weir and two culverts (at chainage BRACKLEY 47845). This was checked using the same sets of initial conditions and scenarios and although the instabilities were removed, large differences remained between the two sets of initial conditions for the wettest climate change scenario. However, after further discussions with Tom Rouse it became clear that the hotstart conditions for the wettest scenario included floodplain flows as well as high in-channel conditions, a very extreme test of initial conditions! A hotstart with high in-channel flows, but no floodplain flows, using the wettest scenario, gave very similar flows to those using the original initial conditions and so these original conditions were adopted, along with the slightly modified network.

Secondly, in the Roxton to Earith model, instabilities occurred at one section of the floodplain (chainage O2GM_FP_LB 2800) where converging water over higher ground 'leapt' up by several metres. This was corrected by Tom Rouse by marginally lowering the floodplain (by 5 cm for 20 m) and simulating flow using a weir rather than in an open channel, which meant that flow continuity is calculated more simply and in this case more realistically. This correction was tested for a variety of events and climate change scenarios and proved stable.

8.2 Baseline flooding

8.2.1 Actual baseline

The Bedford Ouse catchment experienced a number of flood events in the period from 1961 to 2001, which have varied in location, magnitude and season. A simple analysis of the baseline hydrological run was undertaken to identify the most significant flood events on a catchment scale. For each of the 21 catchments, the months of the highest daily peaks were identified and ranked. By using months, the selection of multiple high flow days relating to the same flood event, or more minor events, were generally excluded (although the full month would be modelled anyway – see below). The ranks were then aggregated to help identify the most significant periods of high flows. In addition, the month of the top ten gauged daily flows (excluding repeats in a month) at Bedford were identified for the same period from the National River Flow Archive (note that Bedford is the lowest downstream, long-term, reliably gauged site on the Bedford Ouse). This was supplemented by documented records of floods and flood impacts (see Figure 6-8). The final selection was made on the basis of significance (magnitude over the catchment) and provision of a variety of times between September and April. The selected flood events are:

- December 1979 (24 November to 24 December inclusive)
- September 1992 (7 September to 11 October inclusive)
- April 1998 (25 March to 22 April inclusive)
- October/November 2000 (26 September to 17 November inclusive).

These flood events were modelled in NAM using the UKMO gridded rainfall data and corrected MOSES PET data (see Section 6.2.2) and routed in MIKE11. The rainfall–runoff modelling in NAM was undertaken for the whole time period, but the hydraulic modelling was restricted to the periods in parenthesis above, which gave a minimum warm-up of two weeks prior to the start of the event and a recession period of at least ten days.

No separate results of the baseline run are presented in this section, rather they are used as a comparison with the results of the future runs (see below). There is more confidence in using the results in this way, as there is deviation between the baseline observed and modelled flows using the daily rainfall data (see Section 6.1.2.4).

8.2.2. Stochastic baseline

The stochastic record is long and ideally subsections of the record would be run; this would balance the benefits of the stochastic timeseries record with model and processing time efficiency. Therefore, the baseline rainfall and flow records were examined in order to see whether there were adequate relationships for selecting likely periods of flood-producing rainfall; tThis is described in Appendix 2. Overall, it was difficult to find any single metric that adequately defined the amount of rainfall that would likely lead to flooding. This is unsurprising given that no catchment rainfall–runoff model exists based on event rainfall alone!

Therefore, it was decided to run the stochastic record through the hydrological model. It was intended to run the complete 750-year series, but this proved impossible in NAM (a single run appeared to be limited to 170 years of daily data), so two 150-year runs were undertaken, with the first being used to hotstart the second, thus providing a 300-year hydrological output. It is not feasible to undertake hydraulic modelling for the 300 year record (this would take around two weeks to run each scenario). High flow events were therefore analysed on the basis of individual catchment flows, using two methods. Firstly, the highest 1-hour flows from both of the two 150-year ensemble members, for each scenario, were extracted and the dates compared across the five upper catchments (see Figure 6-1). Secondly, the 3-hour flows[40] were summed across the five upper catchments, for each scenario, and the independent event dates extracted. Finally, three events were selected for each scenario, with the second method taking precedence in deciding which to choose. The three events are those with the three highest independent peaks in the 300-year stochastic flow series. These events (as defined by the flow hydrograph), with an antecedent period of approximately two weeks, were run through the hydraulic model in two batches (Tove, and Upper Ouse) to provide flow and water level at Newport Pagnell. Abstractions and discharges were extended, as for the main modelling.

Results of the baseline stochastic runs are presented alongside those for the future in Section 8.4.

[40] Note that 3-hour flows (results at 00:00, 03:00, 06:00 etc.) were extracted for timeseries analysis, rather than the 1-hour results, due to the volume of data. A comparison between 1-hour and 3-hour peaks for each scenario and individual catchment showed that the latter were within 3% of the former in all but one case (6%).

8.3 Future flooding: perturbation approach

8.3.1 Changes in runoff

8.3.1.1 Summary

The *general* pattern of change in monthly runoff is for small changes (positive and negative) between January and March, then an increasing reduction in runoff with the largest reductions between August and October followed by a decreasing reduction in November and December. However, this general pattern, the direction and magnitude of winter change, and the magnitude of summer change, all vary significantly between catchments and scenarios.

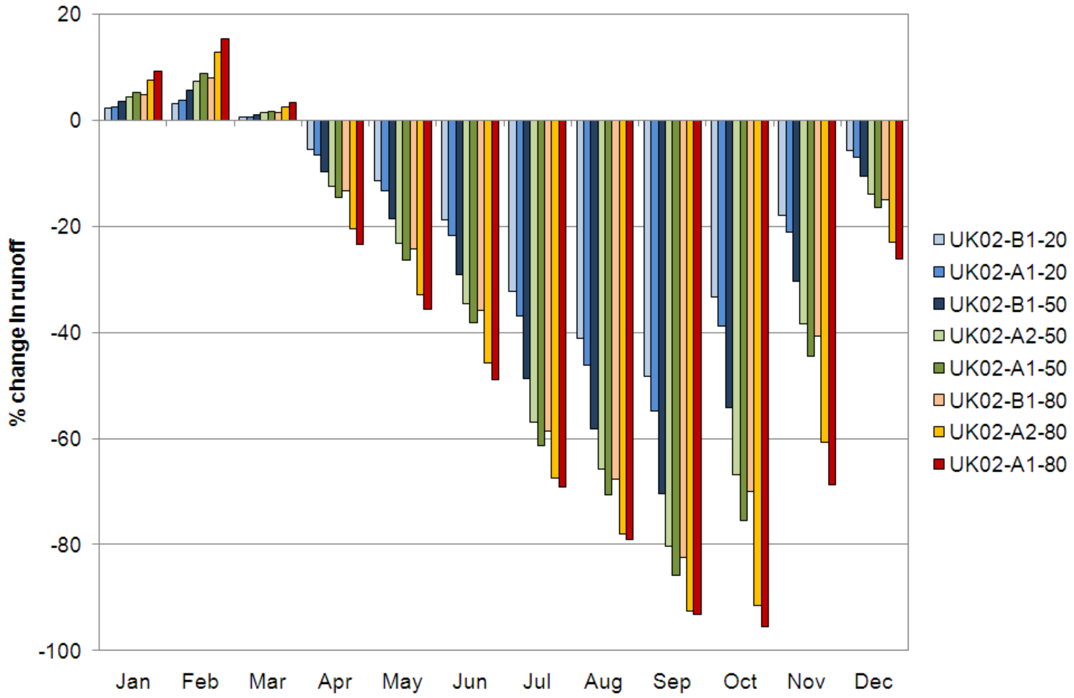
Broadly, three different types of catchment response have been identified: enhanced, subdued and reduced. These are described below, including their relationships to catchment characteristics. The role of different climate change scenarios is also significant, and whilst the general catchment responses are followed, within the winter half of the year three of the five ENSEMBLES 2080s scenarios are more influenced by the climate change factors and are therefore exceptions or extremes; these are KNMI-A1B-80, MPI-A1B-80 and SMHI-A1B-80 (note that the first two of these are based on the same GCM; this is discussed further in Section 8.3.5).

More detailed assessments have been made for catchments that exemplify the response types and for those which are anomalous; those that exemplify the response type generally have no or little groundwater abstractions, whereas the anomalies are often because of the assumptions regarding groundwater abstractions. The more detailed assessments rely on the examination of additional model information such as the components of flow, actual rainfall and evaporation, and movements of water including infiltration and recharge. These assessments are focused on exemplar scenarios (generally UK02-A1-80, ETH-A1B-80 and KNMI-A1B-80), which provide a contrast from dry to wet respectively.

It should be noted that there is lower confidence in individual catchment results due to the temporal resolution of the rainfall dataset used, and although this applies mainly to extreme events, it was found that the daily rainfall timestep influenced recharge and baseflow. This also suggests that a sub-daily profile of PET may be beneficial.

The results focus on the 2080s scenarios: three from UKCIP02 with different emissions scenarios, and five from ENSEMBLES with the same emissions scenario. The results from the 2020s and 2050s from the UKCIP02 scenarios follow the pattern of those of the 2080s with reduced magnitude (see Figure 8-1), in the same way that the climate change scenarios are pattern scaled from the 2080s (specifically from the SRES A2 emissions scenario) (Hulme *et al.*, 2002).

Figure 8-1 Change in average monthly runoff from the Alconbury Brook catchment in the 2080s compared to the baseline under different UKCIP02 scenarios

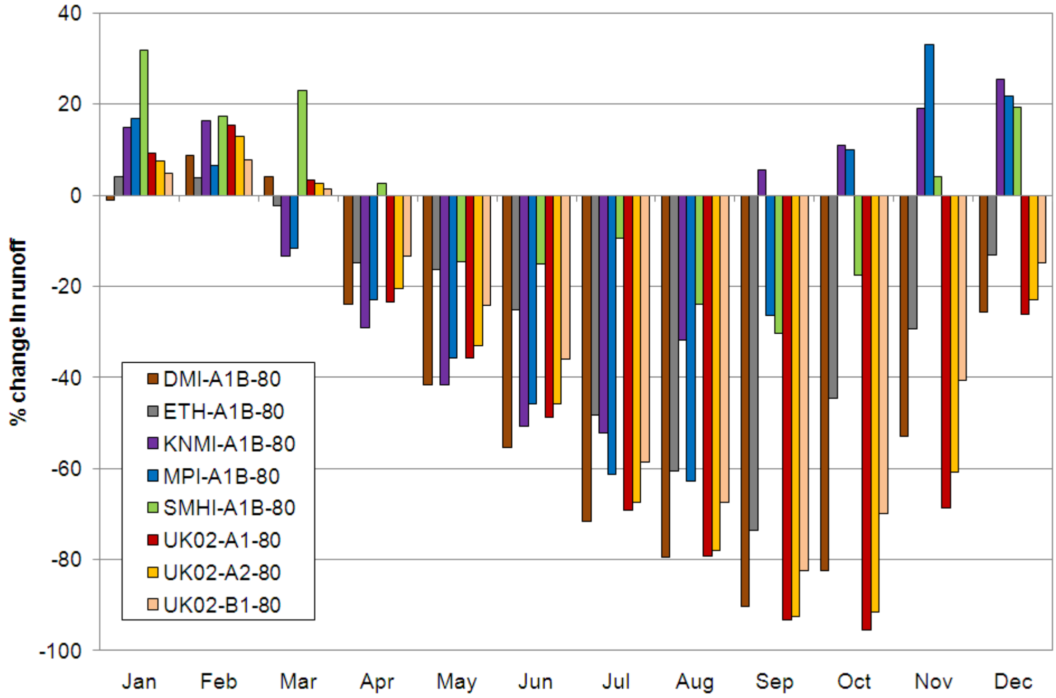


The baseline is that modelled for the period 1961 to 1990. For details of models, see Table 8-1. Original in colour.

8.3.1.2 Enhanced response

The enhanced response shows increases in winter flow and large decreases in summer flow, with a peak reduction typically occurring in September. The precise changes are highly scenario dependent, but typically show a winter monthly increase of 0 to 15%. The maximum monthly reductions are highly variable, between approximately 20% and 90%. The catchments with this type of response are the Upper Tove, Lower Tove, Alconbury Brook (see Figure 8-2), Ellington Brook, Ivel and the Bedford Ouse between Offord and Earith. These catchments have a mixture of hydrological response classes (see Section 5.1.2.6; Atkins, 2003b), although all have a baseflow index (BFI-HOST) of 0.5 or less, except the Ivel (see below).

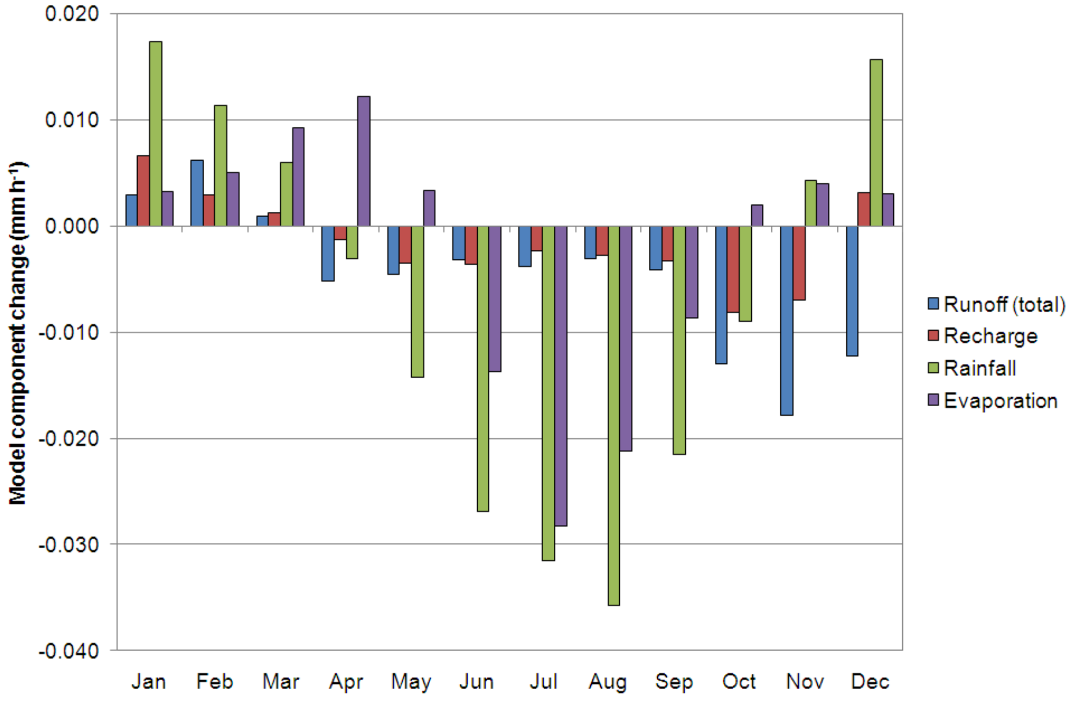
Figure 8-2 Change in average monthly runoff from the Alconbury Brook catchment in the 2080s compared to the baseline under different scenarios



The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. Original in colour.

A detailed examination was carried out for the Alconbury Brook catchment, a rural area of 116 km^2 with a semi-regulated response to rainfall, medium runoff and groundwater storage (BFI-HOST of 0.3) and no groundwater abstractions (Atkins, 2003b). The modelled baseline BFI was 0.36 and baseflow accounts for the majority of average flow between May and September. However, due to the relatively limited role of groundwater, recharge is less important, allowing changes in winter effective precipitation to create surface runoff (see Figure 8-3). Actual evaporation in summer reduces under climate change, meaning that changes in net precipitation are small, even where absolute changes in precipitation are large. The reduction in actual evaporation occurs because relative soil moisture, already low in summer, becomes even lower in this catchment under climate change, nearing zero in the lower or root zone storage[41] in August and September under the UK02-A1-80 scenario. However, relative soil moisture recovers quickly and is approximately the same as the baseline in winter (see Figure 8-10 and the related comparison with the Bedford Ouse between Bedford and Roxton, below).

Figure 8-3 Change in average monthly rainfall–runoff model components for the Alconbury Brook catchment in the 2080s compared to the baseline under the UK02-A1-80 scenario

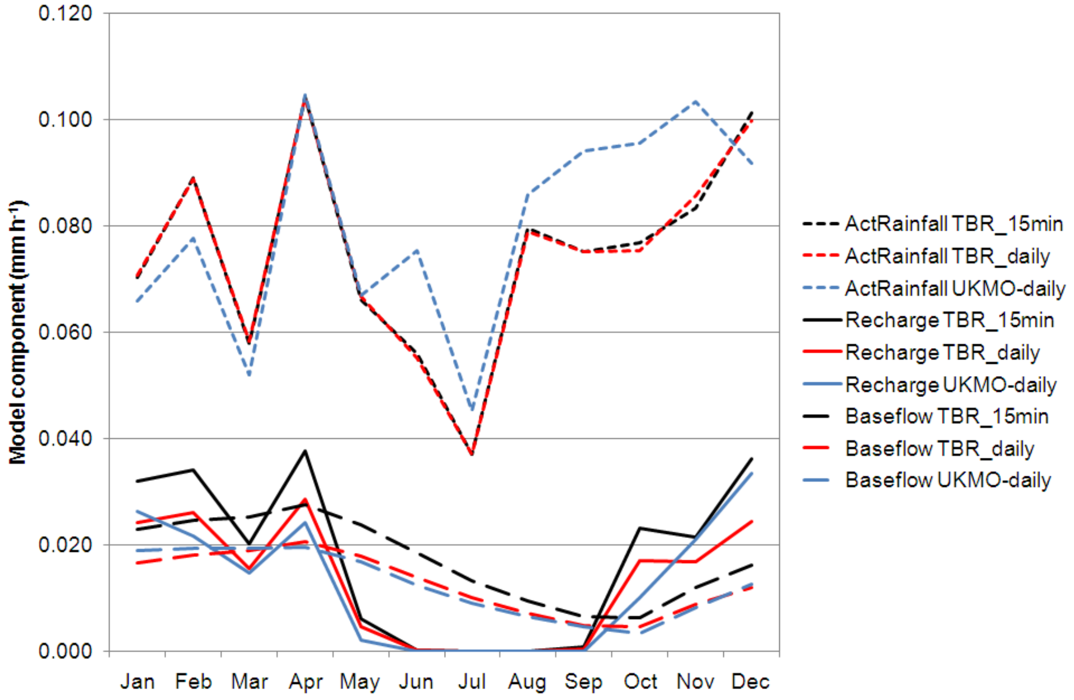


Note that runoff includes baseflow and was converted to intensity (mm h^{-1}) from cumecs based on the catchment area. The baseline is that modelled for the period 1961 to 1990. For details of the scenario, see Table 8-1. Original in colour.

[41] The lower or root zone storage in NAM is the soil layer below the surface from which vegetation can draw water for transpiration; the moisture content of this zone controls the amount of water that recharges groundwater, as well as interflow and overland flow (DHI, 2007).

The Ivel has larger reductions in flow, with a maximum monthly reduction of between 53% and 100%, despite a larger baseflow index (BFI-HOST) of 0.6 (Atkins, 2003b). This is because the model computes no baseflow for the baseline period (and scenarios), as groundwater abstractions exceed recharge by almost 10 times. This means that summer reductions in rainfall lead to severe reductions in runoff (there is also a very large long-term reduction in groundwater level). However, recharge itself is also influenced by net rainfall, and given the use of an alternative rainfall dataset, a comparison was undertaken to assess the relative significance of groundwater abstractions and rainfall datasets. This was undertaken in detail for the Twin catchment (for which the runs were available, see Section 6.1.2.3) and more briefly for the Ivel, for the period September 1995 to September 2001 inclusive using a model timestep of 15 minutes. For the Twin (see Table 6-4 for details of the runs), recharge appears to be most affected by rainfall timestep, rather than the rainfall record (see Figure 8-4, the difference between the black and red runs being greater than that between the blue and red runs). Within the Bedford Ouse NAM model, recharge appears to be very sensitive to rainfall time resolution and more recharge occurs with fine-resolution rainfall, presumably because greater values of net rainfall are produced, albeit over short periods. The average difference in recharge between the original and adopted rainfall datasets is 0.005 mm per hour; this is 280 times the average groundwater abstraction rate in the Twin catchment, but groundwater abstractions are very low. By contrast, the difference is just under half the average groundwater abstraction rate in the Ivel catchment. A simpler comparison for the Ivel, of the original run with the main run for this study (which used a 1 hour model timestep), produced an average reduction in recharge that equates to 7% of the average groundwater abstraction rate. The reduction in recharge associated with the change of dataset was 29%, with rainfall 11% lower. However, even in the original run, average abstraction exceeded average recharge and no baseflow was generated; it is known that the groundwater abstractions reduce the water balance to almost zero in this catchment (and those in the Middle and Lower Ouzel, see below) (Atkins, 2003b). In conclusion, while the use of a different rainfall dataset is significant, it is the groundwater abstractions that cause the lack of baseflow in this catchment. This suggests that groundwater abstractions at baseline levels will not be sustainable in future. A potential further complication for other catchments may be that recharge changes between the baseline and the period investigated here (approximately the calibration period); for example, for the Ivel modelled recharge is 28% higher in the latter. Application of the same monthly groundwater abstraction profile to a period with lower recharge will also lower baseflow.

Figure 8-4 Average monthly recharge, actual rainfall and baseflow from the Twin catchment for the period September 1995 to September 2001 for different combinations of rainfall data and timesteps



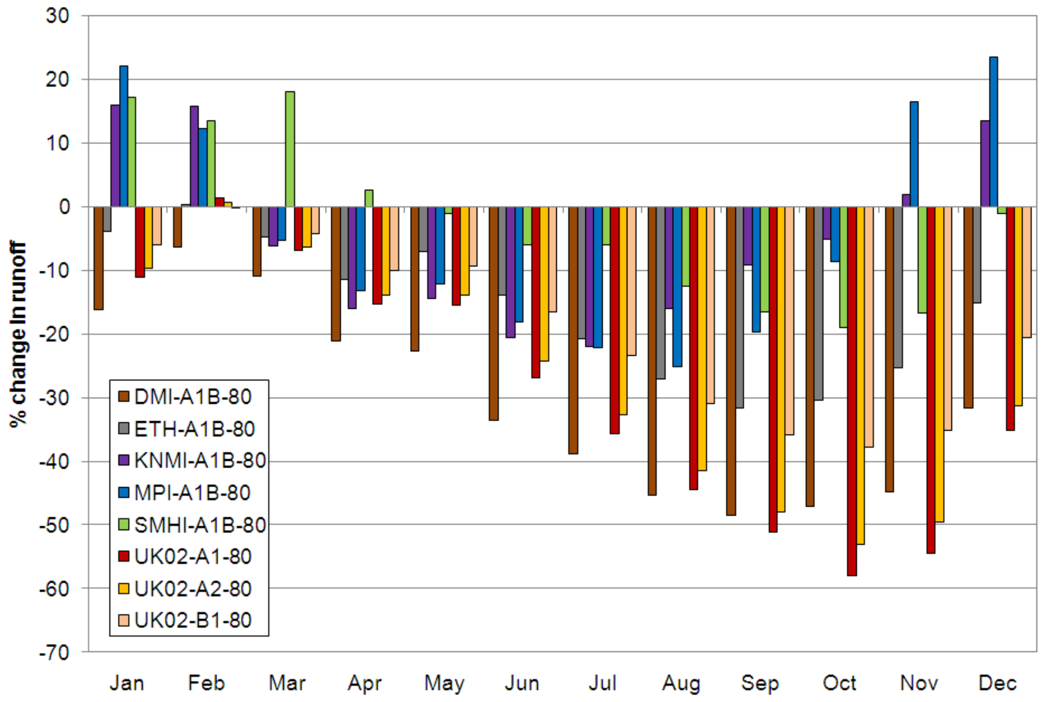
Note that graph is based on monthly data: the lines are provided for ease of reference. For details of runs, see Table 6-4. Original in colour.

The Ouse between Buckingham and Milton Keynes also follows the enhanced pattern, but shifted one month forward, and has *increased* flows in July and August in all except two scenarios. However, the absolute changes are small and flows are generally low in this catchment (modelled baseline Q50 is 0.055 cumecs). The catchment also has a low baseflow index, has a high proportion of urban land (18%) and exhibits rapid runoff.

8.3.1.3 Subdued response

The subdued response shows decreases in every month, except in a few cases, but the decreases are generally less than 20% and with a maximum reduction, in October, of between 40% and 60%. The catchments with this type of response are the Upper Ouse, Flit (see Figure 8-5), Hiz, Tributary of Flit, and Tributary of Hiz. These catchments are all classified as having a regulated or semi-regulated response to rainfall, low or medium volume of runoff and high or medium groundwater storage, with BFI-HOST ranging between 0.5 and 0.8 (Atkins, 2003b).

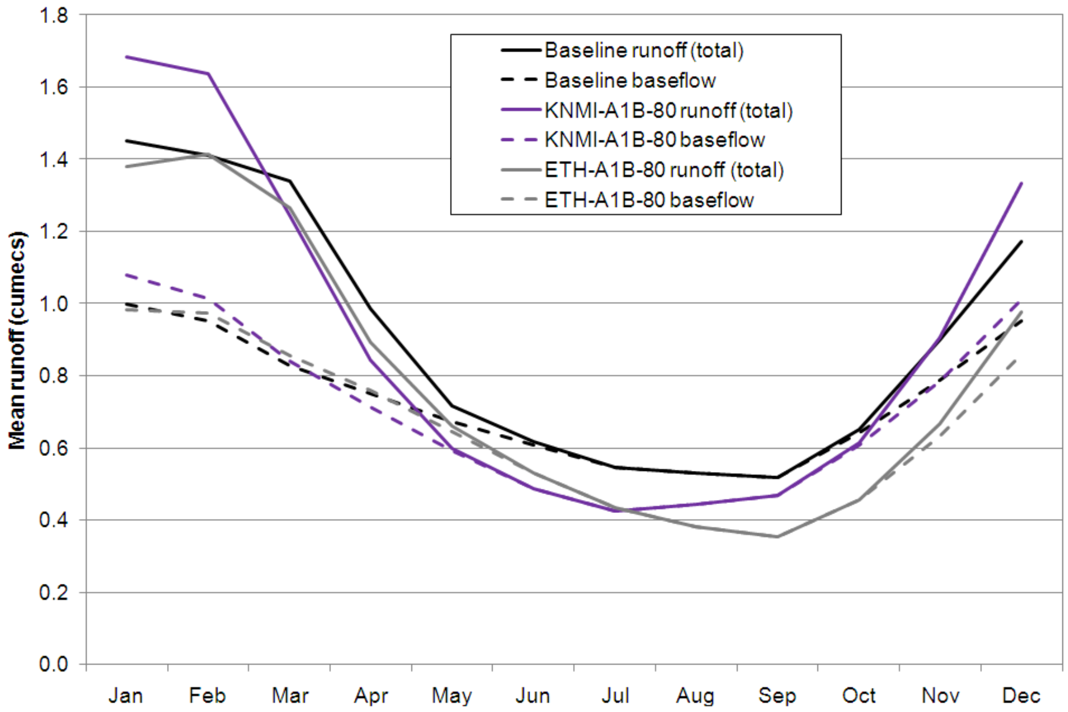
Figure 8-5 Change in average monthly runoff from the Flit catchment in the 2080s compared to the baseline under different scenarios



The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. Original in colour.

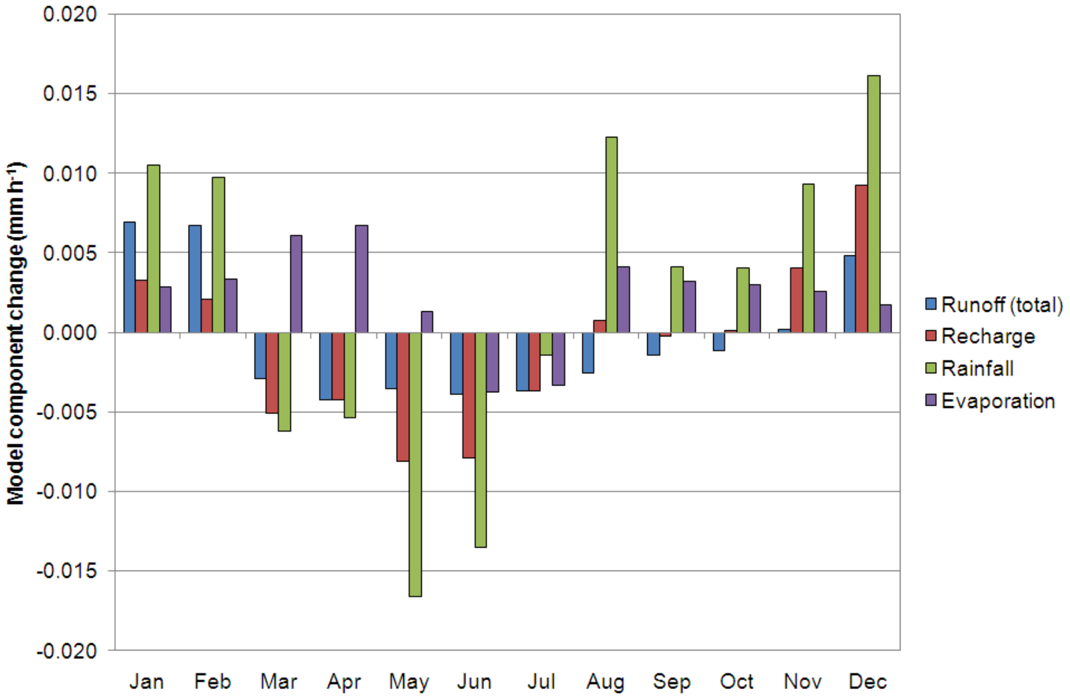
A detailed examination was carried out for the Flit catchment, a rural area of 120 km^2 with a semi-regulated response to rainfall, medium runoff and groundwater storage (BFI-HOST of 0.6) and very low groundwater abstractions (Atkins, 2003b). The modelled baseline BFI was 0.81 and baseflow accounts for virtually all flow between May and October (see Figure 8-6). This remains the case under climate change scenarios, but a contrast exists between a scenario such as KNMI-A1B-80 and the more central ETH-A1B-80 where the latter is more dependent on baseflow in late autumn and early winter, with flows lower than the baseline. The KNMI-A1B-80 scenario (see Figure 8-7) generates higher flows than the baseline because of the increases in rainfall that commence in late summer, which are larger than the increases in evaporation. In contrast, under the ETH-A1B-80 (Figure 8-8), recharge takes longer to commence and increases in total flow do not typically occur. The groundwater component of the catchment has a major influence on flows, with effective precipitation more focused on recharge, at least initially, when compared with the Alconbury catchment.

Figure 8-6 Average monthly total runoff and baseflow from the Flit catchment in the 2080s compared to the baseline under the ETH-A1B-80 and KNMI-A1B-80 scenarios



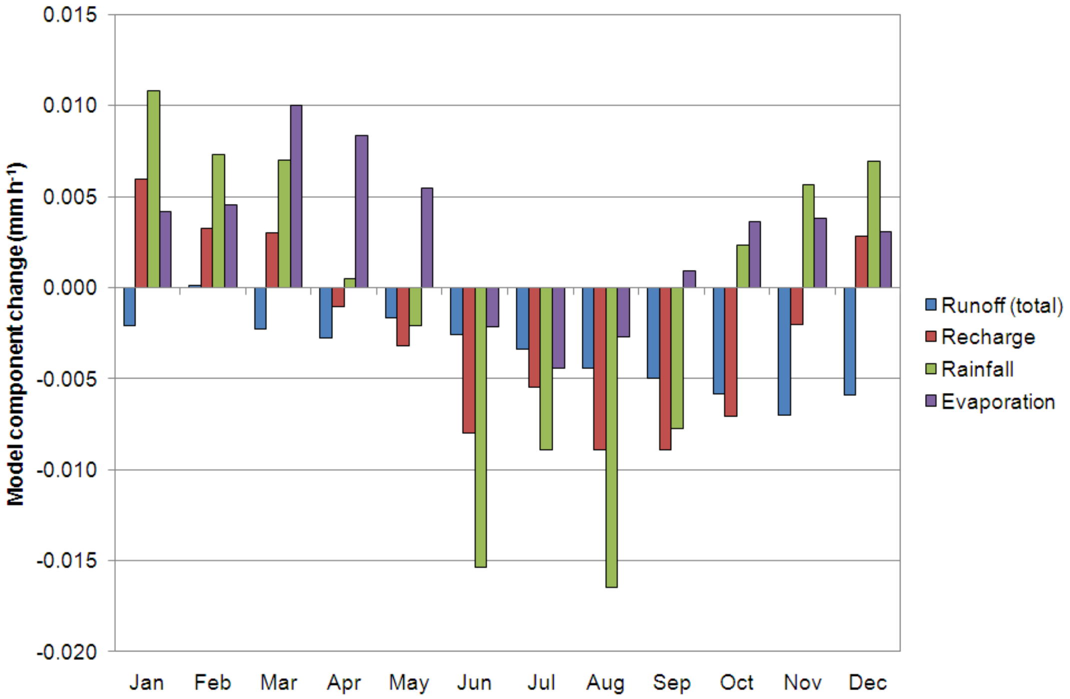
Note that graph is based on monthly data: the lines are provided for ease of reference. The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. Original in colour.

Figure 8-7 Change in average monthly rainfall–runoff model components for the Flit catchment in the 2080s compared to the baseline under the KNMI-A1B-80 scenario



Note that runoff includes baseflow and was converted to intensity (mm h^{-1}) from cumecs based on the catchment area. The baseline is that modelled for the period 1961 to 1990. For details of the scenario, see Table 8-1. Original in colour.

Figure 8-8 Change in average monthly rainfall–runoff model components for the Flit catchment in the 2080s compared to the baseline under the ETH-A1B-80 scenario

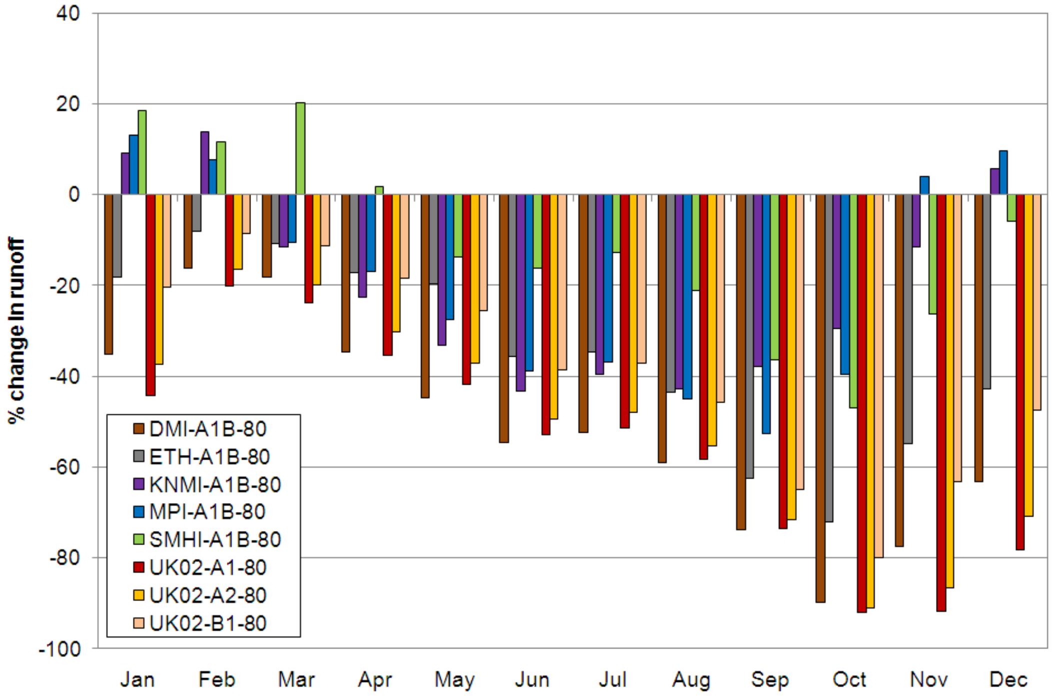


Notes as for Figure 8-7 above.

8.3.1.4 Reduced response

The reduced response shows large flow reductions throughout the year, with a few exceptions, with very large reductions in autumn. The exceptions are an increase in winter flow for three of the ENSEMBLES scenarios, and for all scenarios some catchments show a limited reduction or a slight increase in flow in February. The catchments with this type of response are the Twin, the three catchments of the Middle and Lower Ouzel, the Bedford Ouse between Newport Pagnell and Bedford and between Bedford and Roxton (see Figure 8-9), and the Kym. The catchments with the reduced response type are all classified as having a rapid response to rainfall, high volume of runoff and low groundwater storage, with a BFI-HOST of 0.4 or less (Atkins, 2003b).

Figure 8-9 Change in average monthly runoff from the tributaries of the Bedford Ouse between Bedford and Roxton in the 2080s compared to the baseline under different scenarios

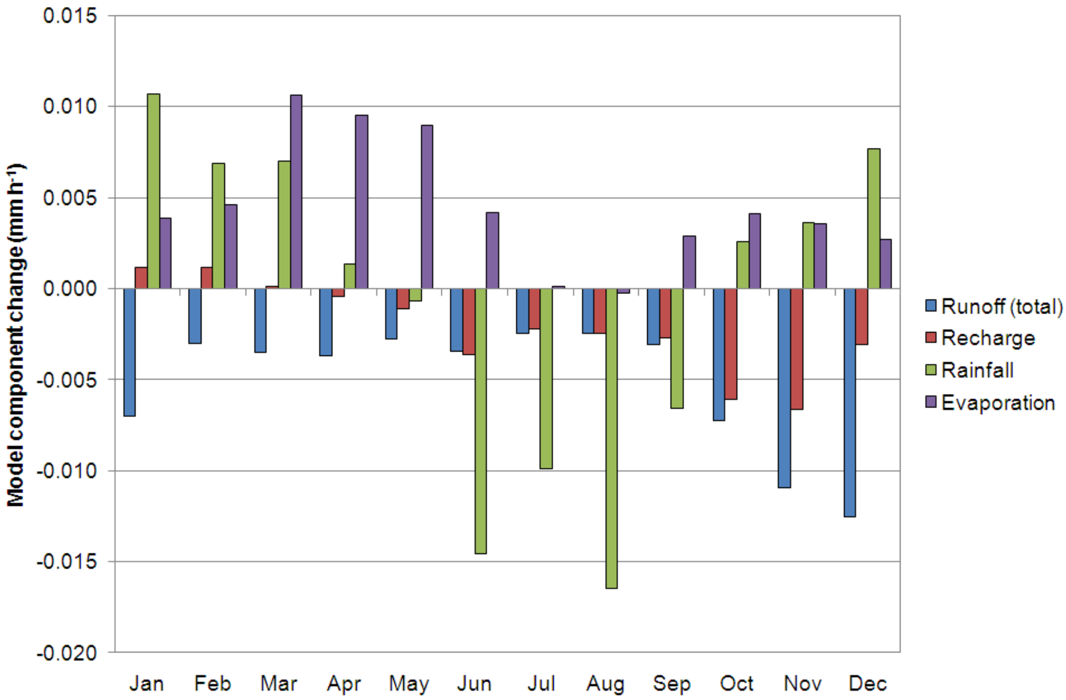


The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. Original in colour.

Two of the catchments of the Middle and Lower Ouzel (7A and 7B) have no modelled baseflow. Like the Ivel, both have water balances that have been calculated as close to zero (Atkins, 2003b). It was found that Catchment 7B has groundwater abstractions almost twice that of recharge in the original models. Catchment 7A has groundwater abstractions that are approximately a quarter of recharge; the change in rainfall dataset caused a 17% reduction in average rainfall and a 77% reduction in average recharge (for the period September 1995 to September 2001 inclusive), just sufficient for abstraction to exceed recharge.

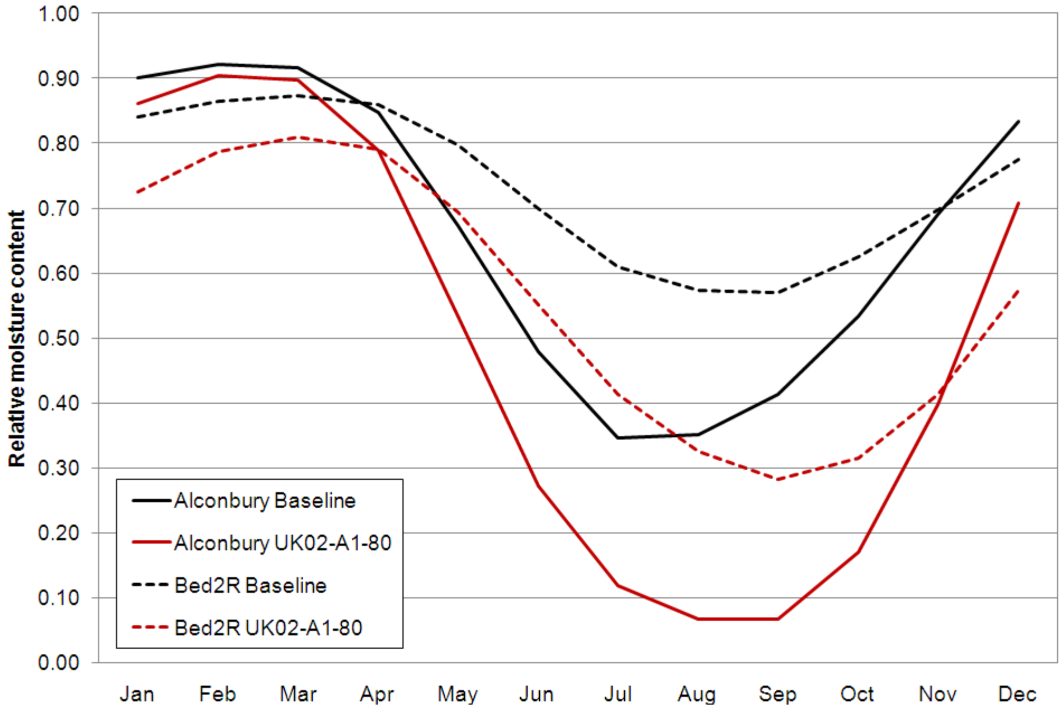
A detailed examination was carried out for the tributaries of the Bedford Ouse between Bedford and Roxton. This is a largely rural catchment (10% urban), of 192 km^2, with a rapid response to rainfall, high runoff, low groundwater storage, no groundwater abstractions and a BFI-HOST of 0.4 (Atkins, 2003b). The modelled baseline BFI was 0.46 with baseflow accounting for the majority of average flow between May and October. The catchment experiences large evaporative losses, combined with large declines in summer rainfall (see Figure 8-10). Although there are large increases in winter rainfall, and positive changes in effective precipitation, average monthly relative soil moisture remains lower than the baseline and therefore runoff is typically lower. This is in contrast with the Alconbury catchment (see above) where soils become too dry for evaporation to increase in summer (despite similar increases in PET) but recover quickly to facilitate runoff in winter, aided by more positive rainfall change factors for the ENSEMBLES scenarios (Figure 8-11).

Figure 8-10 Change in average monthly rainfall–runoff model components for the tributaries of the Bedford Ouse between Bedford and Roxton in the 2080s compared to the baseline under the ETH-A1B-80 scenario



Note that runoff includes baseflow and was converted to intensity (mm h^{-1}) from cumecs based on the catchment area. The baseline is that modelled for the period 1961 to 1990. For details of the scenario, see Table 8-1. Original in colour.

Figure 8-11 Relative moisture content of the lower zone storage for the Alconbury catchment and the tributaries of the Bedford Ouse between Bedford and Roxton for the baseline and the UK02-A1-80 scenario



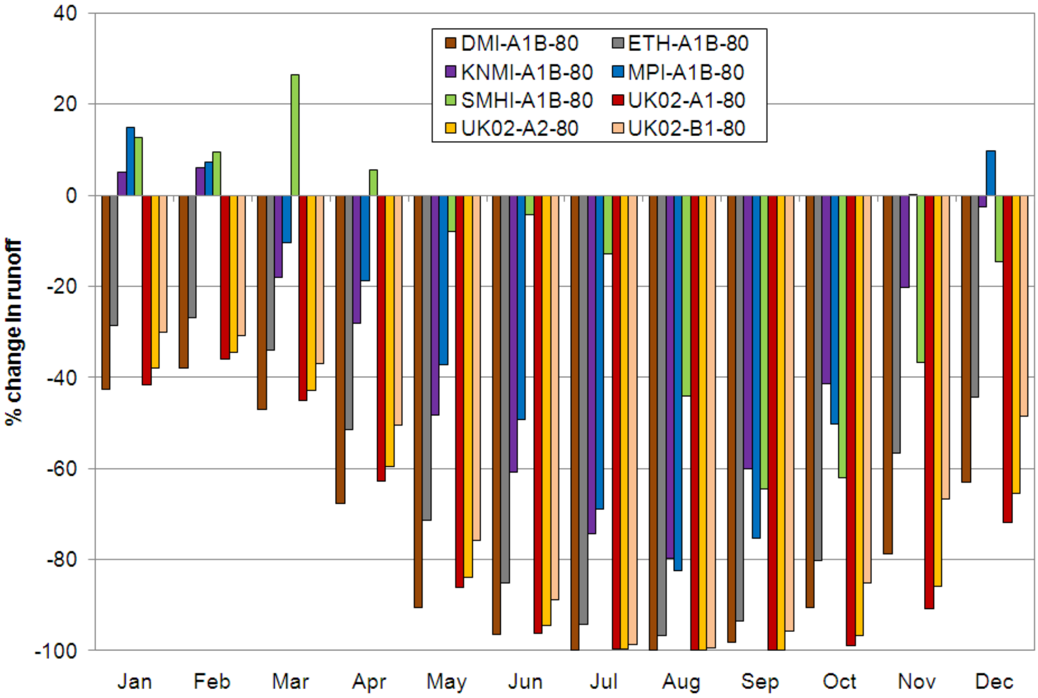
Note that graph is based on monthly data: the lines are provided for ease of reference. The baseline is that modelled for the period 1961 to 1990. For details of the scenarios, see Table 8-1. Original in colour.

Two further catchments, the Upper Ouzel and the Bedford Ouse between Roxton and Offord show even larger reductions, including in summer when flows fall by up to 100%. These catchments have a semi-regulated response to rainfall events, and a BFI-HOST of 0.5 and 0.4 respectively (Atkins, 2003b).

The very large reductions in the Bedford Ouse between Roxton and Offord are due to an error in the model set up, where a groundwater abstraction was set to 10,000 times what it should be. This means that no baseflow is modelled (even in the baseline run) after the first October. Therefore changes in summer flows in particular are severe, as they are entirely dependent on surface flows, which are much more responsive to changes in rainfall and evaporation. However, the error appears to have very little effect on the four flood events, which in any case compare the modelled baseline and scenarios. Furthermore, the effect on peaks flows and levels on the key downstream receptors is likely to be negligible as this is only one of 21 catchments and flows are significantly attenuated (see below).

The very large reductions in the Upper Ouzel (see Figure 8-12) are a result of changes in overland flow, interflow and particularly baseflow. The UK02-A1-80 scenario was examined in detail, and in it baseflow declines to almost zero, which explains the almost complete loss of flow in summer. This is caused by a significant decline in recharge (34%), and groundwater abstractions (held constant in the model) then become greater than recharge leading to a lowering of the groundwater depth by approximately 2.5 m per decade (note that this is the simulated response under the average climate of the 2080s). This suggests that groundwater abstractions at baseline levels will not be sustainable in future. However, the findings are complicated by the change in rainfall dataset and the differences in recharge between different time periods. Using the same time period as for the similar assessments above (although note that the values are very sensitive to the time period used), the change in rainfall dataset leads to a reduction in recharge of 32% and the change in time period to a reduction of 6%.

Figure 8-12 Change in average monthly runoff in the 2080s from the Upper Ouzel catchment compared to the baseline under different scenarios



The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. Original in colour.

8.3.1.5 Concluding discussion

The results demonstrate divergence in the ENSEMBLES runs, with three of the five examined (two out of four different driving GCMs) producing increases in winter runoff regardless of catchment characteristics, the latter only influencing the magnitude of runoff. Thus it is difficult to establish an overall conclusion from the scenarios which demonstrates the importance of considering multiple GCMs. For example, a selection of just two of three

GCMs could have resulted in biased conclusions (e.g. all wet); ideally more than the four GCMs considered here would be assessed.

In general, uncertainties appear to increase at smaller scales and as the process moves through the uncertainty cascade, from scenarios to changes in runoff. This is due to the increasing number of variables (rainfall, PET, catchment characteristics) and the heterogeneity of the catchments. This emphasises the benefits of adopting a catchment-specific approach in terms of climate change scenarios and rainfall–runoff modelling.

The influence of PET appears to be significant, because although all scenarios have large increases in winter rainfall (see Figures 7-2 and 7-5), not all produce increases in winter flow. Furthermore, in terms of the number of scenarios producing increases in runoff, the future high flow season appears to be focused on January and February rather than autumn or spring. It appears that the flood season is delayed due to large summer moisture deficits, whereas in spring rainfall is reduced from April onwards. However, catchment characteristics have a strong modifying effect (see below). The PET change factors are very large (see Figures 7-7 and 7-9) and it is unclear whether this is at least partly an outcome of using a temperature-based formula: even though there is some bias correction by dividing the future PET by the baseline and applying the change to MOSES, it may be that the increase is overestimated; further research in this area would be beneficial.

There are similarities between the enhanced and reduced responses outside of winter, which is perhaps unsurprising given the similarities in catchment characteristics such as baseflow index. However, based on a comparison of Alconbury Brook and the tributaries of the Bedford Ouse between Bedford and Roxton, there appear to be subtle differences in changes in effective precipitation and soil moisture that have important implications for winter runoff.

Summer and winter runoff is also sensitive to the time resolution of rainfall. In particular, recharge in the Bedford Ouse NAM model appears to be very sensitive and more recharge occurs with fine-resolution rainfall, presumably because greater values of net rainfall are produced, albeit over short periods. This has important implications for seasonal baseflow. It also suggests that a sub-daily profile of PET may be beneficial. Therefore, future studies using these models, particularly for the purposes of examining recharge and baseflow, should use a sub-daily or disaggregated daily rainfall input and further work should determine the need for sub-daily PET.

Some of the results suggest that groundwater abstractions at baseline levels (an assumption in the model runs) will not be sustainable in the future as they lead to a lowering of groundwater levels and reduction in baseflow.

8.3.2 Changes in high flow duration and thresholds

Changes in high flow duration and high flow duration thresholds are highly scenario dependent, although there are also large variations between catchments, which relate strongly to catchment response type. In this section, changes are expressed in terms of maximum baseline flow and baseline flow duration thresholds, in particular Q10, Q1 and Q0.1, meaning the flows exceeded 10%, 1% and 0.1% of the timeslice respectively.

8.3.2.1 Changes in high flow duration thresholds and maximum flow

Three of the five ENSEMBLES scenarios (KNMI-A1B-80, MPI-A1B-80, SMHI-A1B-80) led to enhanced runoff for nearly all of the 21 catchments at the Q1 and Q0.1 flow thresholds, although enhanced maximum peaks only occurred in just over half the catchments (Table 8-3). In contrast, the other scenarios generally returned reduced runoff for high flow events.

Table 8-3 Number of catchments for which baseline high flow thresholds are exceeded in the scenario

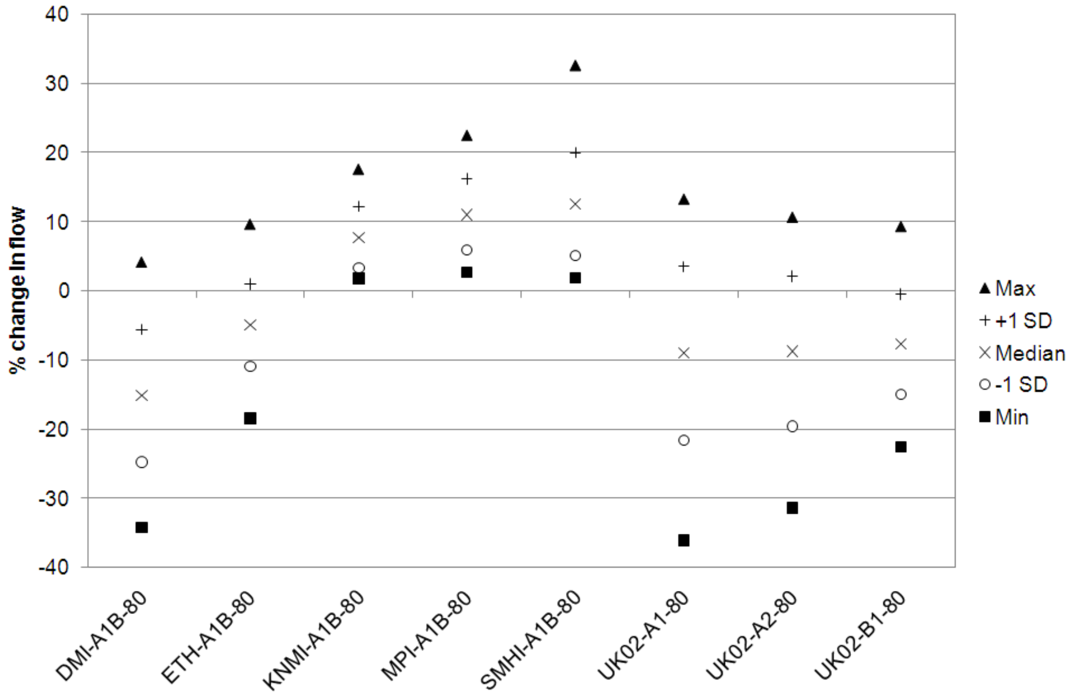
Scenario	Q10	Q1	Q0.1	Max
DMI-A1B-80	0	2	2	3
ETH-A1B-80	0	3	5	5
KNMI-A1B-80	11	21	20	11
MPI-A1B-80	12	21	21	14
SMHI-A1B-80	15	21	19	12
UK02-A1-80	0	4	4	6
UK02-A2-80	0	4	4	5
UK02-B1-80	0	4	3	5

Note that there is a total of 21 catchments. For details of scenarios, see Table 8-1.

In terms of the size of the change, for the three ‘wet’ ENSEMBLES scenarios, the median of the catchments had an increase in Q1 of around 10%, with a range from 2% to over 30% for the SHMI-A1B-80 scenario (see Figure 8-13). In contrast, under other scenarios, the biggest catchment increase was around 10%, with the lowest catchment decrease being greater than 30%.

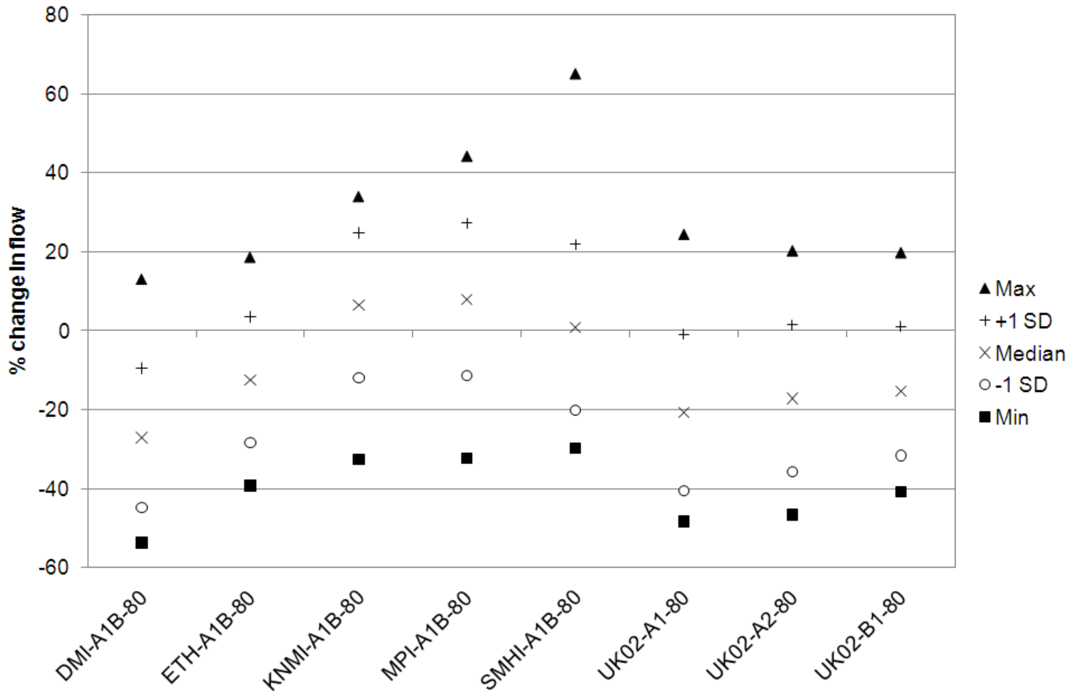
For maximum flow the changes remain scenario dependent, particularly in terms of the median of the catchments, but there is a much greater range (see Figure 8-14).

Figure 8-13 Change in Q1 flow threshold for the Bedford Ouse catchments in the 2080s compared to the baseline under different scenarios



The symbols show the maximum of the 21 catchments (Max), the median plus one standard deviation (+1 SD), the median, the median minus one standard deviation (-1 SD) and the minimum (Min). The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1.

Figure 8-14 Change in maximum flow for the Bedford Ouse catchments in the 2080s compared to the baseline under different scenarios



Notes as for Figure 8-13 above.

The sizes of the changes have been compared with the 20% indicative sensitivity range for peak flows (see Table 8-4). No more than four catchments exceeded an enhancement of 20% at the Q1 and Q0.1 flow thresholds, and no more than five did so for the maximum peak, with the highest enhancements relating to the MPI-A1B-80 and SMHI-A1B-80 scenarios. However, for these scenarios the increases were much larger than 20%, particularly for maximum flow as illustrated in Figure 8-14.

Table 8-4 Number of catchments where baseline flow thresholds are exceeded by more than 20%

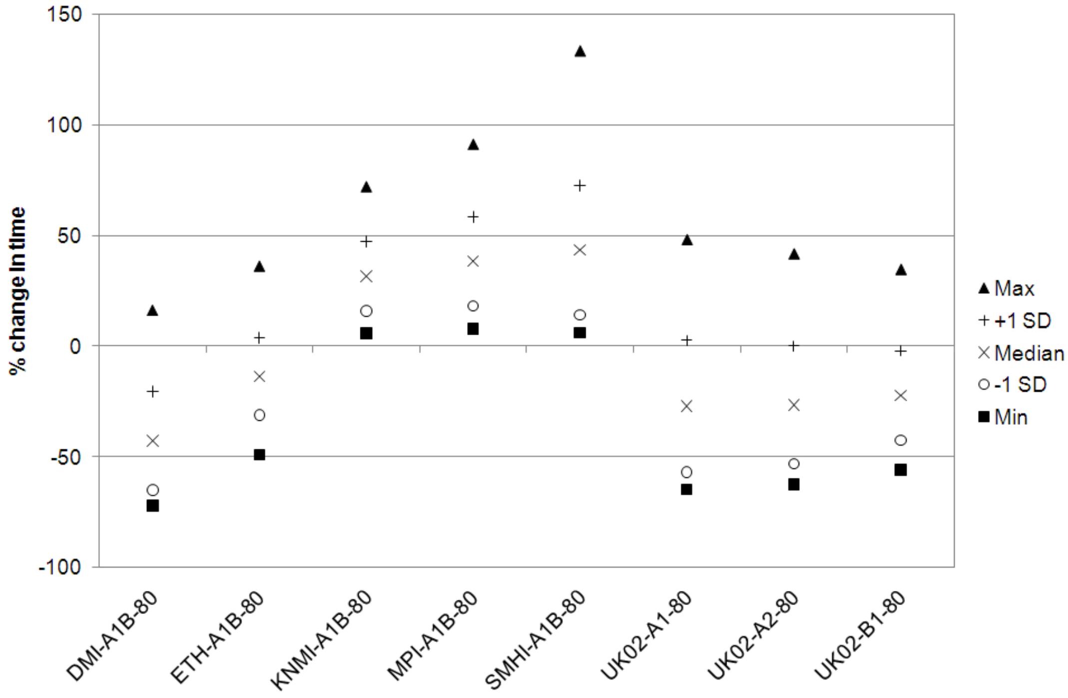
Scenario	Q10	Q1	Q0.1	Max
DMI-A1B-80	0	0	0	0
ETH-A1B-80	0	0	0	0
KNMI-A1B-80	0	0	0	3
MPI-A1B-80	0	2	3	5
SMHI-A1B-80	0	4	4	4
UK02-A1-80	0	0	0	2
UK02-A2-80	0	0	0	1
UK02-B1-80	0	0	0	0

Note that there is a total of 21 catchments. For details of scenarios, see Table 8-1.

8.3.2.2 Changes in time over baseline high flow duration thresholds

The change in time over baseline flow thresholds is also highly scenario dependent. All catchments under the three ‘wet’ ENSEMBLES scenarios exhibit an increase in time over the baseline Q1 threshold, whereas most catchments under the other scenarios experience a decrease (see Figure 8-15).

Figure 8-15 Change in time over the baseline Q1 flow threshold for the Bedford Ouse catchments in the 2080s compared to the baseline under different scenarios



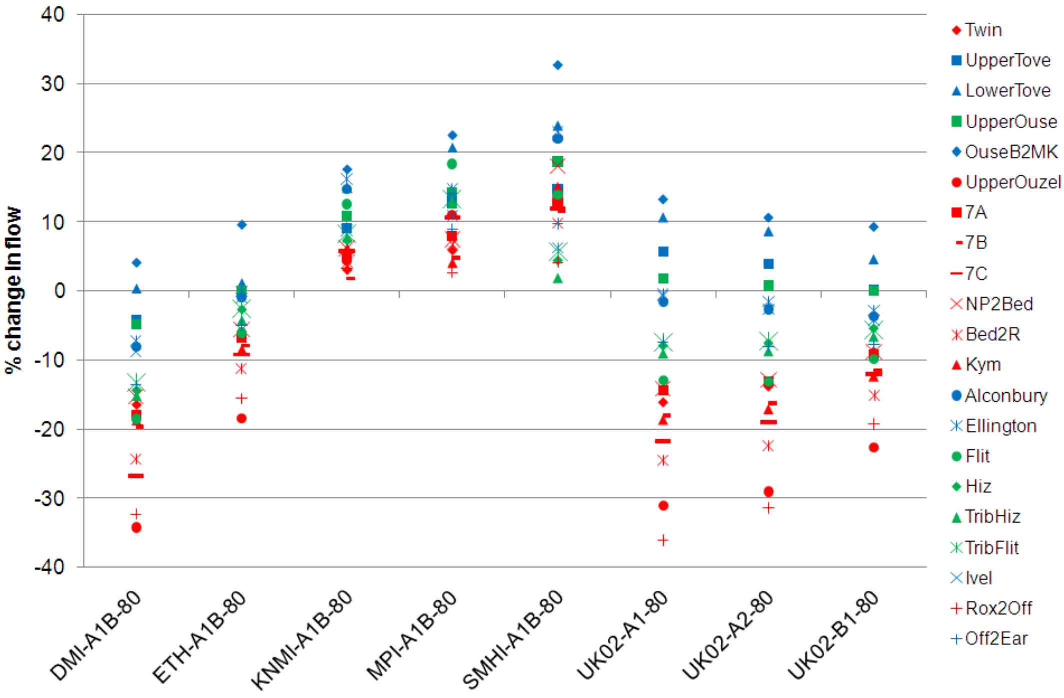
The symbols show the maximum of the 21 catchments (Max), the median plus one standard deviation (+1 SD), the median, the median minus one standard deviation (-1 SD) and the minimum (Min). The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1.

8.3.2.3 Changes in relation to response types

The catchment response types introduced in Section 8.3.1 are also apparent for high flows, although less so for maximum flows. Figure 8-16 shows the change in Q1 flow threshold (as simplified in Figure 8-13) but with each catchment identified and coloured according to response type (blue being enhanced, green subdued and red reduced). The highest changes (although not always positive) are from catchments with the enhanced response type, the lowest are from catchments with the reduced response type, with catchments of the subdued response in between. Catchment response has less influence for maximum flows (not shown), although the lower changes are from catchments with the reduced response.

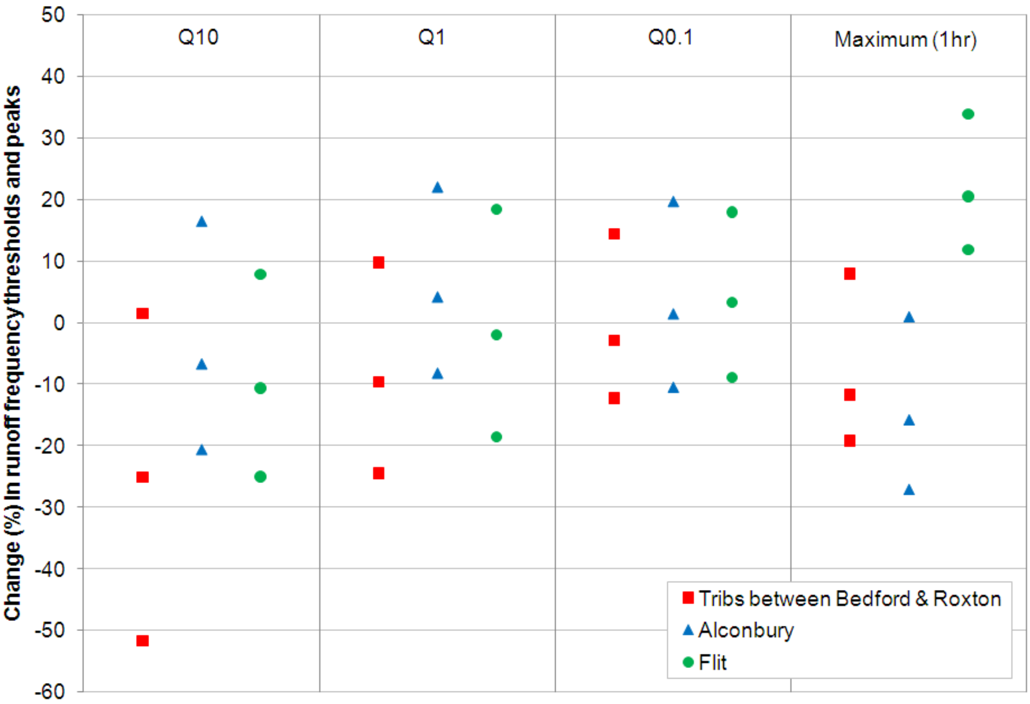
For the three response type exemplar catchments, changes in various flow thresholds are illustrated in Figure 8-17. These follow the same pattern noted above, although above Q0.1 the Flit (subdued) shows much larger increases (the Flit had the largest increases in maximum flow for five of the eight 2080s scenarios).

Figure 8-16 Change in Q1 flow threshold for the Bedford Ouse catchments (classified by response type) in the 2080s compared to the baseline under different scenarios



Each catchment is coloured according to its response type (blue being enhanced, green subdued and red reduced). The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. For details of catchments, see Table 5-2. Original in colour.

Figure 8-17 Change in flow thresholds for the three response type exemplar catchments in the 2080s compared to the baseline under different scenarios



Results show the lower, average and upper scenarios of the eight 2080s model scenarios (see Table 8-1). The baseline is that modelled for the period 1961 to 1990. For details of catchments, see Table 5-2. Original in colour.

8.3.3 Changes in runoff for extreme historical events

Changes in runoff for extreme historical events are highly scenario dependent, although there are also large variations between catchments, which relate to catchment response type for some (seasonal) events.

8.3.3.1 Changes in baseline event peak flow

The number of catchments for which baseline peak flows are exceeded depends strongly on the scenario (see Table 8-5). Note that for the events with multiple peaks, the scenario event maximum is not always coincident with the baseline event maximum, and the baseline event maximum also varies between catchments. Therefore the maximum peak across the event was selected, based on the broad event period defined in Section 8.2.2.

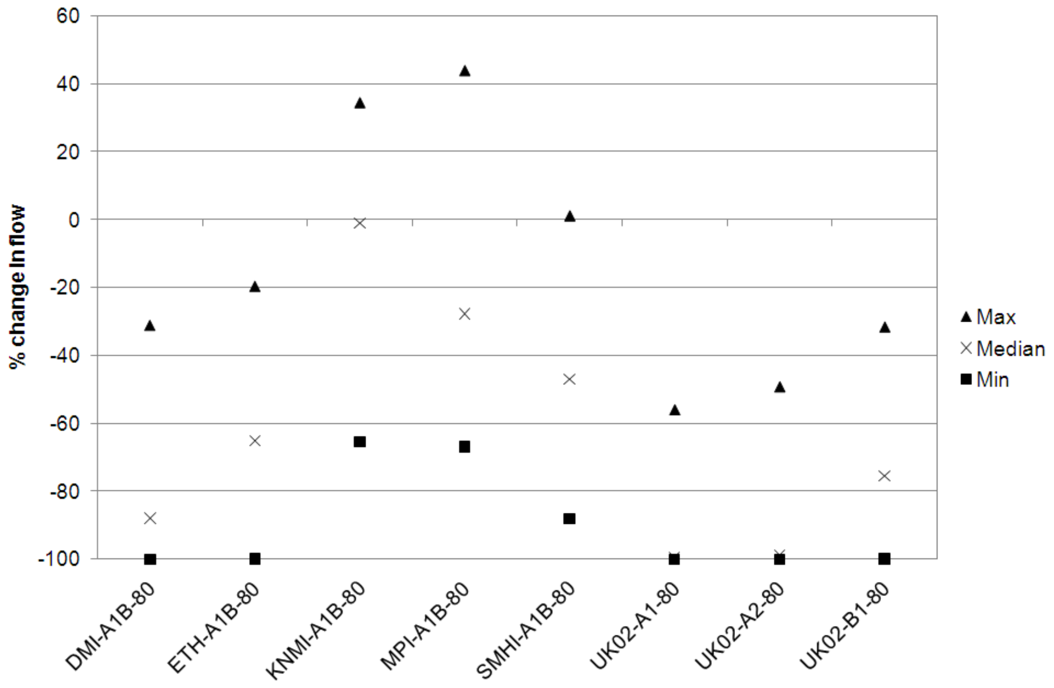
Table 8-5 Number of catchments where event maximum peaks are exceeded in the scenario

Scenario	December 1979	September 1992	Easter 1998	Autumn 2000
DMI-A1B-80	2	0	0	0
ETH-A1B-80	4	0	2	2
KNMI-A1B-80	20	10	0	15
MPI-A1B-80	21	5	0	20
SMHI-A1B-80	16	1	8	5
UK02-A1-80	7	0	1	0
UK02-A2-80	7	0	0	0
UK02-B1-80	6	0	0	0

Note that there is a total of 21 catchments. For details of scenarios, see Table 8-1.

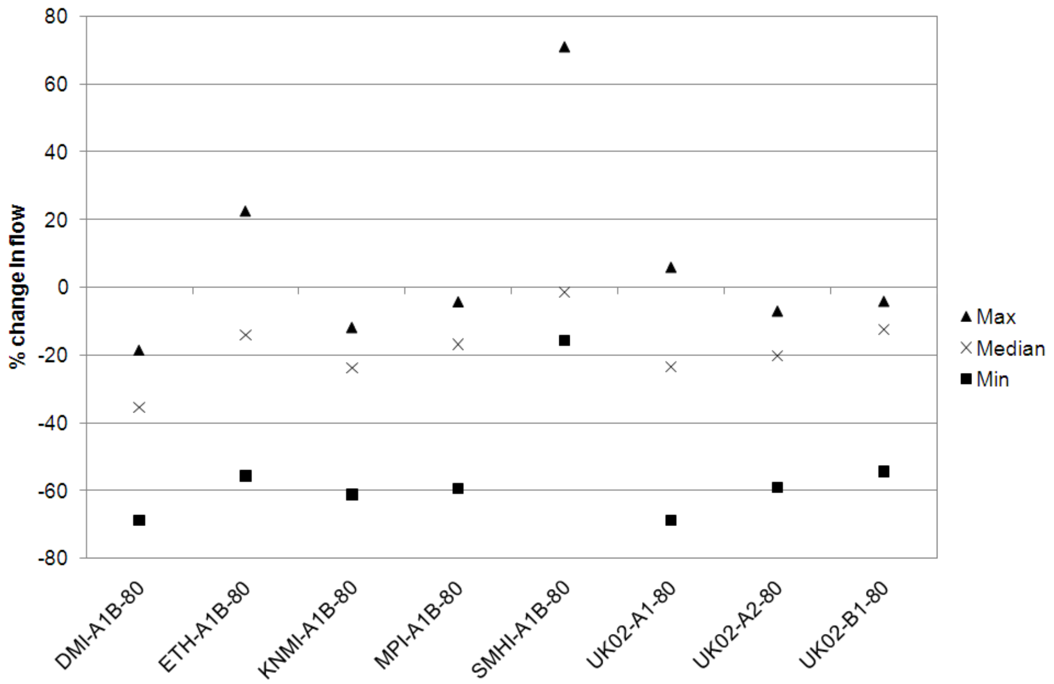
In terms of the size of changes, there were large differences between events. The greatest range was for the December 1979 event (not shown), with the catchments returning the lowest changes having decreases of 100% under some scenarios (i.e. no flow under the scenario) compared to a catchment with an increase of more than 100% under the MPI-A1B-80 scenario. For the September 1992 event (Figure 8-18), there are several catchments with decreases of or close to 100%. The Easter 1998 event (Figure 8-19) also experiences reduced maximum flows, whereas the Autumn 2000 event (not shown, but see Figure 8-20) experiences increases for the KNMI-A1B-80 and MPI-A1B-80 scenarios of 4% and 11% respectively for the median of the catchments.

Figure 8-18 Change in maximum flow for the Bedford Ouse catchments for the September 1992 event as perturbed for the 2080s compared to the baseline under different scenarios



The symbols show the maximum of the 21 catchments (Max), the median and the minimum (Min); standard deviations are not shown due to the skewness of the results for several scenarios. The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1.

Figure 8-19 Change in maximum flow for the Bedford Ouse catchments for the Easter 1998 event as perturbed for the 2080s compared to the baseline under different scenarios



Notes as for Figure 8-18 above.

The sizes of the changes have been compared with the 20% indicative sensitivity range for peak flows (see Table 8-6). The number of catchments where event maximum peaks are exceeded by more than 20% varies by event and scenario. In general only the three wet ENSEMBLES scenarios are relevant, but even under these there is only one increase above 20% during the Easter 1998 event, although up to 16 under the December 1979 event. However, there were many more exceedences when considering these individual events compared with flow thresholds (see Table 8-4). This raises the question of how the 20% indicative sensitivity range is interpreted and applied.

Table 8-6 Number of catchments where event maximum peaks are exceeded by more than 20%

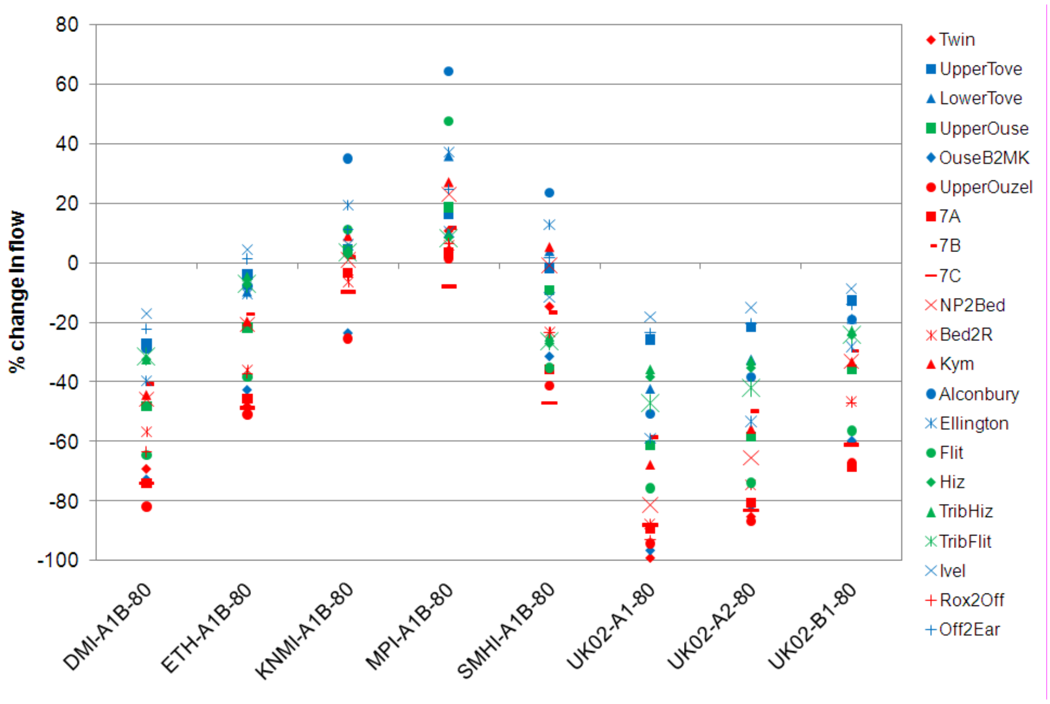
Scenario	December 1979	September 1992	Easter 1998	Autumn 2000
DMI-A1B-80	0	0	0	0
ETH-A1B-80	0	0	1	0
KNMI-A1B-80	16	3	0	1
MPI-A1B-80	15	2	0	7
SMHI-A1B-80	8	0	1	1
UK02-A1-80	2	0	0	0
UK02-A2-80	1	0	0	0
UK02-B1-80	0	0	0	0

Note that there is a total of 21 catchments. For details of scenarios, see Table 8-1.

8.3.3.2 Changes in relation to response types

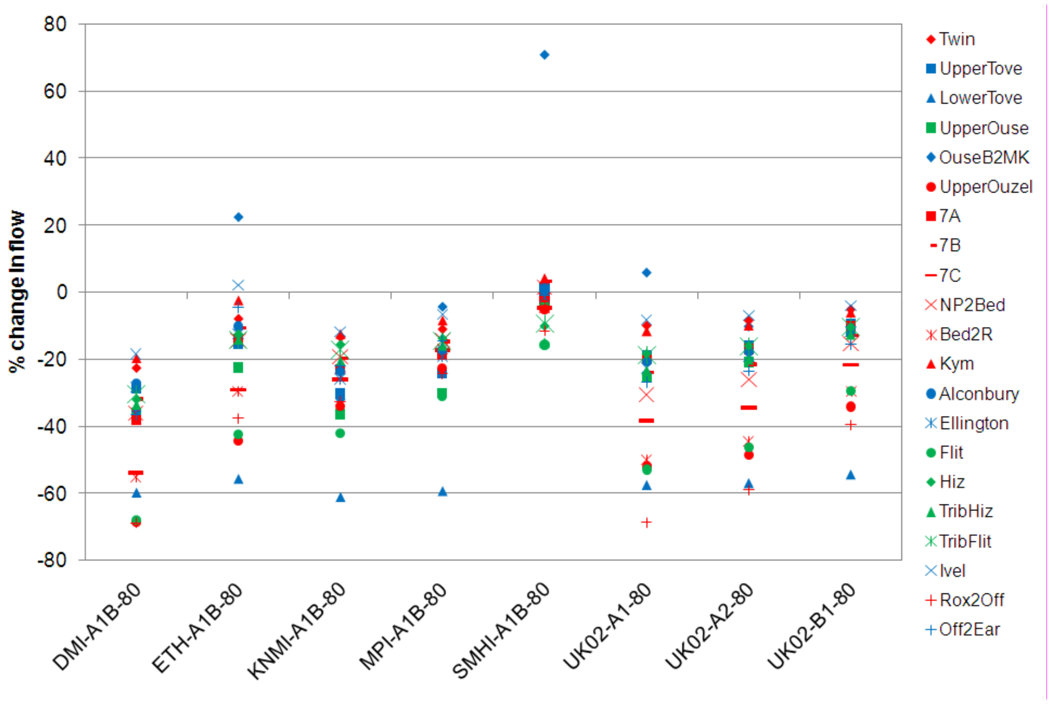
The catchment response types introduced in Section 8.3.1 are also apparent for high flow events, but not for every event. Figure 8-20 shows the change in maximum flow for the Autumn 2000 event, with each catchment identified and coloured according to response type (blue being enhanced, green subdued and red reduced). The highest changes (although not always positive) are from catchments with the enhanced response type, the lowest are from catchments with the reduced response type, with catchments of the subdued response in between. A similar pattern was exhibited for the December 1979 event. However, for the events in the summer half of the year, September 1992 and in particular Easter 1998 (see Figure 8-21), the relationship is mixed.

Figure 8-20 Change in maximum flow for the Bedford Ouse catchments (classified by response type) for the Autumn 2000 event as perturbed for the 2080s compared to the baseline under different scenarios



Each catchment is coloured according to its response type (blue being enhanced, green subdued and red reduced). The baseline is that modelled for the period 1961 to 1990. For details of scenarios, see Table 8-1. For details of catchments, see Table 5-2. Original in colour.

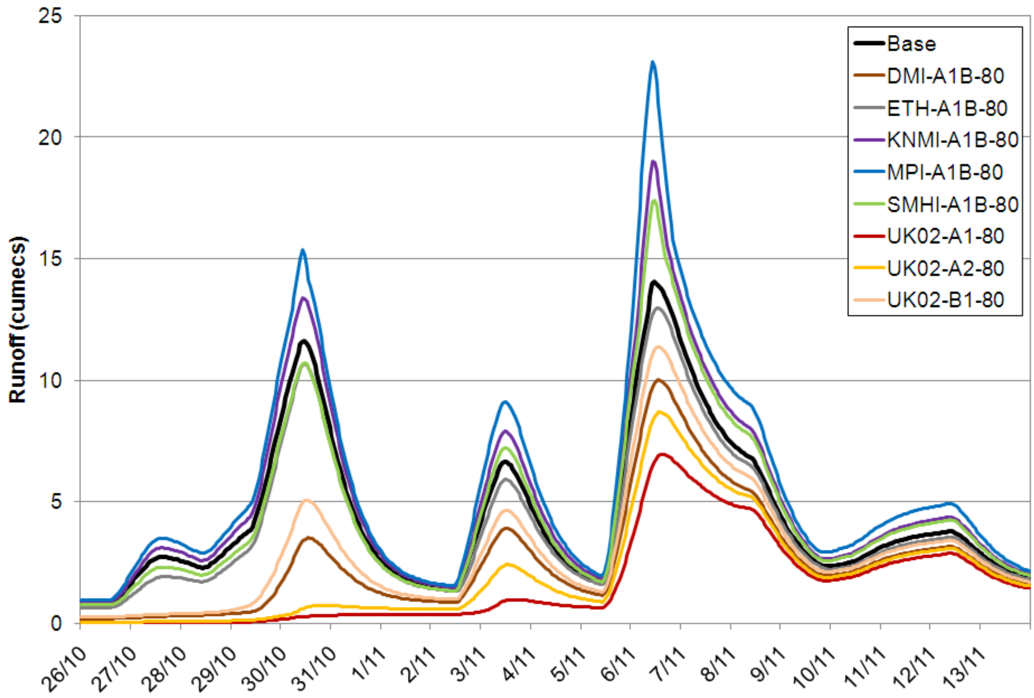
Figure 8-21 Change in maximum flow for the Bedford Ouse catchments (classified by response type) for the Easter 1998 event as perturbed for the 2080s compared to the baseline under different scenarios



Notes as for Figure 8-20 above.

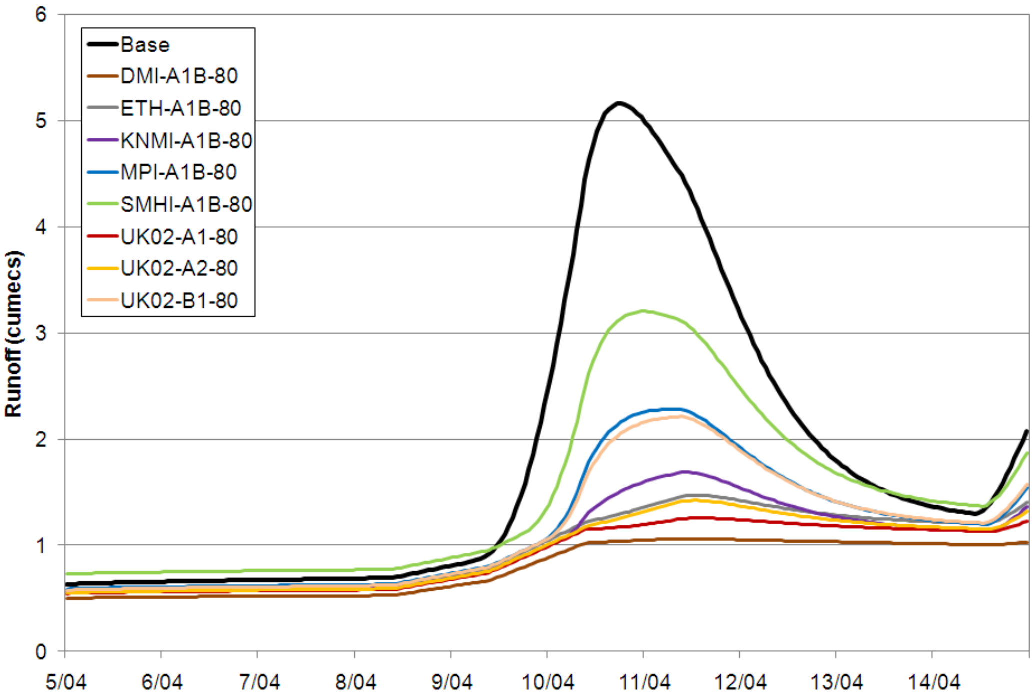
The three response type exemplar catchments conform to the expected pattern, but not for every event. For Alconbury Brook, runoff under the scenarios responds in a relatively similar manner to the baseline, at least after October (see for example Figure 8-22; note that hydrographs of all four events for the three response type exemplar catchments are shown in Appendix 3). In contrast, there is a more subdued response to rainfall in the Flit catchment and under some scenarios the change in rainfall and the effects of antecedent conditions mean that significant runoff is no longer generated (see Figure 8-23). Major reductions in flow are apparent for the tributaries of the Bedford Ouse between Bedford and Roxton, for example in the September 1992 event (Figure 8-24). Large reductions were also apparent for this event for Alconbury Brook whereas at least some flow is sustained for all scenarios for the Flit (Figure 8-25). For Easter 1998, the Flit catchment response remains subdued (Figure 8-23) whereas the response of the tributaries of the Bedford Ouse between Bedford and Roxton, and in particular Alconbury Brook (Figure 8-26) is more similar to the baseline, presumably because the catchments are close to saturation and respond quickly to rainfall. However, the Easter 1998 event is generally not exceeded because April rainfall change factors are negative or only slightly positive.

Figure 8-22 Modelled runoff from the Alconbury Brook catchment for the Autumn 2000 event and under different scenarios for the 2080s



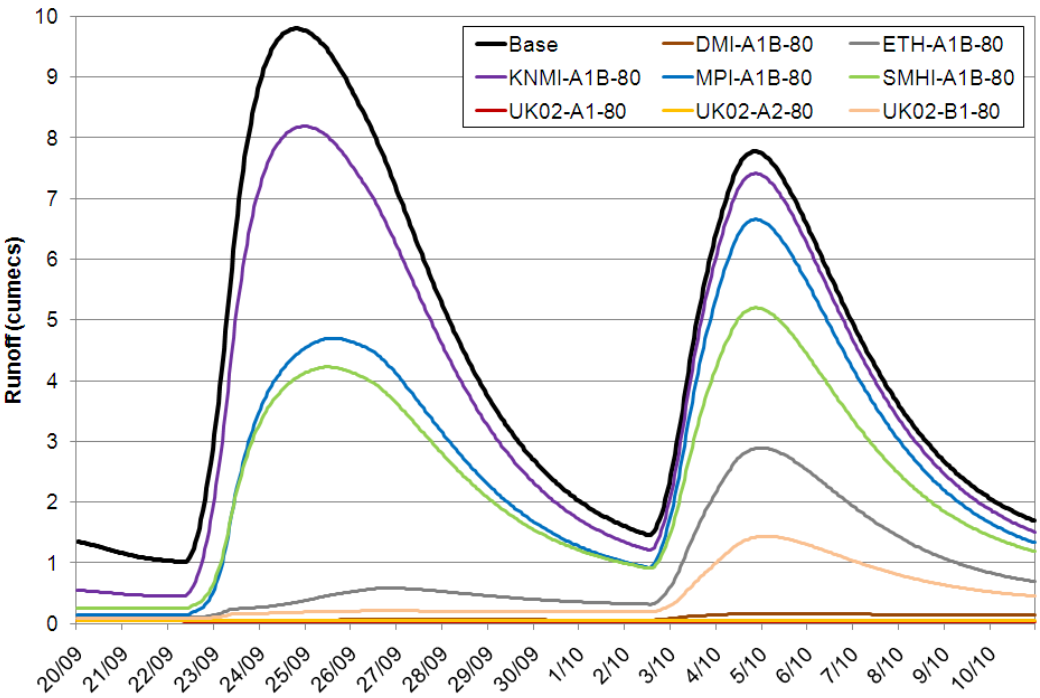
For details of scenarios, see Table 8-1. Original in colour.

Figure 8-23 Modelled runoff from the Flit catchment for the Easter 1998 event and under different scenarios for the 2080s



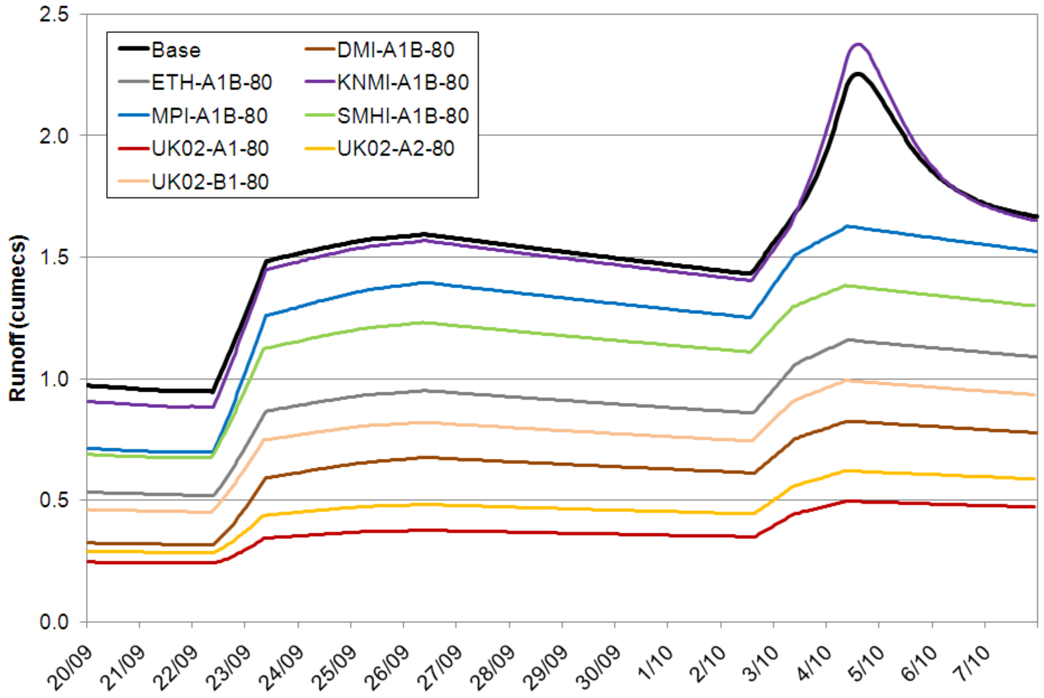
For details of scenarios, see Table 8-1. Original in colour.

Figure 8-24 Modelled runoff from the tributaries of the Bedford Ouse between Bedford and Roxton for the September 1992 event and under different scenarios for the 2080s



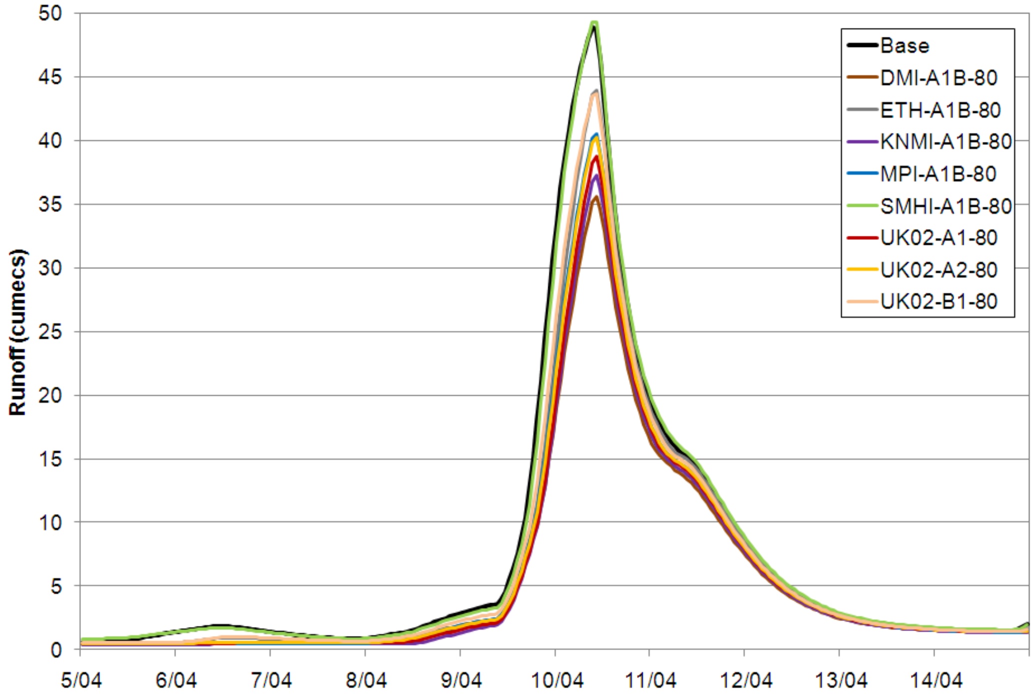
For details of scenarios, see Table 8-1. Original in colour.

Figure 8-25 Modelled runoff from the Flit catchment for the September 1992 event and under different scenarios for the 2080s



For details of scenarios, see Table 8-1. Original in colour.

Figure 8-26 Modelled runoff from the Alconbury Brook catchment for the Easter 1998 event and under different scenarios for the 2080s



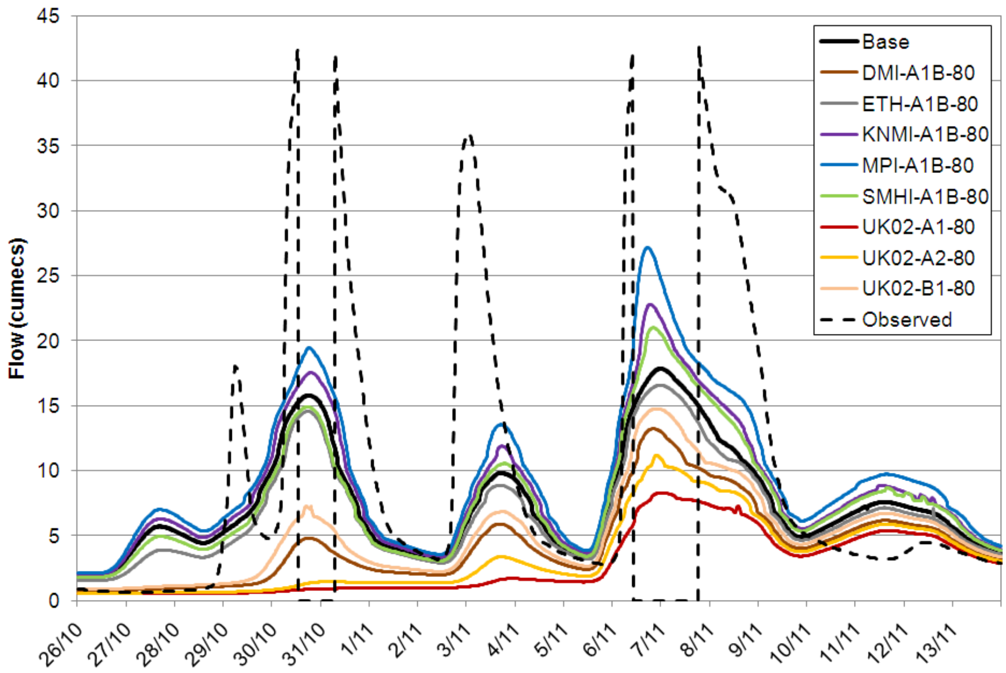
For details of scenarios, see Table 8-1. Original in colour.

8.3.3.3 Modelled event runoff compared to observed baseline flow

As described in Section 6.1.2.3, there were large differences in modelled runoff (for the Twin catchment) for the Easter 1998 event depending on the rainfall dataset and timestep, and the model timestep. However, in terms of the main change introduced, that of a daily timestep, the effects on water level at St Ives Staunch (for Easter 1998, the biggest event) were found to be within the uncertainty range associated with freeboard.

Modelled baseline and perturbed flow can also be compared with observations. Modelled flow (routed runoff) at New Brampton Weir (downstream of the confluence of Alconbury and Ellington Brooks) has been compared with observed flow (note these are based on levels but are converted to flows using rating curves) (Figure 8-27). As expected (from the work described in Section 6.1.2.3), the observed flows are significantly greater than the modelled flows, and these differences are greater than the differences between the modelled scenarios. This means that there is little confidence in the absolute results, but there should be greater confidence in the relative results between the modelled baseline and scenario because the daily rainfall timestep is used in all the model runs. The latter could be tested by perturbing baseline rainfall data of different timesteps, although the perturbation would be based on changes at the daily level, as there is a lack of robust information on future changes in rainfall at the sub-daily level. It should also be noted that there are issues with the flow rating at Brampton; for example, very high flows drop to zero as illustrated in Figure 8-27. A comparison of water levels at St Ives Staunch is provided below.

Figure 8-27 Modelled flow at Brampton for the Autumn 2000 event and under different scenarios for the 2080s along with observed flow



For details of scenarios, see Table 8-1. Original in colour.

8.3.4 Changes in flows and levels at downstream receptors for extreme historical events

Results were extracted for seven model nodes, representing the following seven important receptors in the downstream part of the catchment, including urban areas and protected habitats (see Section 5.2.2 and Figure 5-7):

- Great Ouse at Offord
- Mill Channel at Godmanchester
- Portholme Meadow
- Great Ouse at St Ives
- Fen Drayton Lakes
- Great Ouse just upstream of Brownshill Staunch
- Great Ouse at the inflow to the Ouse Washes

Four of these model nodes are on the Bedford Ouse itself (preceded in the list above, and in the model, by 'Great Ouse'); at Offord and particularly at St Ives there are large areas of floodplain to one side of the channel, whereas the channel is embanked at the other two nodes. Mill Channel is a parallel channel, Portholme Meadow is on the floodplain between Mill Channel and the main channel, and Fen Drayton Lakes is on the floodplain downstream of St Ives.

8.3.4.1 Summary

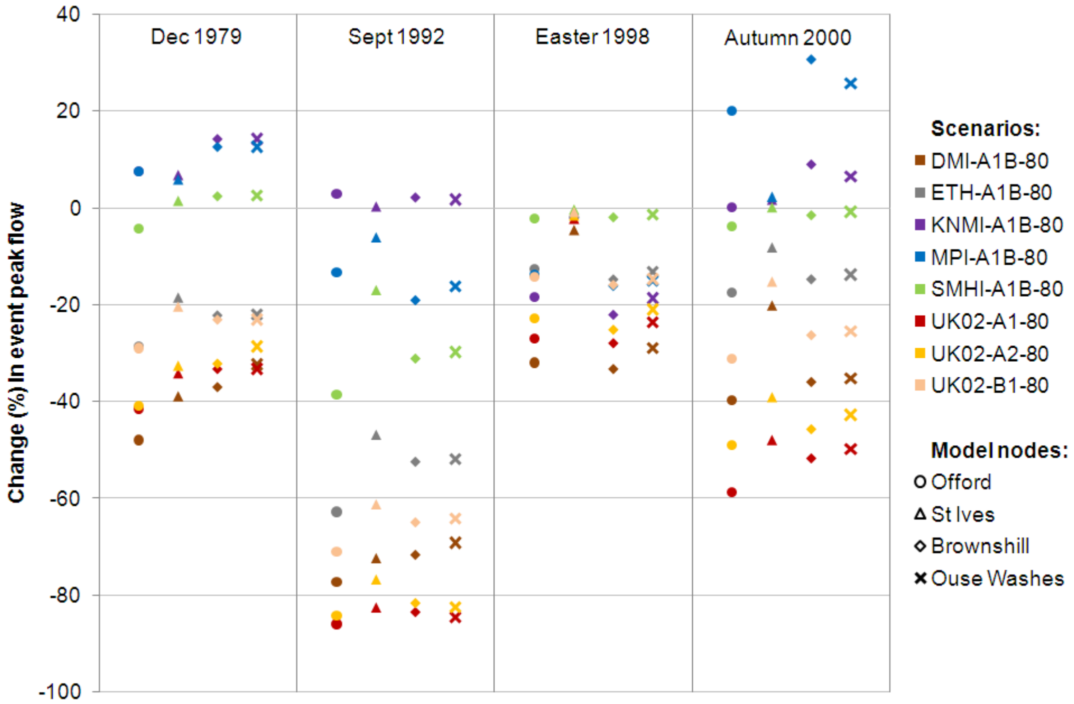
The hydraulic results show that the maximum future peak water levels and flows across the scenarios did not exceed the maximum modelled baseline event (Easter 1998) for all but the most upstream node examined, Offord, and then only marginally. In general, for the September 1992 event the baseline was exceeded by the KNMI-A1B-80 scenario, the Autumn 2000 event also by the MPI-A1B-80 scenario and the December 1979 event also by the SMHI-A1B-80 scenario (except at Offord), but these were always less than the Easter 1998 modelled baseline. For the Easter 1998 event, flows and water levels under the scenarios were less than those for the modelled baseline. However, it is possible that an alternative event, for example between January and March, could yield higher flows and water levels than for the Easter 1998 event.

8.3.4.2 Detailed results

Graphs of flow and water level for the four events for the Great Ouse at St Ives (see Figure 5-7), plus water level results for the Easter 1998 and Autumn 2000 events for the other six receptors are presented in Appendix 3.

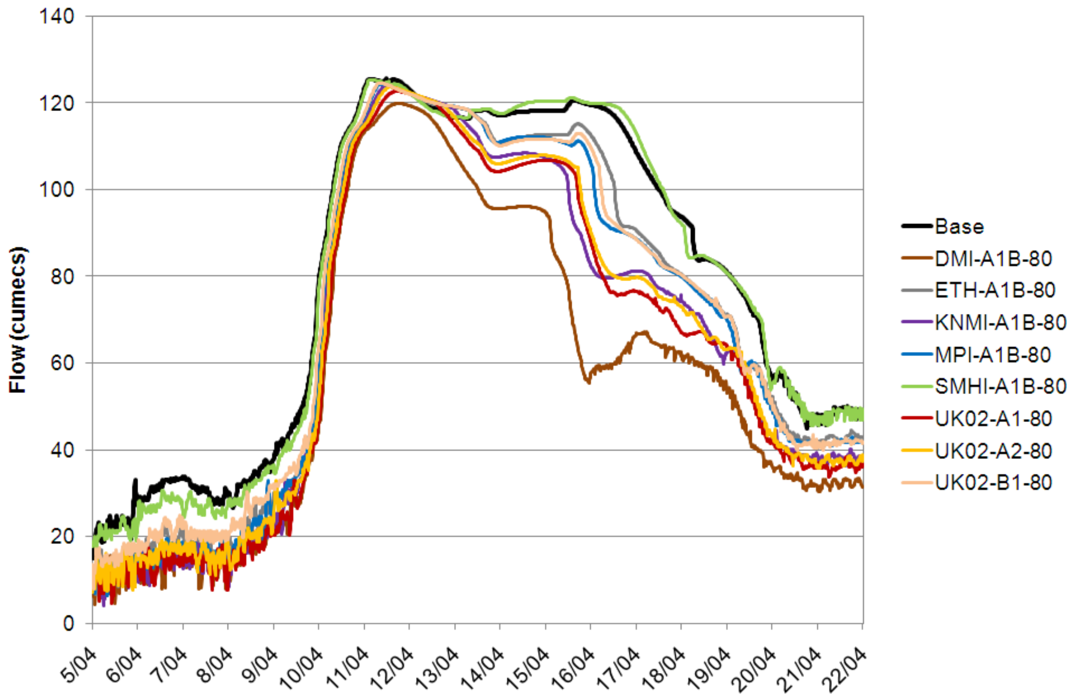
Figure 8-28 shows the change in peak flows for the 2080s compared to the four historical events for the four Bedford Ouse nodes (represented by different shapes) under different scenarios (represented by colours). In general, peak flows decline in future, although the precise magnitude and direction of change is dependent on the scenario and the timing of the event. Only the three ‘wet’ ENSEMBLES scenarios produce higher peak flows for at least one event. The autumn and winter events experience the greatest increases, although several scenarios have large declines, particularly in autumn, which relates to the effects of antecedent conditions noted above. The September event experiences the largest declines, with some scenarios producing very little flow (see also Figure A3-15) as rainfall reductions are large and soils very dry. In contrast the Easter 1998 event experiences the narrowest range and smallest declines as scenarios are responding more similarly, especially at St Ives (see Figure 8-29); however, there is no increase in flow due to generally lower rainfall in April. It is possible that an alternative event, for example with different antecedent conditions but especially one occurring at some point in January or February, would yield much greater flows, with saturated soils and large rainfall change factors. For example, the KNMI-A1B-80 and MPI-A1B-80 scenarios result in a decrease in flow for the Easter 1998 event; April change factors for these scenarios are -8.9% and -6.2% respectively, which compares with 15.6% and 17.6% in January, and 18.3% and 7.1% in February. It is recommended that the events of January 2001 and January 2003 are examined, but with consideration given to the potential that more recent events may be influenced by climate change.

Figure 8-28 Change in peak flow for the four Bedford Ouse nodes in the 2080s compared to the four historical events under different scenarios



The chainages for the model nodes (represented by shapes, and from left to right) are: 'GREAT OUSE 156477.50', 'GREAT OUSE 172034.94', 'GREAT OUSE 181425.00' and 'GREAT OUSE 184623.31'. For details of scenarios, see Table 8-1. Original in colour.

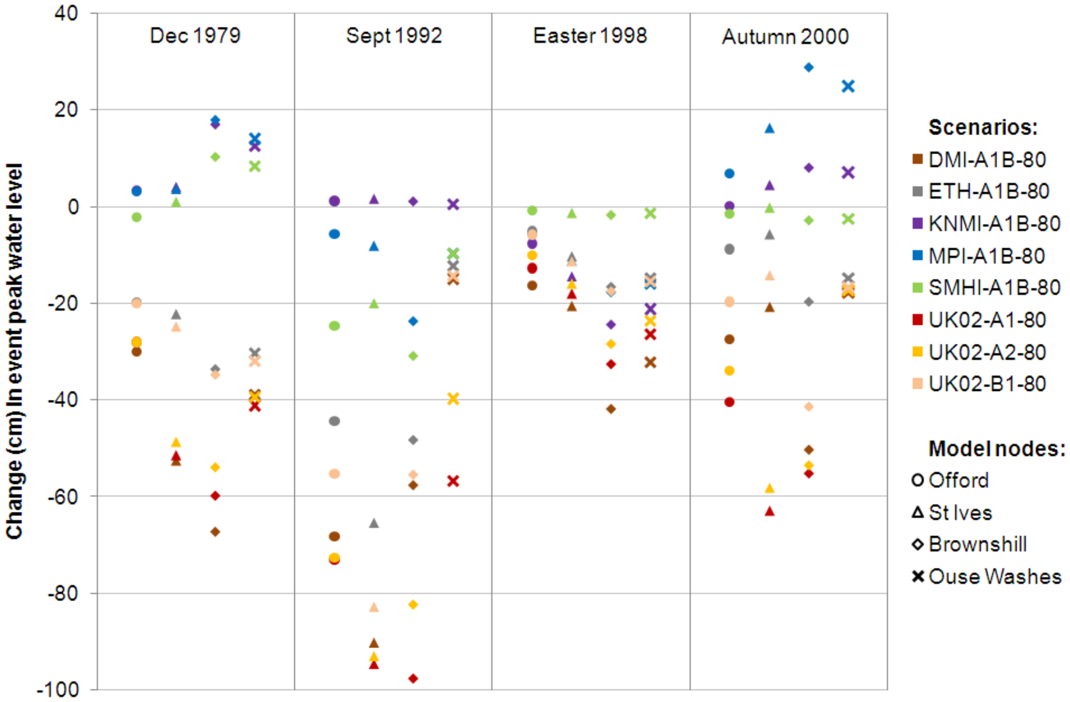
Figure 8-29 Modelled flow on the Great Ouse at St Ives for the Easter 1998 event and under different scenarios for the 2080s



Results for model node at chainage 'GREAT OUSE 172034.94'. For details of scenarios, see Table 8-1. Original in colour.

The effect of the peak flow changes described above on peak water levels is illustrated in Figure 8-30. The changes are similar in pattern to the flow changes (but note that the water level changes are absolute, in cm, despite the similar numbers on the y-axes). The changes are large compared with the typical freeboard allowances for modelling and engineering uncertainties used in the design of flood defence infrastructure which range from 30 cm to 45 cm, of which around 25 cm relates to hydrological and hydraulic modelling[42]. The divergence in the scenarios complicates decisions concerning adaptation.

Figure 8-30 Change in peak water level for the four Bedford Ouse nodes in the 2080s compared to the four historical events under different scenarios



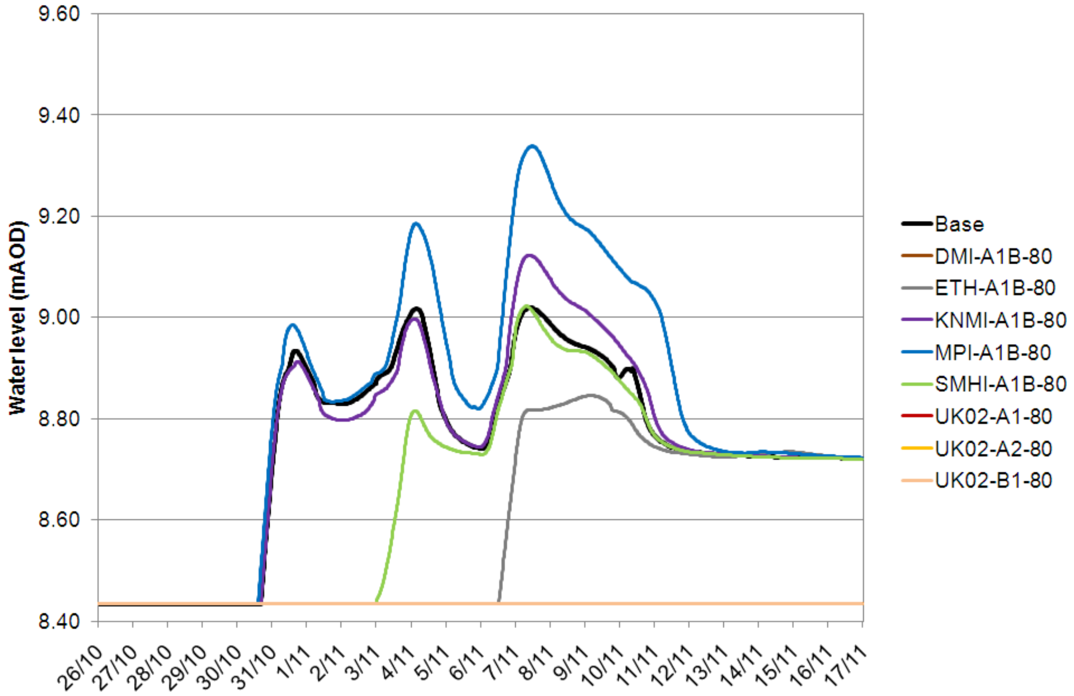
The chainages for the model nodes (represented by shapes, and from left to right) are: 'GREAT OUSE 156385.00', 'GREAT OUSE 172094.86', 'GREAT OUSE 181530.00' and 'GREAT OUSE 184701.61'. For details of scenarios, see Table 8-1. Original in colour.

For Mill Channel the pattern of change in flow was similar to that on the Bedford Ouse, but the relative reductions were less severe. In contrast the two floodplain sites exhibited large changes, with a divergence depending on the scenario. Under all events except for Easter 1998, for the drier ENSEMBLES scenarios and the for UKCIP02 2080s scenarios, peak flows were generally reduced to zero or very close to zero; the floodplain is no longer required because of the flow reductions. Baseline flows were already low for the December 1979 event, but for the September 1992 event peak flow on Portholme Meadow declines from over 22 cumecs to zero. In contrast, the three 'wet' ENSEMBLES scenarios have much smaller reductions and also produce increases in peak flow, particularly for the December

[42] Total modelling uncertainty is typically +/- 250mm (Tom Rouse, Atkins, personal communication)

1979 and Autumn 2000 events. Figure 8-31 shows the modelled water levels at Portholme Meadow, which illustrates the effect of the large increases in flow under the KNMI-A1B-80 and MPI-A1B-80 scenarios. Also apparent is the delayed response to the use of the floodplain under the SMHI-A1B-80 and ETH-A1B-80 scenarios, with flow under other scenarios insufficient to generate floodplain flow. For the Easter 1998 event flows were reduced by about 60% across all scenarios, although they were similar under the SMHI-A1B-80 scenario which has a modest 1.6% increase in April rainfall across the Bedford Ouse catchment (the highest).

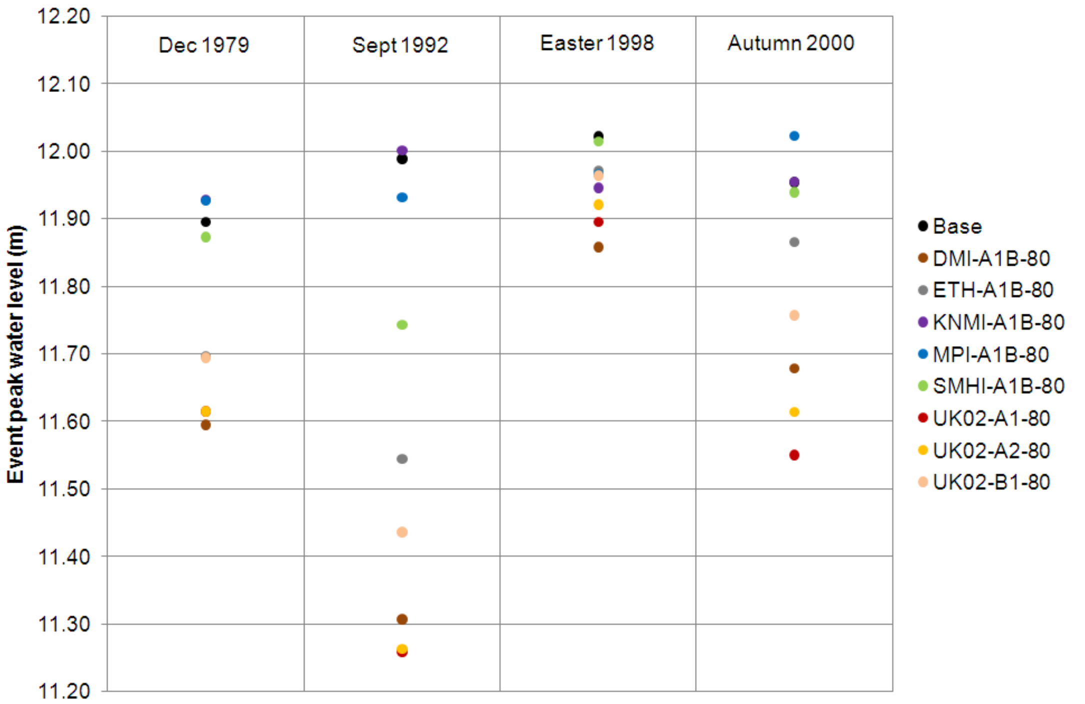
Figure 8-31 Modelled water levels on Portholme Meadow for the Autumn 2000 event and under different scenarios for the 2080s



Results for model node at chainage 'GM_FP_CLOW 2400.00'. For details of scenarios, see Table 8-1. Original in colour.

In terms of the absolute changes in peak flow and water level across events and scenarios, the maximum modelled baseline event (Easter 1998) was not exceeded except at the most upstream node, Offord. For Offord the MPI-A1B-80 scenario for the Autumn 2000 event exceeded the 1998 modelled baseline peak flow by just 0.8 cumecs and level by 1mm (see Figure 8-32), which is well within the modelling uncertainty range. However, an alternatively timed event, as discussed above, could produce higher water levels.

Figure 8-32 Modelled peak water level at Offord for four historical events and under different scenarios for the 2080s



Note that for the Autumn 2000 event the base is approximately the same and is occluded in the Figure by the KNMI-A1B-80 scenario. Results for model node at chainage 'GREAT OUSE 156385.00'. For details of scenarios, see Table 8-1. Original in colour.

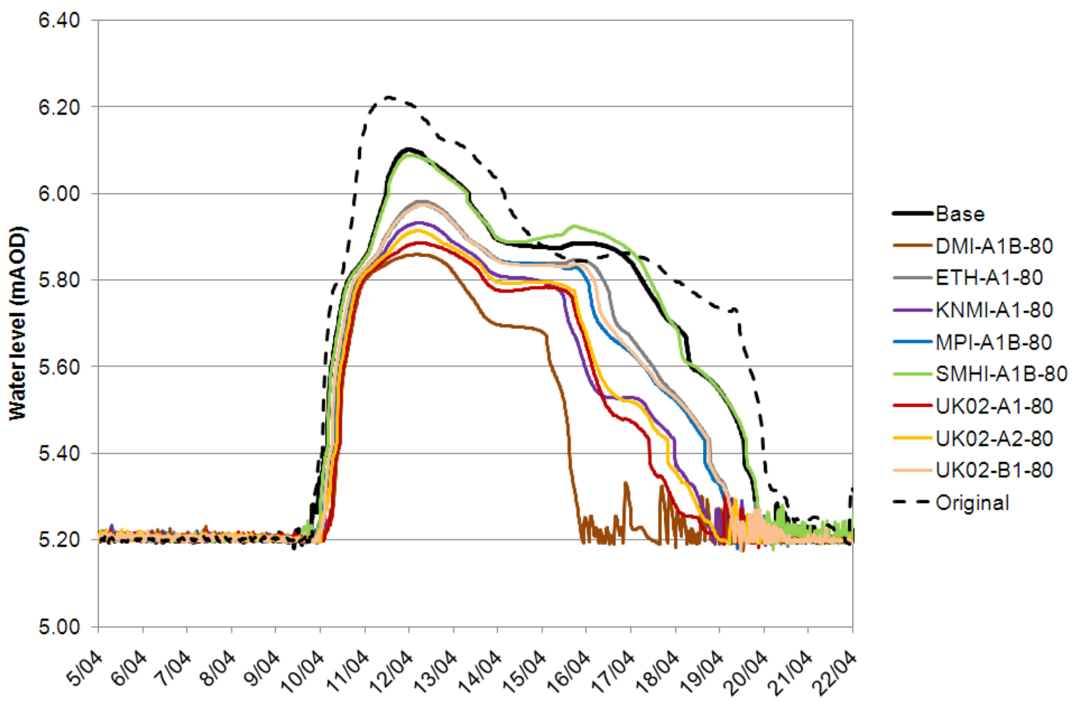
The results show that the upstream flow increases are somewhat attenuated downstream by the wide floodplains. Therefore, while some large increases in catchment flow are modelled for the autumn and winter events, the changes in flow and level are generally smaller. For example, under the MPI-A1B-80 scenario, for the December 1979 event, 15 of the 21 catchments have increased runoff of more than 20% (with an arithmetic average across all 21 of 32%), whereas none of the Bedford Ouse nodes experiences an increase in flow above 13%. Increases in water levels are also limited by the presence of wide floodplains, so increases in flow for the same event and scenario of 7.5% and 5.8% for Offord and St Ives, only translate into increases in level of 3.2 cm and 3.6 cm respectively.

In terms of the 20% indicative sensitivity range, there were only three runs which resulted in greater changes in flow for the Bedford Ouse nodes. All related to the MPI-A1B-80 scenario for the Autumn 2000 event, with increases of 20% at Offord, 31% at Brownshill Staunch and 26% at the inflow to the Ouse Washes. There were much larger increases than 20% for the two floodplain sites under the three 'wet' ENSEMBLES scenarios for the autumn and winter events, largely because absolute baseline flows were low, whereas under the scenarios the floodplains become inundated and experience similar absolute increases in flow to the Bedford Ouse nodes.

8.3.4.3 Modelled event water levels compared to original levels

Modelled baseline and perturbed water levels can be compared with the original modelled levels, the latter including a correction procedure (see Section 6.1.2.3). Modelled water levels at St Ives Staunch (Figure 5-7), downstream of the node referred to above, have been compared with the original model results (Figure 8-33). As expected, there is some difference between the baseline levels (just over 12 cm at the peak), but this is small compared to the size of the peak and the scenario range. Therefore greater confidence can be placed in these results compared with those of individual catchments. Nonetheless, the comparison also indicates that more confidence should be placed in the relative results between the modelled baseline and scenarios, rather than in the absolute results.

Figure 8-33 Modelled water levels at St Ives Staunch for the Easter 1998 event and under different scenarios for the 2080s along with originally modelled water levels



Results for model node at chainage 'GREAT OUSE 173585.00'. For details of scenarios, see Table 8-1. Original in colour.

8.3.5 Effect of emissions scenarios and climate models

The ENSEMBLES models are all driven by the same emissions scenario (SRES A1B), whereas the three UKCIP02 scenarios used are driven by three further emissions scenarios (SRES A1, A2 and B1). As noted in Section 8.3.1.2, the results for the UKCIP02 scenarios for the Alconbury catchment (enhanced response type) are intuitive, with the highest emissions producing the greatest extremes in line with the change factors, especially those for precipitation, which are more seasonally variable. However, the results for the Alconbury catchment may not be replicated in other parts of the catchment, because changes in flows and levels for the four events in the downstream part of the catchment show that for the UKCIP02 scenarios the highest emissions produce the greatest negative extremes only. This is likely to be due to the higher PET values, which are more significant for the subdued and reduced response types.

The differences in the results between emissions scenarios in the UKCIP02 scenarios are less than the differences between the climate models in the ENSEMBLES scenarios. This conclusion applies to: exemplar response type catchment runoff; high flows and extreme events; and flows and water levels in the lower catchment. The use of alternative GCMs (e.g. those in ENSEMBLES) driven by different emissions scenarios has not been explored due to availability, but it would be useful to examine the behaviour of different emissions scenarios in GCMs that produce wetter results.

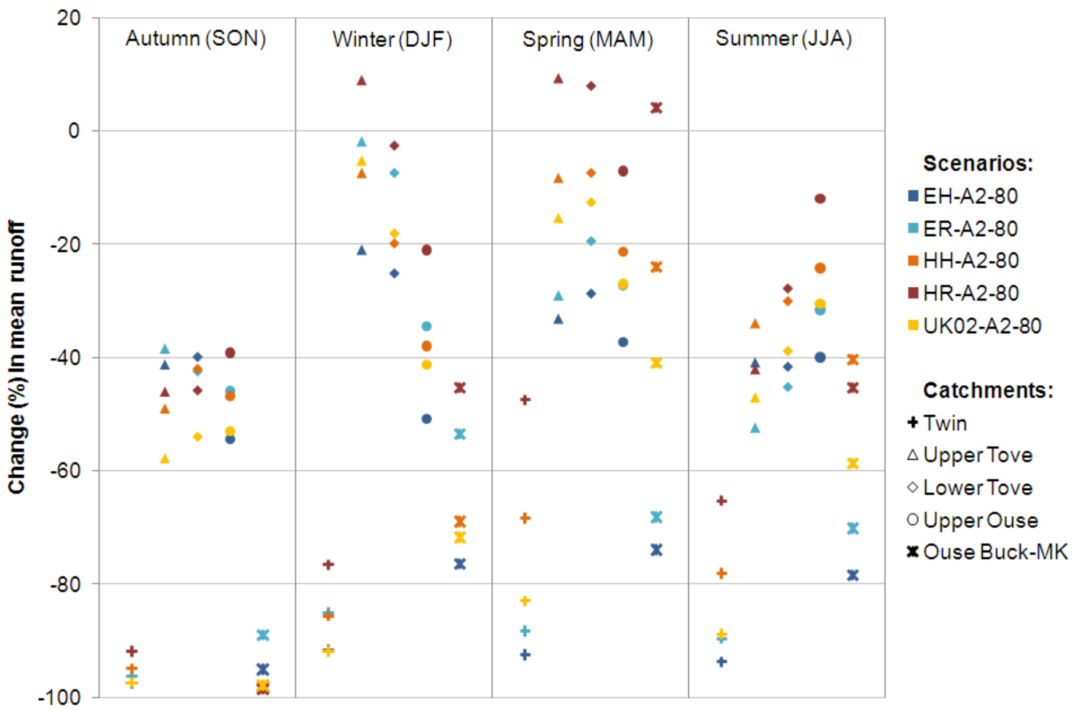
The KNMI-A1B-80 and MPI-A1B-80 scenarios are driven by the same GCM. The similarity of the results (exemplar response type catchment runoff; high flows and extreme events; and flows and water levels in the lower catchment), when compared with the other ENSEMBLES scenarios driven by different GCMs, shows that the uncertainties in downscaling using RCMs are less than those relating to GCMs. The RCM uncertainties are less than those associated with the emissions scenarios examined. This pattern of decreasing uncertainty from GCMs, through emissions, to downscaling to RCMs, is consistent with the Eden results (see Section 9.2.3) and other research (reviewed in Sections 3.1.3 and 3.2.1).

8.4 Future flooding: stochastic approach

8.4.1 Changes in runoff

Runoff in the 2080s is reduced compared to the baseline for all but four of the runs (see Figure 8-34). The reductions in runoff are most severe in autumn, for the Twin and the Ouse between Buckingham and Milton Keynes, and generally for the ECHAM4-driven scenarios. The HIRHAM RCM tends to lead to greater reductions compared to the RCAO RCM, but the differences between the driving GCMs are greater.

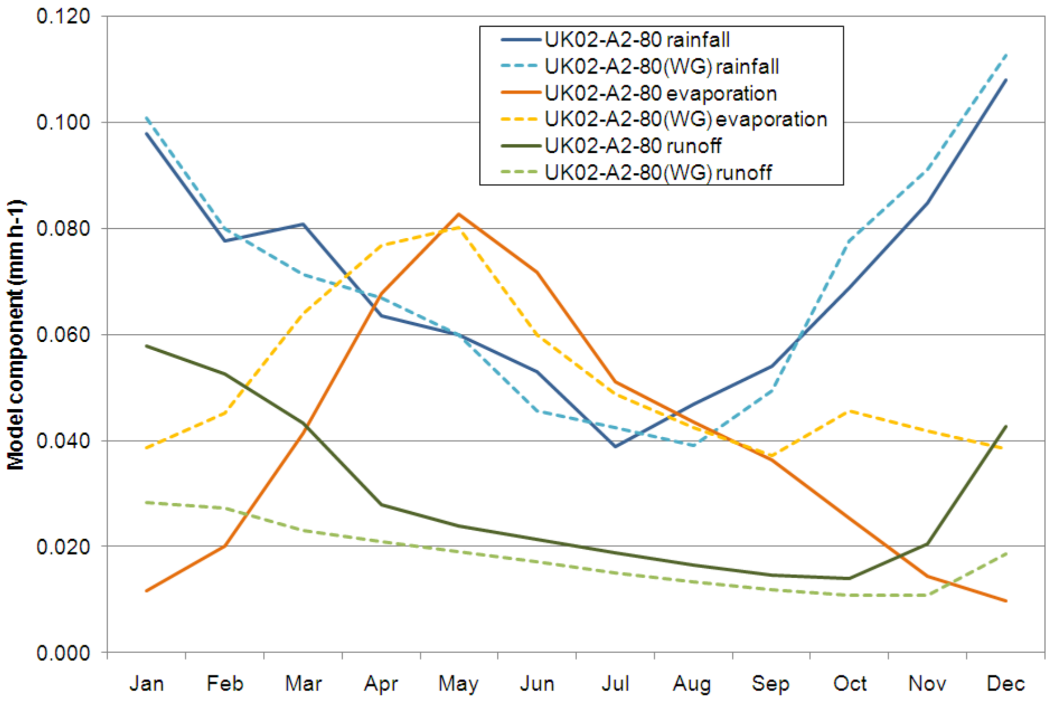
Figure 8-34 Change in mean runoff from the five catchments above Newport Pagnell in the 2080s compared to the baseline under different scenarios derived from EARWIG



Results are from 300-year runs for the catchments (from left to right) Twin, Upper Tove, Lower Tove, Upper Ouse and the Ouse between Buckingham and Milton Keynes. For details of scenarios, see Table 8-2. For details of catchments, see Table 5-2. Original in colour.

The changes in runoff are shifted downwards compared to the perturbation approach, including for the common scenario (UK02-A2-80). This difference is a result of the higher PET in EARWIG (as described in Section 6.1.3). The effect of alternative PET on runoff has been evaluated by comparing rainfall, evaporation and runoff under the perturbation and stochastic methods from the baseline and UK02-A2-80 scenario. This has been undertaken for the Upper Ouse, a rural catchment (3% urban) of 153 km^2 with a semi-regulated response to rainfall, medium runoff, medium groundwater storage, low groundwater abstractions and a BFI-HOST of 0.6 (Atkins, 2003b). Baseline runoff (not shown) is similar under both approaches, except between January and March when it is lower under the stochastic approach due to lower rainfall and higher PET. However, the differences in runoff are much larger under the UK02-A2-80 scenario and extend throughout the year, although are highest between December and March (Figure 8-35). With similarities in rainfall, the differences are mainly caused by the discrepancies between the evaporation results, which are particularly large between October and March.

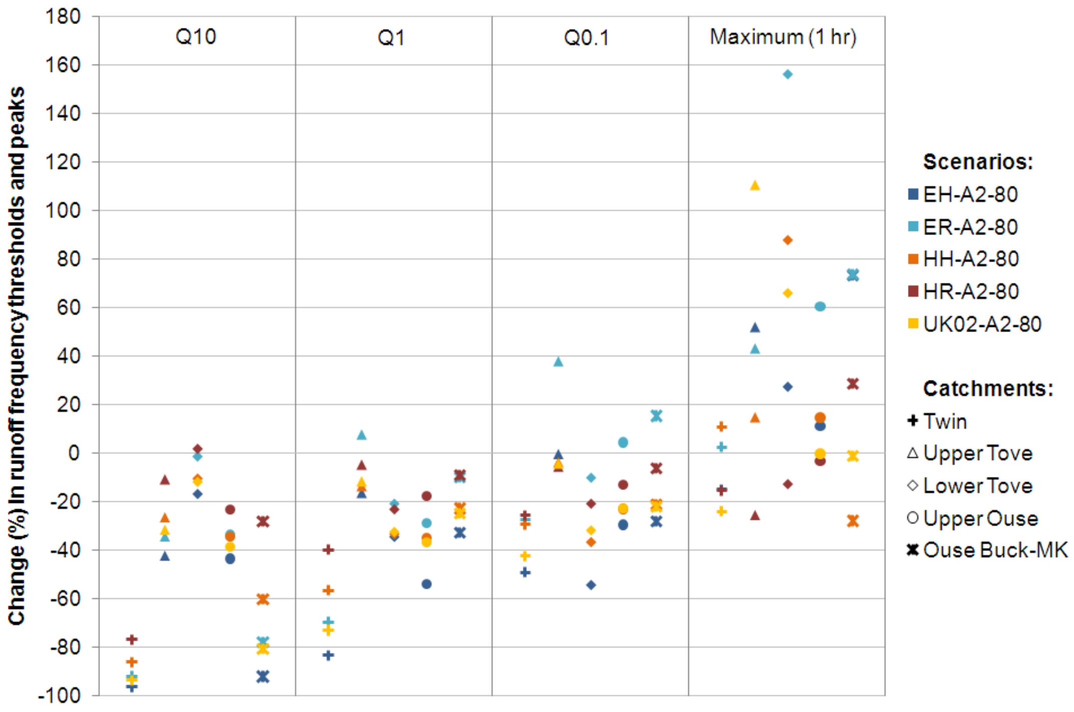
Figure 8-35 Average monthly rainfall, evaporation and runoff for the Upper Ouse catchment under the UK02-A2-80 scenario as derived using the perturbation and stochastic methods



Note that runoff includes baseflow and was converted to intensity (mm h^{-1}) from cumecs based on the catchment area. Note that graph is based on monthly data: the lines are provided for ease of reference. The run with 'WG' in parenthesis refers to the weather generator i.e. the stochastic method. For details of the scenario, see Table 8.1. Original in colour.

Changes in runoff frequency thresholds show that only the most extreme events increase under climate change, but these increase dramatically (Figure 8-36). Such events are unlikely, being the maxima from 300-year runs (although note that it is not anything like the 1 in 300 year event, as the weather generator is only calibrated on 30 years of data), with only four separate runs exceeding any of the Q10, Q1 or Q0.1 baseline frequency thresholds. The remaining runs show reductions in frequency thresholds, which increase from Q0.1 to Q10. Reductions are most severe for the Twin, and for the ECHAM4–HIRHAM GCM–RCM combination, although the pattern for the maxima is mixed.

Figure 8-36 Change in runoff frequency thresholds and peaks for the five catchments above Newport Pagnell in the 2080s compared to the baseline under different scenarios derived from EARWIG

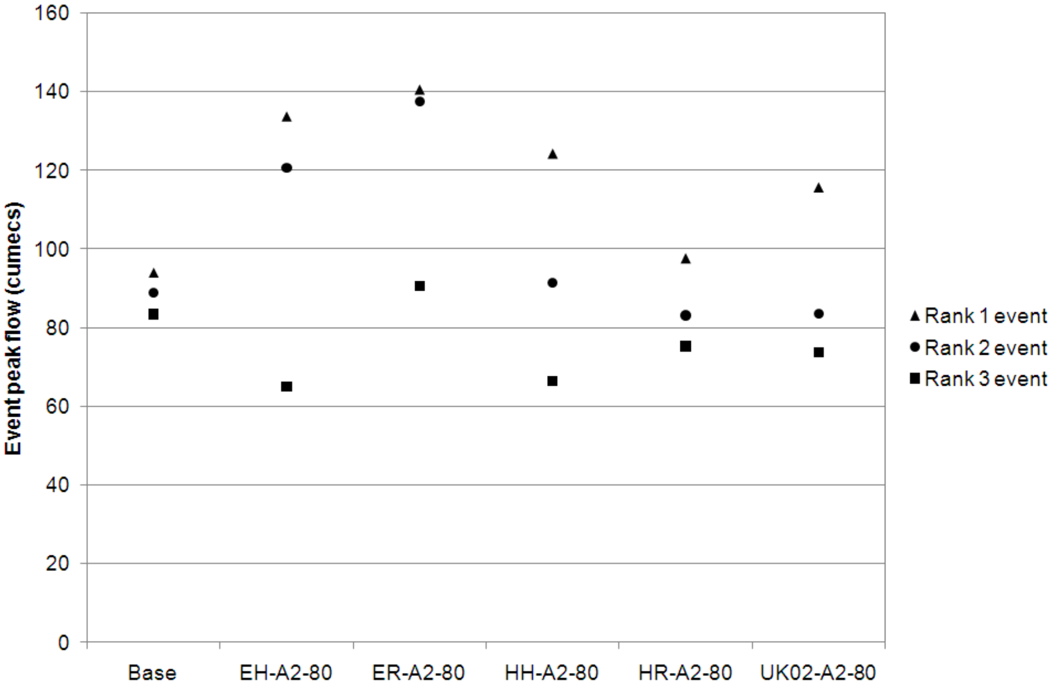


Results are from 300-year runs for the catchments (from left to right) Twin, Upper Tove, Lower Tove, Upper Ouse and the Ouse between Buckingham and Milton Keynes. For details of scenarios, see Table 8-2. For details of catchments, see Table 5-2. Original in colour.

8.4.2 Changes in flows and water levels at Newport Pagnell

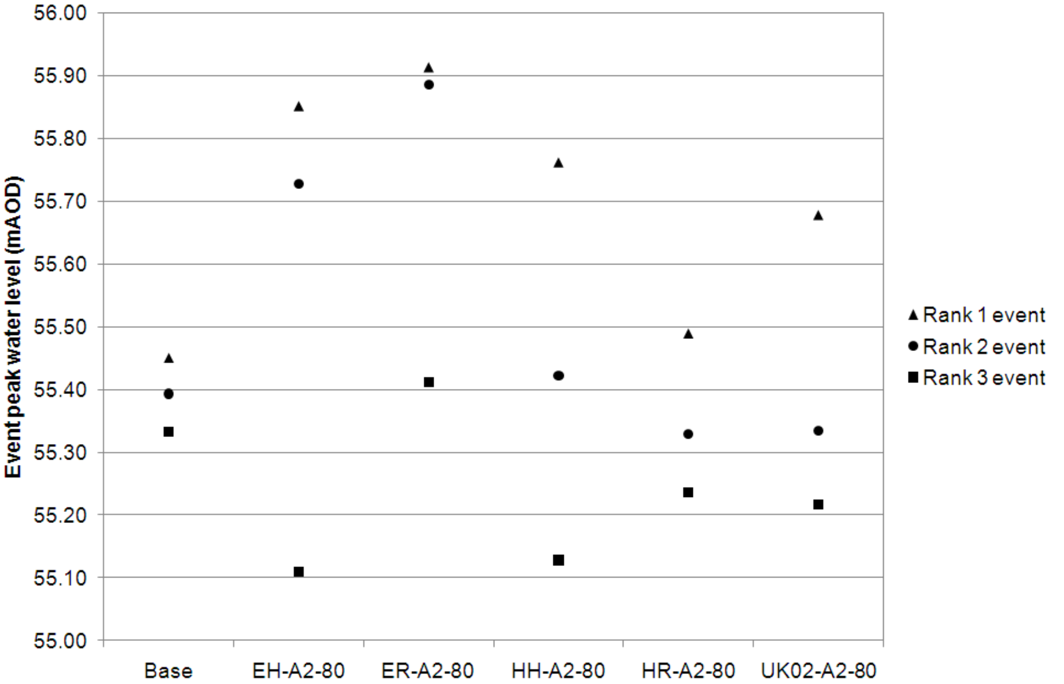
Runoff from each catchment has been routed to Newport Pagnell using the hydraulic model. Given the computational resource, this has been restricted to the highest three events of each 300 year run (see Section 8.2.2). The change in peak flow for the three highest events of the baseline and scenarios is illustrated in Figure 8-37. This shows a wider spread of extreme event peak flows under the scenarios: the first ranks all increase (in four of the five runs by more than 20%), the second rank events increase in three and decrease in two and all but one of the third rank events decrease. In terms of maximum water level (Figure 8-38), the results show that the highest of the scenarios and events was 55.91 mAOD, considerably higher than the baseline maximum of 55.45 mAOD; the Easter 1998 event modelled maximum was 55.12 mAOD.

Figure 8-37 Peak flow at Newport Pagnell for the three most extreme events in 300-year runs representing the baseline and the 2080s under different scenarios derived from EARWIG



The derivation of the three most extreme events is discussed in Section 8.2.2. Results for model node at chainage 'GREAT OUSE 56604.00'. For details of scenarios, see Table 8-2.

Figure 8-38 Peak water level at Newport Pagnell for the three most extreme events in 300-year runs representing the baseline and the 2080s under different scenarios derived from EARWIG



Notes as for Figure 8-37 above.

8.4.3 Catchment sensitivity

Given that all five catchments have the same meteorological inputs, the modelling illustrates the sensitivity of the catchments. This reflects the catchment characteristics and can be related to the catchment response types introduced above. For example, the Twin is classified as reduced and experiences large decreases in seasonal and high flow, whilst the Tove catchments are classified as enhanced and have the smallest reductions or greatest increases in winter and spring flow, and in extreme flow. Other characteristics such as urbanisation (particularly prominent for the Upper Tove and the Ouse between Buckingham and Milton Keynes) and catchment size (the Lower Tove is just 77 km^2) may also influence high flows.

8.4.4 Concluding discussion

The stochastic approach provides additional information compared with the perturbation method, particularly in terms of natural variability and how this may change in future. However, further runs (more than the equivalent of ten runs of 30 years) may be required to explore the uncertainty, especially for extreme events. The sensitivity of such events to daily rainfall and to the higher PET of EARWIG, both of which tend to reduce runoff, should also be explored, along with alternative emissions scenarios.

9. Future flooding: the Eden

This chapter details the hydrological and hydraulic model runs undertaken, and describes the effect of the scenarios developed in Chapter 7 on future flooding in the Eden catchment, which was introduced in Chapter 5. The first part summarises the model runs, the final perturbation method and assumptions. The second part summarises the effects on future flooding.

9.1 Model runs

The modelling for the Eden catchment was based on perturbations of three rainfall–runoff models calibrated on three flood events in the 1990s: February 1990, February 1995 and January 1999. The models were already set up in the ISIS modelling package, which incorporates the FEH rainfall–runoff model for the event-based hydrology and the ISIS hydraulic components for the hydraulic modelling[43] (see Section 5.1.3.6). The final method of perturbation and assumptions made are summarised in Box 9-1.

The output for each event model consists of (i) hydrographs for each of the 26 catchments (see Figure 5-6) for the three baseline events and the climate change scenarios, and (ii) hydrographs and water levels for various points in the catchment, the analysis here focusing on the key receptors identified in Section 5.2.3 (see Figure 5-8). However, running all 13 of the climate change scenarios produced in Section 7.3 for the 26 catchments and three baseline events would require 1014 FEH input files and produce the same number of hydrographs. Therefore, for each baseline event, it was decided to limit the analysis to six climate change scenarios for the 2080s (see Table 9-1); these will permit comparisons relating to emissions scenarios, GCMs and RCMs, and capture the overall range of uncertainty in the change factors. This will give 18 future scenarios of flooding for the catchment.

Table 9-1 Perturbed full model run schedule for the Eden (three baseline events and six climate change scenarios)

Reference	GCM–RCM	Emissions scenario^	Time period	Rainfall
Base	n/a	n/a	Baseline	Observed (three events)
UK02-B1-80	HadCM3-HadRM3*	B1	2080s	Base perturbed (three events)
UK02-A1-80	HadCM3-HadRM3*	A1FI	2080s	Base perturbed (three events)
KNMI-A1B-80	ECHAM5-RACMO**	A1B	2080s	Base perturbed (three events)
SMHI-A1B-80	BCM-RCA**	A1B	2080s	Base perturbed (three events)
MPI-A1B-80	ECHAM5-REMO**	A1B	2080s	Base perturbed (three events)
DMI-A1B-80	ARPEGE-HIRHAM**	A1B	2080s	Base perturbed (three events)

GCM–RCM output from *UKCIP02, **ENSEMBLES. ^IPCC SRES.

[43] Version 41 of the Eden model was used, under licence from the Environment Agency.

Box 9-1 Final model perturbation and assumptions

For each event model, the data for perturbation (rainfall depth, *SAAR*, *CWI*; see Section 7.3.1) were extracted from each of the 26 catchments. Rainfall depth and *SAAR* were perturbed (proportionally) using the relevant monthly and annual change factors respectively, as described in Section 7.3.1.

For *CWI*, no breakdown was given in the FEH model set up in terms of *API*5 and *SMD*. The usual assumption by modellers is to assume that *SMD* is zero, a conservative position^. Given the timing of the events, in January and February, it is likely that *SMD* was at or close to zero. Future scenarios of PET suggest that *SMD* deficits are more likely in winter in future, although perhaps only in early winter following higher summer deficits and before higher winter rainfall recharges the soil. Therefore, it was assumed that *SMD* was zero and will remain zero in future for January and February in this wet catchment, which is likely to experience large increases in winter rainfall. In terms of perturbation, it was therefore assumed that the difference between the figure for *CWI* and 125 (the constant in the *CWI* formula, see Eqn. 7.1) related only to *API*5. Unfortunately, this led to negative values of *API*5 for six catchments under the 1995 calibration event, which indicates that for these catchments at least, a positive *SMD* was present. Reference in the model build report (Flynn and Rothwell, 2000) was made to a residual *SMD*, but it is unclear how this was applied and so *API*5 was adjusted to zero for these sub-catchments, meaning that *CWI* remained the same under climate change. For the majority of catchments, and the other two events, *API*5 was perturbed proportionally (as with rainfall depth) and added back to the constant to produce the future *CWI*.

BF was based on observations for nearly all the catchments in the 1990 and 1995 event models, with the FEH formula (see Eqn. 7.6) used for the 1999 event model. As discussed in Section 7.2.3, the perturbations are based on the catchment descriptors (*CWI* and *SAAR* from above). These were then used directly in the FEH calculation of *BF*. Where observations exist, a *BF* change factor was created based on future and baseline *BF* and then applied to the baseline observation of *BF*.

All other inputs (*URBEXT*, *SPR*, *Tp*, minimum flow, time delay and hydrograph scaling) were held constant. The hydrographs were then routed using the same hydraulic model and parameters as for the baseline, to give combined flows and levels.

^Yiping Chen, Atkins, personal communication.

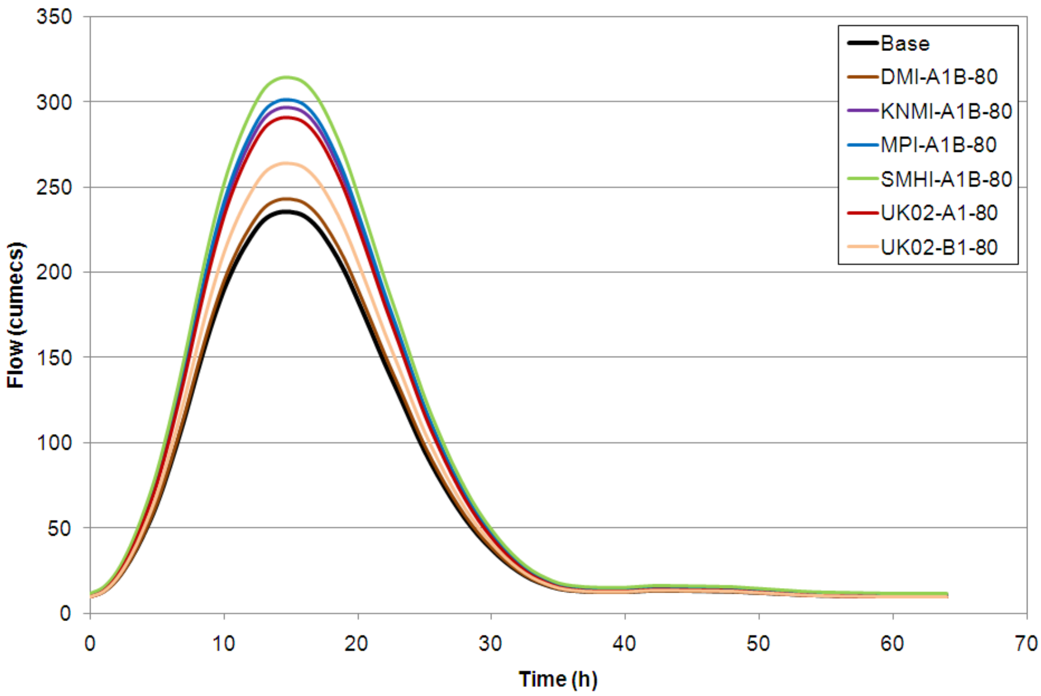
9.2 Future flooding

This section presents the results in three parts. Firstly, changes in runoff from the 26 catchments, from all three baseline events, are described; secondly the corresponding changes in flows and levels at the downstream receptors are examined; and thirdly the effects of emissions scenarios and climate models are considered. It should be noted that there has been no re-interpretation of the rainfall or PET series used in the baseline models. Therefore, the baselines are presented as a comparison to the future modelling results.

9.2.1 Changes in runoff for three historical events

The model results show that peak runoff is exceeded for all three events, for all 26 catchments, under all six scenarios, except in three cases (out of 468). However, even in these cases (catchments 5, 6 and 11 under the DMI-A1B-80 scenario, in the 1999 event), the reductions were very small (-0.2%, -0.4% and -0.5% respectively). A typical hydrograph is illustrated in Figure 9-1, based on the Irthing catchment (see Table 5-4 and Figure 5-6), which shows stacking curves corresponding to the scenarios.

Figure 9-1 Change in peak flow for the Irthing catchment for the January 1999 event as perturbed for the 2080s under different scenarios

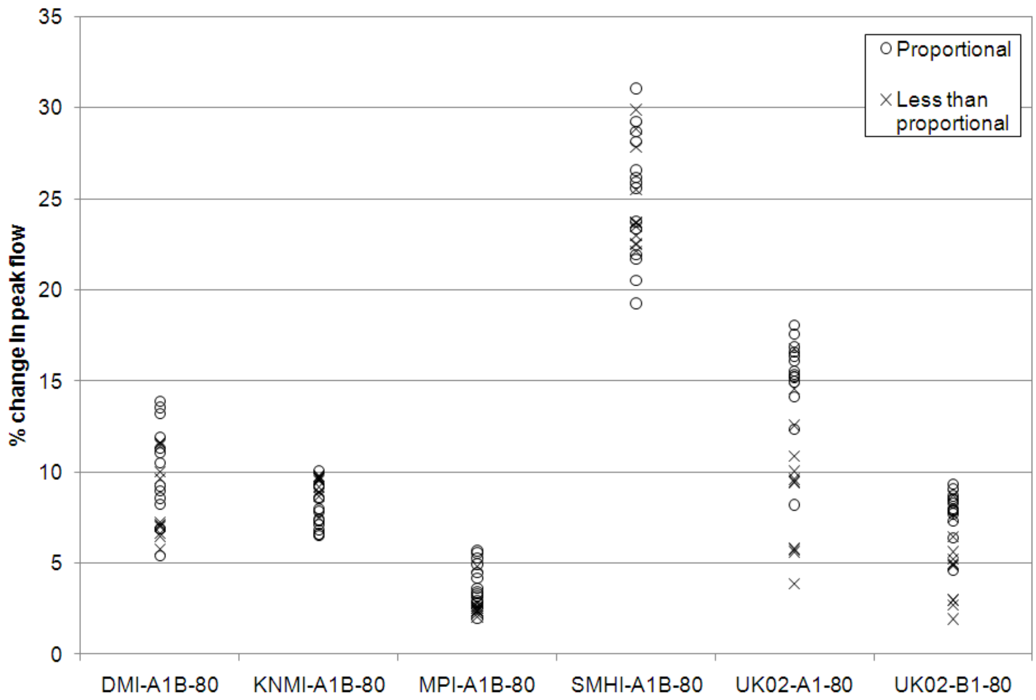


For details of scenarios, see Table 9-1. Original in colour.

The size of the increases varies depending on the scenario and event. For the February events (see Figures 9-2 and 9-3), the median of the catchments had an increase of between 3% and 16%, with the exception of the SMHI-A1B-80 scenario (24% and 27% respectively) which also had a large range. In contrast, for the January 1999 event (Figure 9-4), the median of the catchments is above 20% (lowest minimum 10%; highest maximum 52%) for all scenarios except UK02-B1-80 (11%) and DMI-A1B-80 (3%).

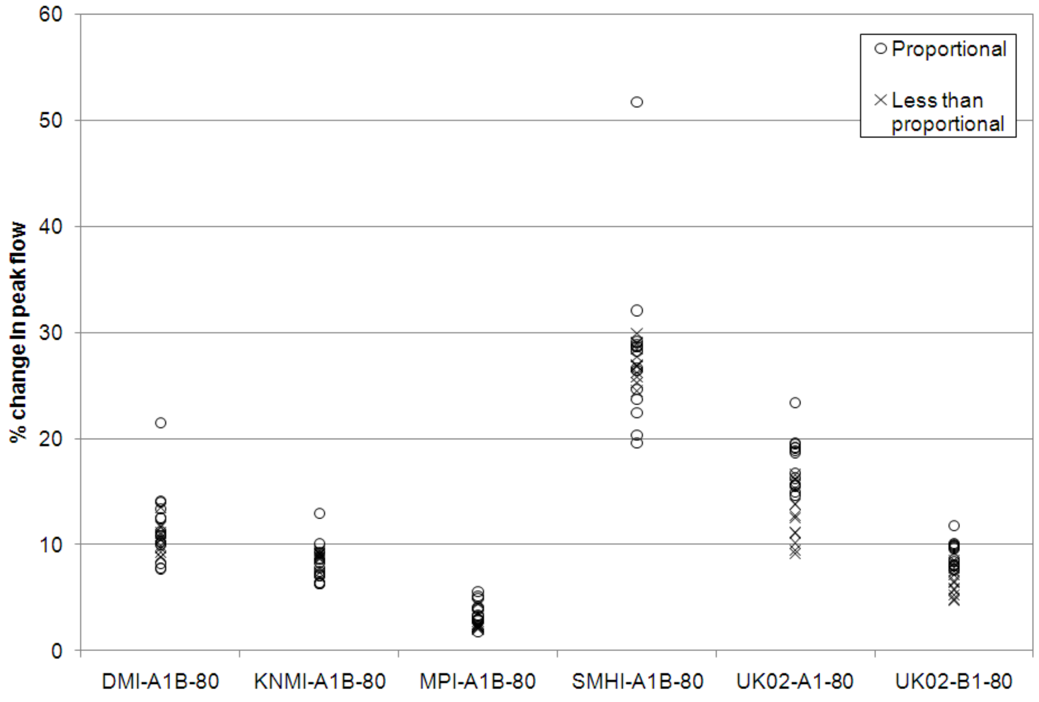
The symbols in these figures are classified according to how the peak runoff relates to the monthly precipitation change factor: circles illustrate those catchments that respond in an approximately proportional way based on all events and scenarios, and the crosses show those catchments which have a less than proportional response. Note that not all reduced catchments appear as the lowest uplifts in the figures because the classification is based on all events and scenarios and because precipitation change factors vary across catchments. The responses are discussed further below.

Figure 9-2 Change in peak flow for the Eden catchments for the February 1990 event as perturbed for the 2080s under different scenarios



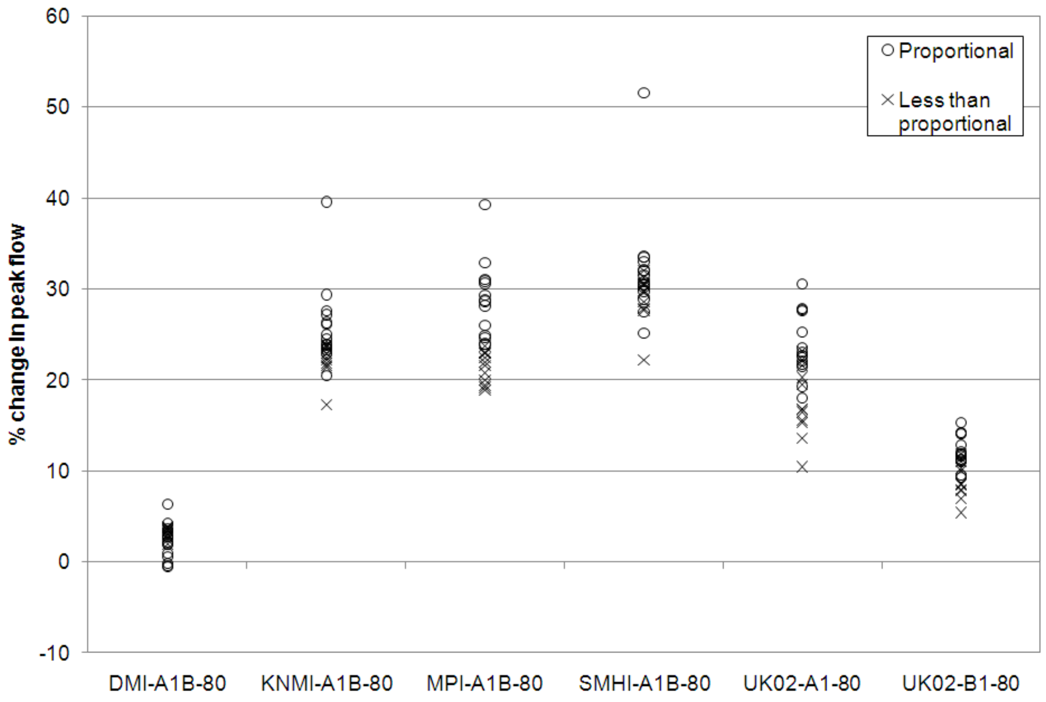
The symbols show the results from the 26 catchments, as discussed in the text above. For details of scenarios, see Table 9-1.

Figure 9-3 Change in peak flow for the Eden catchments for the February 1995 event as perturbed for the 2080s under different scenarios



Notes as for Figure 9-2 above.

Figure 9-4 Change in peak flow for the Eden catchments for the January 1999 event as perturbed for the 2080s under different scenarios



Notes as for Figure 9-2 above.

The sizes of the changes have been compared with the 20% indicative sensitivity range for peak flows (introduced in Section 3.2.2.2) (see Table 9-2). This shows that the perturbed January 1999 event experienced increases greater than 20% in most or all catchments in four or the six scenarios considered. However, the SMHI-A1B-80 scenario also produced increases across all but one catchment for the February events.

Table 9-2 Number of catchments where baseline event peak flows are exceeded by more than 20%

Scenario	February 1990	February 1995	January 1999
DMI-A1B-80	0	1	0
KNMI-A1B-80	0	0	25
MPI-A1B-80	0	0	22
SMHI-A1B-80	25	25	26
UK02-A1-80	0	1	16
UK02-B1-80	0	0	0

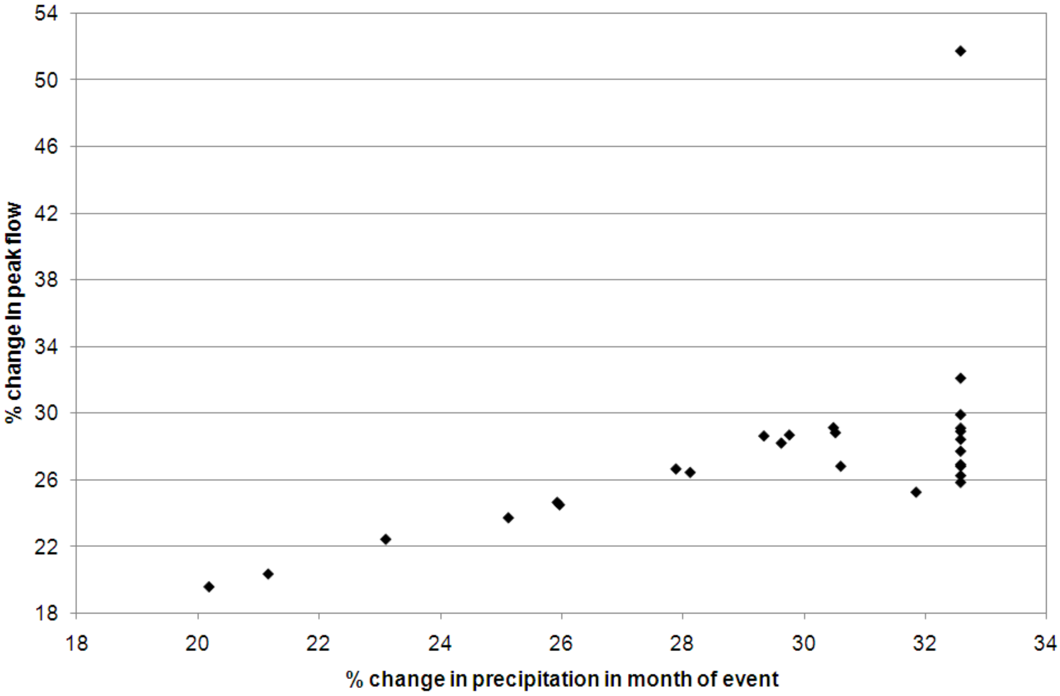
Note that there is a total of 26 catchments. For details of scenarios, see Table 9-1.

Despite the relative simplicity of the rainfall–runoff model, the responses of the catchments are complex and depend on catchment characteristics, the nature of the events and also vary depending on the climate change scenario.

As noted above, a general differentiation has been made between those catchments responding to monthly changes in rainfall in an approximately proportional way (14 catchments) and those which respond in a less than proportional way (12 catchments), although there is a continuum between the two.

The response types are evident for most events and scenarios. For example, the 1995 event under the SMHI-A1B-80 scenario is illustrated in Figure 9-5. Three elements are notable: firstly the proportional response of 14 catchments; secondly the reduced response of 11 catchments (most of which are in close proximity and share the same precipitation change factor); and thirdly a single outlier from the very small (4.4 km^2) Greenholme Beck catchment (see Table 5-4 and Figure 5-6) which could be separately classified as greater than proportional. For the 1990 and 1995 events, under the KNMI-A1B-80 and MPI-A1B-80 scenarios, the catchments showing the less than proportional responses overall give a greater than proportional response, whilst for some others, for example the 1999 event under the UK02-A1-80 and UK02-B1-80 scenarios, the pattern is more mixed with a higher number of reduced responses.

Figure 9-5 Change in peak flow compared to change in monthly precipitation for the Eden catchments for the February 1995 event as perturbed for the 2080s under the SMHI-A1B-80 scenario



For details of the scenario, see Table 9-1.

A proportional response is logical because the monthly change factor is the most important perturbation and via the event rainfall it has the same proportional effect on peak surface flow (i.e. excluding baseflow). The effect of the monthly change factor on percentage runoff is an order of magnitude less in percentage terms, and where baseflow is small compared to total peak runoff, the effects of the monthly change factor (via CWI) and the annual change factor (via SAAR) on baseflow are negligible. A sensitivity test comparing the overall influence of the monthly and annual change factors for the Irthing catchment (see Table 5-4 and Figure 5-6), a largely rural area of 294 km^2 with a SPR of 73%, is presented in Table 9-3.

Table 9-3 Sensitivity of peak flow in the Irthing catchment to changes in monthly rainfall and annual rainfall based on perturbations of the January 1999 event

		% change in annual rainfall		
		-7.5	0	10
% change in monthly rainfall	0	-0.3	0.0	0.4
	5	5.1	5.4	5.8
	10	10.5	10.8	11.2
	15	15.9	16.2	16.6
	20	21.4	21.7	22.1
	25	27.0	27.3	27.7
	30	32.5	32.8	33.2

Catchment characteristics reflect the two response types. Those catchments responding less than proportionally are the cluster of small catchments in the north-west of the catchment (numbers 12 to 20; see Table 5-4 and Figure 5-6) along with the tributaries of the Lower Middle Eden (catchment 8). These are on average smaller (with the exception of the latter, without which average catchment size would be just 24.9 km^2), with a lower annual average rainfall and lower proportion of runoff, although urbanisation is greater (see Table 9-4).

Table 9-4 Average catchment characteristics for those catchments responding proportionally and less than proportionally to monthly changes in rainfall

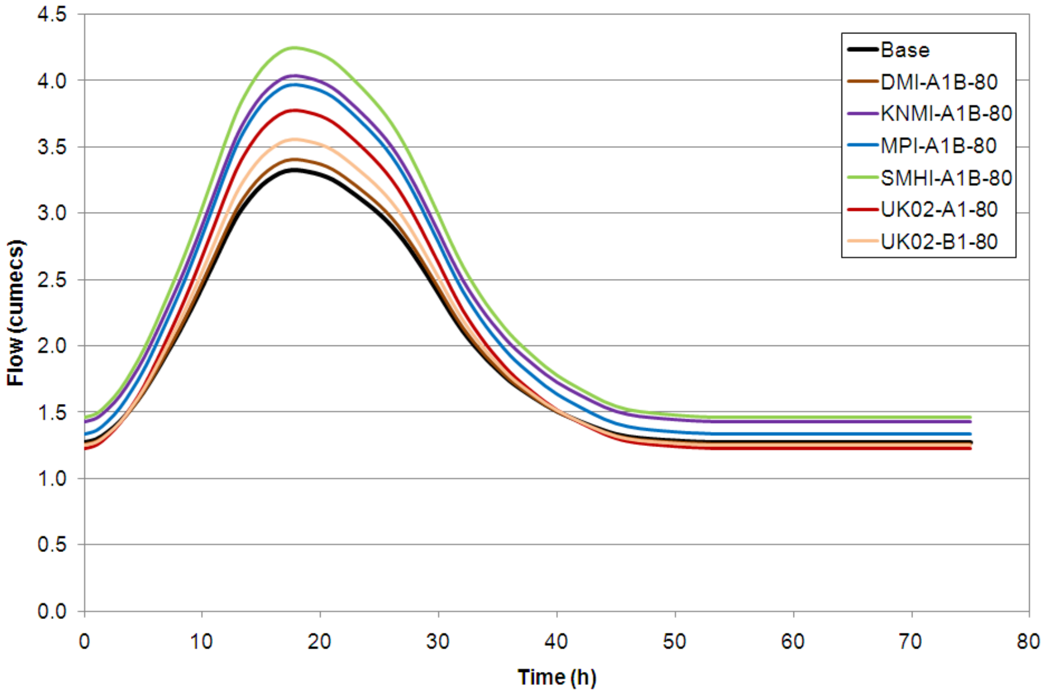
Catchment characteristic	Proportional	Less than proportional
Area (km^2)	123.0	47.8
SAAR (mm)	1225	837
SPR (%)	51.8	18.9
URBEXT (%)	0.4	2.5

However, baseline event characteristics are also important. Total event rainfall is particularly significant, and on average this is nearly half for the less than proportional catchments as compared to the proportional catchments (see Table 9-5). When event rainfall is relatively low the change in peak runoff can be lower than proportional because baseflow is a relatively high proportion of the total peak runoff (for example see Figure 9-6). Although baseflow is sensitive to changes in annual rainfall, the latter tend to be smaller than monthly changes and the effect on the total runoff is also less. The effect of catchment size and SPR is limited when event rainfall is low.

Table 9-5 Average event rainfall for those catchments responding proportionally and less than proportionally to monthly changes in rainfall

Event	Proportional	Less than proportional
February 1990	39.0 mm	15.7 mm
February 1995	59.2 mm	28.5 mm
January 1999	47.9 mm	27.1 mm

Figure 9-6 Change in peak flow for the tributaries of the Lower Eden for the January 1999 event as perturbed for the 2080s under different scenarios



For details of scenarios, see Table 9-1. Original in colour.

9.2.2 Changes in flows and levels at downstream receptors for extreme historical events

Results were extracted for five model nodes, representing important receptors in the downstream part of the catchment identified in Section 5.2.3 and Figure 5-8:

- The Petteril at Botcherby Bridge
- The Caldew upstream of Holme Head Weir
- The Eden at Warwick Bridge
- The Eden at the M6 Motorway Bridge
- The Eden at Sheepmount

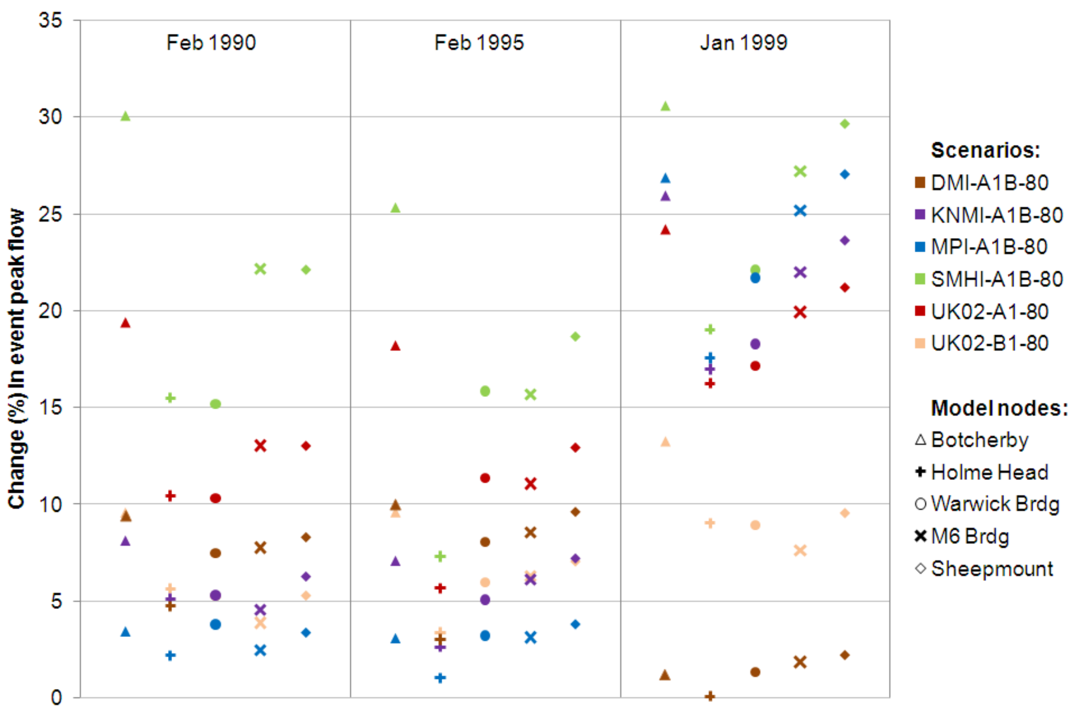
Graphs of flow and water level for the three events for the Eden at Sheepmount (see Figure 5-8), plus water level results for the three events for the other four receptors are presented in Appendix 4.

The hydraulic results show an increase in peak water levels and flows at all receptors for all three events and under all scenarios. However, there are large differences in the size of the increases between receptors, events and scenarios.

Figure 9-7 shows the change in peak flows for the 2080s compared to the three historical events for the five receptors (represented by different shapes) under different scenarios (represented by colours). The results for the West Coast Mainline Railway Bridge are not presented separately, because they are very similar to those at Sheepmount. Peak flows increase in all cases, particularly for the January 1999 event as January precipitation change factors are generally greater than those for February, with the exception of the DMI-A1B-80 scenario. The increase in peak flows tends to be higher downstream on the Eden, which reflects the additional contribution of flow from the Irthing, Petteril and Caldew catchments, all of which respond proportionally in at least their upper reaches. The pattern of change in peak flows is strongly related to the pattern of monthly change factors of the scenarios; the magnitudes are less closely related compared with individual catchments, which is to be expected with these aggregated results, which also model the timing of catchment inputs and the effect of floodplain flows and storage.

In terms of the 20% indicative sensitivity range, for the February events only three unique locations (all for the SMHI-A1B-80 scenario) exceed 20%, with the majority of results much lower. In contrast, for the January event, at least four scenarios exceed 20% for three of the locations.

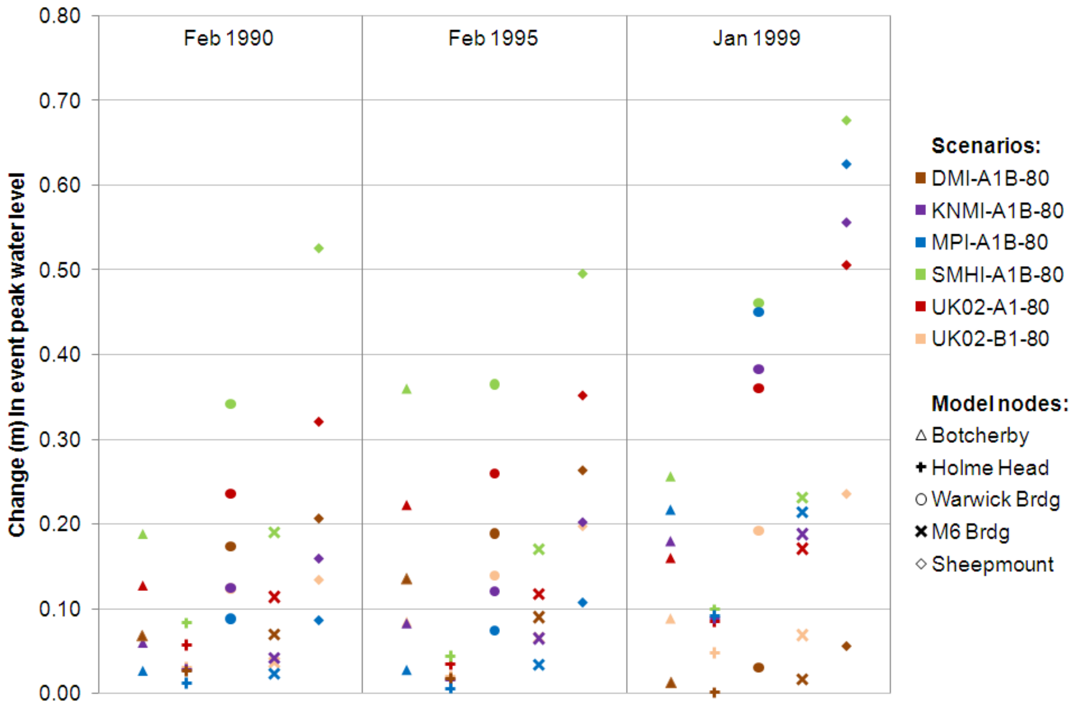
Figure 9-7 Change in peak flow for the five selected receptors in the Eden catchment for the 2080s compared to the three historical events under different scenarios



The model nodes for the locations (represented by shapes, and from left to right) are: ‘P11081BU’, ‘C20000SU’, ‘E77500BU’, ‘ED65153U’ and ‘ED55152’ (see Figure 5-8). For details of scenarios, see Table 9-1. Original in colour.

The effect of the peak flow changes described above on peak water levels is illustrated in Figure 9-8. For some locations, fairly large (proportional) increases in flow translate into more modest increases in (absolute) water level. For example, on the Eden at the M6 Motorway Bridge, an increase in flow of 27% (1999 event, SMHI-A1B-80 scenario) equates to an increase in water level of 23 cm. In contrast at Sheepmount, a 30% increase in flow (same event and scenario) produces a 68 cm increase in water level. For the Caldew just upstream of Holme Head Weir, none of the scenarios increases water levels by more than 10 cm. These results reflect site characteristics and location with respect to inflows (a 30% increase in flow at Sheepmount representing a large increase in the volume of water).

Figure 9-8 Change in peak water level for five locations in the Eden catchment for the 2080s compared to the three historical events under different scenarios



The model nodes for the locations (represented by shapes, and from left to right) are: 'P11081BU', 'C20000SU', 'E77500BU', 'ED65153U' and 'ED55152' (see Figure 5-8). For details of scenarios, see Table 9-1. Original in colour.

Some of the changes are large even compared with the freeboard allowance of 45 cm recommended in Atkins (2006a). Given that the three events were not particularly extreme compared to typical design standards, then these values are high. However, the addition of the 20% indicative sensitivity range to 200-year design flow from all catchments produced a 55 cm increase in water level at Sheepmount (ibid.). This falls within the range of increases for the perturbed January 1999 event; the KNMI-A1B-80 scenario gave a 56 cm increase based on a 23.9% increase in catchment runoff (geometric mean), which suggests that the increase is fairly insensitive to the return period. Although there is a large range of results, they do suggest that the indicative sensitivity range is plausible, based on the perturbation method used including the use of monthly rainfall change factors. This latter assumption in particular should be tested further.

9.2.3 Effect of emissions scenarios and climate models

The ENSEMBLES models are all driven by the same emissions scenario (SRES A1B), whereas the two UKCIP02 scenarios used are driven by two further emissions scenarios (SRES A1, B1). The results above show that the differences between emissions scenarios in the UKCIP02 scenarios are less than the differences between the climate models in the ENSEMBLES scenarios. This conclusion applies to individual catchment extreme events, and flows and water levels in the lower catchment. The use of alternative GCMs (e.g. those in ENSEMBLES) driven by different emissions scenarios has not been explored due to availability, but it would be useful to examine the behaviour of different emissions scenarios in GCMs that produce wetter results.

The KNMI-A1B-80 and MPI-A1B-80 scenarios are driven by the same GCM. The similarity of the results, when compared with the other ENSEMBLES scenarios driven by different GCMs, shows that the uncertainties in downscaling using RCMs are less than those relating to GCMs. The RCM uncertainties are less than those associated with the emissions scenarios examined. This pattern of decreasing uncertainty from GCMs, through emissions, to downscaling to RCMs, is consistent with the Bedford Ouse results (see Section 8.3.5) and other research (reviewed in Sections 3.1.3 and 3.2.1).

10. Conclusions, implications for policy and practice, and recommendations for research

10.1 Introduction and review of research aims and future flooding framework

This chapter summarises the key findings, implications and recommendations arising from the research. Firstly, the research gaps and objectives set out at the end of Chapters 3 and 4 respectively are revisited and the scenario-based framework of Chapter 4 reviewed. Secondly, the results of the flood modelling presented in Chapters 8 and 9 are summarised. Thirdly, the methods used in each of the catchments are reviewed in terms of their ability to elucidate future flooding and in relation to alternative approaches. Fourthly, some implications for policy and practice are highlighted. Both the methods and implications are related to the case studies, but have wider resonance for studies using similar methods. Finally, recommendations for future research are set out.

A scenario-based framework for assessing integrated floodplain futures has been developed (Chapter 4). The framework involves the downscaling of climate change and socio-economic scenarios to the catchment level, with the evolution and interaction of different pathways leading to alternative floodplain futures, from which management measures can be evaluated. Whilst not addressing the research gaps *per se*, the framework suggests how specific pieces of research could be brought together to provide exploratory futures and to identify anticipatory adaptation measures.

The intention of this research was to use best available catchment models to simulate futures and measures. Although driving flood risk pressures were identified (Chapter 5) and a method for developing socio-economic scenarios produced (see Appendix 1), it was clear that the hydrological models currently used in flood risk management cannot be perturbed to account for a wide range of future socio-economic settings. For example, there are no parameters explicitly representing a variety of land uses, although it is not clear that potential scenarios or catchment characteristics would result in significant changes in flood risk at the catchment scale for drivers such as land use and management. Even assessing socio-economic changes just in relation to receptors (e.g. considering the change in vulnerability of a settlement due to population aging) is challenging given the limited availability of datasets and the level of detail required in any such analysis. Hence recent work in the EU FLOOD*site* programme on a decision support system (Gahey *et al.*, 2009) has focused on receptors (hydraulic components in terms of modelling) and a limited number of indicators. Given the current direction towards holistic catchment management as part of flood risk management (and water management more generally), the development of distributed models would be beneficial, even if they are simpler in terms of the hydrological or hydraulic processes.

Within the scenario framework, the research has focused on climate change and future flooding only. As well as assessing future flooding itself, the research has also sought to evaluate the benefits and drawbacks of using climate model information directly in models used for decision making, which seeks to combine the approaches used in academic studies and in practice. Two alternative modelling methods have been examined: one based on continuous rainfall–runoff modelling and flow routing (for the Bedford Ouse), and the other based on events only (for the Eden). The conclusions from these case studies are presented below.

10.2 Climate change and future flooding: key findings from the case studies

10.2.1 Bedford Ouse

The runoff results showed that future flows (the results focus on the 2080s) are generally higher in winter and significantly lower in summer. Three patterns (including sign and size) of changes in runoff have been identified: seasonally enhanced, subdued and reduced. The subdued response relates to the catchments with a high baseflow index. The enhanced and reduced responses are similar outside of winter, but there appear to be subtle differences in changes in effective precipitation and soil moisture that have important implications for winter runoff.

However, within the winter half of the year three of the five ENSEMBLES scenarios were more influenced by the climate change factors and are therefore exceptions or extremes. Thus it is difficult to establish a single overall conclusion from the scenarios, which demonstrates the importance of considering multiple GCMs; further work would benefit from including more than the four modelled here.

The results from the 2020s and 2050s from the UKCIP02 scenarios follow the pattern of those of the 2080s but with reduced magnitude, reflecting the pattern-scaling in their creation. Change factors from ENSEMBLES for these timeslices suggest that the runoff under the ENSEMBLES scenarios would not show such smooth evolution as the scenarios are based on full transient runs.

The influence of PET on runoff appears to be significant, because although all scenarios have large increases in winter rainfall, not all produce increases in winter flow. Furthermore, in terms of the number of scenarios producing increases in runoff, the future high flow season appears to be focused on January and February rather than autumn or spring. It appears that the flood season is delayed due to large summer moisture deficits, whereas in spring, rainfall is reduced from April onwards. However, catchment characteristics have a strong modifying effect (as noted above). The PET change factors are very large and it is unclear whether this is at least partly an outcome of using a temperature-based formula (Oudin *et al.*, 2005); further research in this area would be beneficial.

Some of the results suggest that groundwater abstractions at baseline levels (an assumption in the model runs) will not be sustainable in future as they lead to a lowering of groundwater levels and reduction in baseflow.

The proportion of catchments that returned enhanced runoff for high flow events depends strongly on the scenario, with three of the five ENSEMBLES scenarios examined leading to enhanced runoff for nearly all of the 21 catchments at the Q1 and Q0.1 baseline flow thresholds. In contrast, the other scenarios generally returned reduced runoff for high flow events. This indicates that the increases in PET are influential for high flows as well as average flows. The catchment response types are also apparent for high flows, although less so for maximum flows.

The results facilitate the assessment of known events ‘with climate change’. Changes in runoff for extreme historical events are highly scenario dependent, although there are also large variations between catchments, which have been related to catchment response type for some (seasonal) events.

The hydraulic model results show that the maximum future peak water levels and flows across the scenarios did not exceed the maximum modelled baseline event (Easter 1998) for all but the most upstream node examined, Offord, and then only marginally. This is despite some of the wet ENSEMBLES scenarios producing increases for the other events, particularly the two in the winter half of the year, and is partly due to the role of the floodplain, which dissipates flow. For the Easter 1998 event, flows and water levels under the scenarios were less than those for the modelled baseline because runoff is not much if at all higher due to lower April rainfall. However, it is possible that an alternative event, for example between January and March, could yield higher flows and water levels than Easter 1998. This conclusion has resonance with Reynard *et al*. (2005) who, using a delta change method, noted that the impact on flood frequency was dependent on the month of occurrence of the main flood events in the baseline series. Therefore, stochastic approaches may assist in providing a more complete view of future flooding.

Under the stochastic modelling, which was limited to the upper catchment, the changes in runoff are shifted downwards compared to the perturbation approach. This difference is a result of the higher PET in EARWIG and demonstrates the sensitivity of the runoff results to the formulation of PET; this is another area that would benefit from further research. It also demonstrates the potential need to re-calibrate models when applying a different formulation of PET. As expected, the results of the hydraulic routing to Newport Pagnell show a wider spread of extreme event peak flows under the scenarios compared with the baseline.

The research has highlighted some of the important uncertainties, for example demonstrating a pattern of decreasing uncertainty from GCMs, through emissions, to downscaling to RCMs, but given the constraints on scenario availability and model run time, only a partial view has been possible.

In general, uncertainties appear to increase at smaller scales and as the process moves through the uncertainty cascade, from scenarios to changes in runoff. This is due to the increasing number of variables (rainfall, PET, catchment characteristics) and the heterogeneity of the catchments. This emphasises the benefits of adopting a catchment-specific approach in terms of climate change scenarios and rainfall–runoff modelling.

There is lower confidence in individual catchment results due to the temporal resolution of the rainfall dataset used, and although this applies mainly to extreme events, it was found that the daily rainfall timestep influenced the amount of modelled recharge and baseflow. In the downstream part of the catchment, the results are more reliable, but are still best interpreted as relative changes.

10.2.2 Eden

Peak runoff was exceeded for all three baseline events examined, for all 26 catchments, under all six scenarios (all relating to the 2080s), except in three cases (out of 468). The size of the increases varied depending on the scenario and timing of the event, with the monthly precipitation change factor the single largest determinant of the change in peak flow. Therefore the SMHI-A1B-80 scenario produced the greatest increases for all three events; the MPI-A1B-80 scenario was next for the January event, but produced the lowest increases for the February events largely because its precipitation change factors for February were the lowest.

Two catchment response types were evident in terms of the relationship between change in peak flow and change in monthly precipitation for the three events examined. Firstly, 14 of the 26 catchments exhibited an approximately proportional response. The other 12 catchments returned a less than proportional response. The latter response was related in particular to lower rainfall during events, which meant that baseflow was a relatively high proportion of the total peak runoff. Although baseflow is sensitive to climate change, particularly annual rainfall in the FEH rainfall–runoff model, changes in this tend to be lower than monthly changes applied to event rainfall, and the effect on the total runoff is also less.

The hydraulic model results show an increase in peak water levels and flows at all downstream receptors examined for all three events and under all scenarios. However, there are large differences in the size of the increases between receptors, events and scenarios. The pattern of change in peak flows at the receptors is strongly related to the pattern of monthly change factors of the scenarios, but the magnitudes are less closely related compared with individual catchments, as the timing of catchment inputs and the effect of floodplain flows and storage are also included. The increase in peak flows tends to be higher downstream on the Eden, which reflects the additional flow from the contributory catchments.

The change in peak water levels varies depending on the site location and characteristics. Some receptors, such as the M6 Motorway Bridge and Holme Head Weir, are relatively insensitive to the (proportional) change in flow, whereas Sheepmount is relatively sensitive, being downstream of all inflows and therefore subject to large volumetric increases.

As with the Bedford Ouse, a pattern of decreasing uncertainty from GCMs, through emissions, to downscaling to RCMs, is evident, but this is based on a limited set of scenarios.

10.2.3 Limitations

There are several limitations with the methodologies applied in the research. The use of a proportional change factor does not allow for a change in variance, which would be highly relevant for flooding. Other limitations relate to the assumptions made in the model set up, for example constant discharges, abstractions and retention levels, all of which could be varied (or varied differently in the case of current dynamic operating rules) in order to manage the water balance of the catchment, resulting runoff, and hydraulic performance. More broadly, the results are an outcome of the particular scenarios modelled, which only capture part of the known uncertainties regarding the elements of the modelling cascade. A number of refinements, and alternative approaches, are suggested in the following sections.

10.3 Methodologies

This section provides conclusions in relation to the methodologies used for the case study modelling. It also reflects on how these sit within wider research into climate change impact assessment and adaptation decision making, which has evolved significantly over the past few years with a move towards ‘bottom-up’ sensitivity or vulnerability-based methods to complement scenario-driven top-down approaches (see Wilby and Dessai (2010) for a review). A brief comparison of these approaches is provided in Table 10-1.

Table 10-1 A simple comparison of scenario- and sensitivity- led approaches

Process	Scenario-led approach	Sensitivity-led approach
Method	Top-down application of available/current GCM–RCM combinations	Starts with threshold-related question(s) and examines sensitivity to change based on plausible futures (guided by wide range of scenarios)
Modelling	Perturbation or stochastic approach; multiple runs	Perturbation or stochastic approach; numerous runs
Decision making	Based on balance of evidence presented by available/current scenarios	Based on balance of evidence in terms of threshold exceedence, (including relationship to current scenarios)
Advantages	Fits current modelling paradigm; relates to specific known scenarios	Allows better exploration of uncertainties; is scenario neutral
Disadvantages	Limited number of scenarios, which are liable to change in future; potential for maladaptation	Harder to implement for complex systems; not clear how sensitivity domain used in decisions

10.3.1 Bedford Ouse: continuous simulation

The use of GCM and RCM information, rather than a single sensitivity factor, provides a number of benefits when assessing the implications of climate change for future flooding based on continuous simulation. Benefits include a geographical interpretation of changes in precipitation and PET, explicit representation of uncertainty related to climate change (emissions uncertainty, model structural uncertainty), and a better understanding of the role of PET and antecedence effects. The method used could be extended to design events (e.g. the 1 in 100 year event) but further research would be required regarding changes in rainfall extremes at different durations. The use of a weather generator has provided new information about catchment sensitivity and extreme events.

However, using GCM and RCM information in a continuous simulation approach presents a number of challenges. Continuous simulation models are data and time intensive and for the Bedford Ouse model a continuous end-to-end simulation was not possible, which also limits the ability to fully explore stochastic variation. The modelling process would need to be significantly more efficient to examine the impacts associated with a larger number of scenarios or ensemble members such as included in UKCP09 (Murphy *et al.*, 2009). Furthermore, having a range of scenarios presents challenges in terms of decision making, particularly where the sign of change diverges, although there were reasonably clear conclusions for the downstream part of the Bedford Ouse.

Understanding the sensitivity of a system to a wide range of futures may provide the most appropriate basis for making adaptation decisions in the short to medium term while uncertainties are large. This may help avoid potential maladaptation based on a partial view of the future (see Table 10-1). Such an approach may not rely on the modelling of a single national sensitivity factor, but several, guided by the scenarios available on a catchment or wider basis. This approach is adopted by Reynard *et al*. (2009) through the application of numerous identical sets of change factors across the UK to create a sensitivity domain and catchment flood response patterns. Adopting this approach for the Bedford Ouse would require a more efficient model; alternatively the output from more simple models could be used with rating curves or a hydraulic model to provide water levels at important receptors. The modelling undertaken in this research has begun to explore the sensitivity of the Bedford Ouse to climate change, for example demonstrating the damping effect of the floodplains on water levels in the lower catchment, and in a different way by using the same stochastic inputs to the upper five catchments. This exploration could be extended based on a wider range of specific GCMs and emissions scenarios or through a wider sensitivity range informed by such scenarios. The latter would provide a scenario-neutral assessment for the Bedford Ouse, against which the ENSEMBLES and UKCP09 projections could be evaluated, along with any future projections. However, it is not yet clear how these assessments would translate into certain decisions, for example the height of a flood defence, given the wider range of potential outcomes, which are not linked to known scenarios (Table 10-1). Approaches that focus on key decision variables such as the uncertainty-based sensitivity analysis framework of Hall and Solomatine (2008), may offer a way forward.

10.3.2 Eden: event-based simulation

The benefits of using GCM and RCM information in event-based simulation are fewer when compared to continuous simulation, but still include a geographical interpretation of changes in precipitation and explicit representation of some of the uncertainty related to climate change. The perturbation is relatively quick to implement and could be quicker if limited to event rainfall and annual rainfall. Furthermore, the method could be applied to specific design events using depth-duration-frequency data if better information were available on changes in extreme rainfall at various durations and return periods. Alternatively, a weather generator could be used, but these have limits in terms of reliable return periods; a 30-year calibration period would limit the reliable return period to between 1 in 10 and 1 in 20 years.

The limitations largely relate to the FEH rainfall–runoff model. In particular, this does not represent the influence of changing PET on effective rainfall, which is significant according to the Bedford Ouse findings. Furthermore, antecedent conditions are only minimally represented and these influence the timing of flooding events, which may alter in future; however, this may be more important for catchments with greater storage, such as the Bedford Ouse.

10.4 Implications for policy and practice

10.4.1 Implications for policy and guidance

Both model approaches used rely on high spatial- and temporal-resolution rainfall data. This is also needed to calibrate weather generators and to evaluate the performance of climate models and radar data. It is therefore imperative that good networks of sub-daily rainfall measurements are maintained.

Generally the current 20% indicative sensitivity range for peak river flow was found to be sufficiently precautionary, but this depends on the assumptions made in the climate change perturbation and on how the figure is interpreted. For the Bedford Ouse, no more than four of the 21 catchments exceeded an enhancement of 20% at the Q1 and Q0.1 flow thresholds, although there is lower confidence in individual catchment results due to the temporal resolution of the rainfall dataset used. However, the range was exceeded more often and by more when considering specific events (the only method used for the Eden) and was greatly exceeded for the floodplain sites. Furthermore, the proportional change factor method of perturbation may suppress the increases in flow if extreme rainfall intensities increase. Therefore, further guidance on the appropriate use of the sensitivity range would be beneficial, particularly in relation to event severity and return period. Fundamentally though the research has demonstrated the added value of applying a range of catchment-specific scenarios, and that continued use of a single national sensitivity range is questionable when scenarios could be used directly (perhaps leading to a set of allowances based on broad location or catchment characteristics) or indirectly via a more comprehensive (e.g. regionally varying) sensitivity analysis.

Given the need to either explore sensitivity or undertake more scenario-based runs, it may be appropriate to review the strategy for model building. This research has demonstrated that the move towards continuous rainfall–runoff models is more appropriate in assessing climate change impacts. To explore sensitivity to socio-economic futures, semi or fully distributed models would be beneficial. At the same time complex models (even those which are lumped such as the Bedford Ouse model) cannot efficiently perform multiple runs (at present). It may not be pragmatic, or desirable, to integrate all interests into one model. However, in order to explore floodplain futures, and decisions pertaining to flood risk management, a clear hierarchy of models is required. For example, a semi-distributed hydrological model could be used to explore broad land use and climatic changes (and their interactions), with the resulting scenarios used as inputs or adjustments to lumped hydrological models, with flows then routed using hydraulic models. The most detailed modelling, including integrated assessment of impacts, could be reserved for the receptors at highest risk. The identification of thresholds within systems would be a particularly fruitful exercise, and these need to relate to specific receptors. For catchments such as the

Bedford Ouse, where water balances are delicate and water levels are controlled, it would be useful to adopt a more reflexive approach, where the user either directly, or via a neural network method, can influence the 'with adaptation' futures.

With a potential increase in flood risk due to climate change, there are a number of implications for policy on flood risk management. In particular, if the change in risk is to be limited then policy needs to consider ways in which to manage runoff generation and to limit exposure of potential receptors. In the former case, the move towards catchment management will be beneficial, and it will be important to integrate flood risk objectives (as articulated in CFMPs and required under the Floods Directive) with those relating to water quality (as set out in River Basin Management Plans). In the latter case, policy will have to respond to the continued pressure for floodplain resources whilst dealing with the greater vulnerability and losses, which have been attributed to an increase in population and capital on, and modification of, the floodplain. Efforts to reduce exposure, for example through flood defences, will need to consider residual risk. The management of uncertainty will also be important; where uncertainties are large, flexible, adaptive approaches, whilst not necessarily optimal, will reduce potential regret. Specific implications for each case study catchment are considered in the following two sections.

10.4.2 Implications for flood risk management in the Bedford Ouse

The increase in winter runoff and the potential for higher peak water levels have implications for flood risk management. In contrast to the scenario-based approach presented in this thesis, the Bedford Ouse CFMP (Environment Agency, 2010) explored three climate change sensitivity figures, with the highest and that used in the CFMP final future scenario being the 20% indicative sensitivity range. This was applied to 10%, 1% and 0.1% APE peak flood flows, produced for the baseline using a broad-scale model, to produce future flood extents. The extents increase compared with the baseline in some locations, but in others they are more restricted by topographic features including flood defences. As noted above, the 20% indicative sensitivity range was generally found to be precautionary. However, this is dependent on the assumptions made including use of a proportional change factor; alternatively timed events could results in much higher flows. Furthermore, validation of the indicative sensitivity range for rare events such as the 1% and 0.1% APE has not been undertaken. The results presented in this thesis show that the need for a fixed precautionary allowance is less in the downstream part of the Bedford Ouse than in contributory catchments and that the modelled change is highly location-specific. Therefore, there is considerable uncertainty in the CFMP future flood scenario, and subsequently derived data (e.g. risk to people and property), especially in the lower catchment.

A mixture of policy responses are set out in the CFMP. For upstream, largely rural areas, the preferred policy is the continuation of existing management at current levels of protection (which will decline in future). For much of the rural Bedford Ouse river corridor the preferred policy is strategic flood storage to help protect downstream urban areas, for the more vulnerable of which the preferred policy is to maintain the level of protection in response to changing risks. Given the conclusions above, and those in the CFMP that “the greatest uncertainty we think there is in our estimates of future flood risk is in the approach we have adopted for increasing future river flows” (Environment Agency, 2010: 772), it is clear that future policy and investment decisions will benefit from more comprehensive analyses. Furthermore, land use and management, although not modelled in the CFMP or this thesis, will be important at least at the local level. Policy also needs to ensure the minimisation of future exposure, for example through development control and the management of social factors that increase vulnerability to flooding. It is particularly important that residual risk is managed by ensuring that areas benefiting from defences, including some recently constructed, do not become highly vulnerable to events beyond the defence standards.

10.4.3 Implications for flood risk management in the Eden

The increase in flood flows and levels has implications for flood risk management. In contrast to the scenario-based approach presented in this thesis, the Eden CFMP (Environment Agency, 2008) explored three climate change sensitivity figures, with the highest and that used in the final future scenario being the 20% indicative sensitivity range. The effect of this is an increase in flood flows and depths, which depend on location. Based on the modelling undertaken for this thesis, and with the associated limitations, the 20% indicative sensitivity range was precautionary except for perturbation of the January 1999 event and more generally for the wettest climate change scenario. Validation of the indicative sensitivity range has not been undertaken for rare events such as the 1% APE used in the CFMP. Therefore, there is considerable uncertainty in the CFMP future flood scenario, and subsequently derived data (e.g. risk to people and property).

A mixture of policy responses are set out in the CFMP. For the rural Eden, Eamont and Lowther, the preferred policies are a reduction or continuation of existing actions, both meaning that flood risk will increase in future. For the rural Caldew and Petteril the preferred policy is the attenuation of flows (e.g. through land management) to benefit downstream areas. For Carlisle and Penrith, the preferred policy is to maintain the level of protection in response to changing risks. The CFMP notes that “assessment of future flood risks are based on national guidance for climate change and are very uncertain as the likely effects of climate change over long timescales are difficult to determine”, and in relation to the modelling approach that “more detailed studies at specific locations would likely be required before any works are carried out” (Environment Agency, 2008: 35); such studies would benefit from a more sophisticated approach to the assessment climate change. As for the Bedford Ouse, policy also needs to ensure the minimisation of future exposure, especially in Carlisle.

10.4.4 Implications for practice

There is an opportunity to add new functionality to the standard modelling software used for flood-related rainfall–runoff and hydraulic modelling. One the major problems encountered in undertaking this research was the inability of current models to deal with ensembles of inputs and take these all the way through the modelling process. Furthermore, the requirement to manually format and label data is very time consuming when dealing with multiple inputs. It may also be possible to introduce downscaling or perturbation techniques into standard software.

For the Bedford Ouse it was found that summer and winter runoff is sensitive to the time resolution of rainfall. In particular, recharge in the Bedford Ouse NAM model appears to be very sensitive and more recharge occurs with fine-resolution rainfall, presumably because greater values of net rainfall are produced, albeit over short periods. Therefore, future studies using such models, particularly for the purposes of examining recharge and baseflow, should use a sub-daily or disaggregated daily rainfall input and further work should determine the need for sub-daily PET.

In this work it was assumed that the bias-correction step of applying the model change to the observed baseline was appropriate. For further work it is recommended that this assumption is tested by perturbing baseline rainfall data of different timesteps. However, the perturbation would be based on changes at the daily level, unless there is an improvement in the information on future changes in rainfall at the sub-daily level.

Given the sensitivity of runoff in the Bedford Ouse catchment to the PET formula, it is recommended either that models are re-calibrated based on the new formula or that some kind of adjustment is made to the alternative formulation.

10.5 Recommendations for future research

There is a need for further research into the downscaling of global and national socio-economic scenarios to sub-regional and local levels. It is at these smaller scales that many decisions regarding adaptation are made (e.g. in catchment management), and if socio-economic *scenarios* (rather than sensitivity factors) are to be part of decision making, then improved processes and information are required.

There is a need to improve the ability to model changes in catchment and floodplain land use and land management in rainfall–runoff and hydraulic models. This will rely on physical models of catchments, based on improved evidence. Furthermore, research into emulation techniques for complex hydrological–hydraulic systems would also be useful in dealing with multiple sensitivity runs and the identification of system thresholds (for example using ‘inverse modelling’).

The modelling on the Bedford Ouse illustrated the importance of evaporation in influencing future catchment water balances and the timing of the winter flood season. Evaporation also appears to determine whether mean winter runoff increased at all, but this requires further research to examine whether this is an artefact of the PET formula or rainfall–runoff model, or a genuine possibility. Furthermore, given the sensitivity of the Bedford Ouse rainfall–runoff models to the rainfall timestep, further work should examine the need for a diurnal representation of PET.

Further research is required regarding change in extreme rainfall, in particular for short-duration events. This will permit a more sophisticated perturbation of rainfall–runoff models that are sensitive to sub-daily rainfall, although this may be via stochastic approaches rather than change factors. Also relevant is how such events behave spatially and whether sensitive catchments within larger systems are likely to experience extreme rainfall in a manner that is likely to compound in terms of flood events downstream. Therefore, there is utility in using weather-type models (e.g. Fowler *et al.*, 2005).

Only a partial assessment of uncertainty was made in this research and it would be useful to extend this. This could be undertaken explicitly, for example to examine the behaviour of different emissions scenarios in GCMs that produce wetter results, using more GCMs, and assessing rainfall–runoff model parameter uncertainty. The UKCP09 projections (Murphy *et al.*, 2009) and weather generator (Jones *et al.*, 2009) offer ways to examine some of these uncertainties in a probabilistic manner, including better representation of natural variability; issues such as variable co-variance and the robustness of sampling from the probability distribution (initially considered in the context of water resources in UKWIR, 2009) would require particular attention[44]. Alternatively, a sensitivity framework could be used (e.g. Reynard *et al.*, 2009), or developed based on catchment-specific data; the latter would assess a wide range of possible values from each element of the uncertainty cascade relevant to the catchment.

[44] Further work on this, commissioned by UKWIR and the Environment Agency, is underway in relation to water resources.

In terms of the stochastic approach, further runs (more than the equivalent of ten runs of 30 years used here) may be required to explore the uncertainty, especially for extreme events. The sensitivity of such events to daily rainfall and to the higher PET of EARWIG, both of which tend to reduce runoff, should also be explored, along with alternative emissions scenarios. A further development would be to use spatial rainfall models such as RainSim (Burton *et al.*, 2008).

Finally, further work is required into the methods used in climate change impact and adaptation assessment, and in developing and appraising strategies for adaptation. The water sector, and flood risk management in particular, will continue to be a useful and highly relevant domain for this research.

Appendix 1. Socio-economic scenarios

This appendix provides the preliminary research undertaken to support the development of business-as-usual and future socio-economic scenarios. This sits alongside the development of the climate baseline and scenarios within the integrated framework for the assessment of floodplain futures. The research established potential methods for producing the BAU and future socio-economic scenarios (but did not apply this to the case study catchments, as explained at the end of Chapter 4). Such an application could then be used in the fluvial modelling process and in the assessment of risk within the floodplain futures.

A1.1 Method for developing business-as-usual socio-economic scenarios

The baseline, or business as usual (BAU) scenario, would be based on an extrapolation of current socio-economic trends (i.e. is likely to be similar to conventional development in Figure 4-2). As with the construction of climate scenarios (see Chapter 7), the global and national socio-economic trends would require 'downscaling' to the catchment level, although the BAU scenario is likely to be consistent with current land-use plans and water management activities at least to some extent and in the short-term.

It is recommended that the BAU scenario, and the future scenarios, concentrate on those driving pressures that have been subjectively defined as significant now, or sensitive to change and therefore potentially significant in the future. This applies to flood risk in the catchment generally, but with a particular focus on flood risk to important receptors (e.g. those identified in Chapter 5). Table A1.1 sets out the key elements that the BAU and future scenarios could consider.

Table A1-1 Description of key scenario elements for use in defining BAU and socio-economic scenarios

Scenario element	Description
Land use	Relative contribution of urban, agricultural and other areas
Rural land management	Management of rural runoff
Floodplain management	Nature of storage and development
Urban storm water management	Coverage and effectiveness of attenuation
Standard of protection	%APE
Value of urban and infrastructure assets and disruption costs	Cost, cost per unit of time (£, £ min^{-1})
Value of agricultural production or land	Cost (£) or cost per unit area (£ ha^{-1})
Social impacts	Number of vulnerable people
Stakeholder behaviour	Level of loss avoidance; uptake and coverage of insurance
Public attitudes and expectations	Demand for reduction in risk
Governance	Nature of regulation and coordination including warning and event response

In terms of the five main dimensions of change identified by Berkhout *et al*. (1999), governance will relate closely to the governance dimension, while stakeholder behaviour and public attitudes will be strongly influence by the social and political values dimension. These two key dimensions will also indirectly influence several other elements, for example influencing the type of agricultural production and defences employed. The other dimensions of change will influence scenario elements: for example demography and settlement patterns will affect social impacts, while the composition and rate of economic growth will influence land use, the standard of protection, value of agricultural production and the value of urban and infrastructure assets. The rate and direction of technological change is less influential, although more sophisticated warning systems may reduce risk in the future.

A generic overview of a possible BAU scenario is set out in Table A1-2.

Table A1-2 Generic overview of the key elements of a possible BAU scenario

Scenario element	**BAU**
Land use	Development on brownfield land, but pressure leads to creeping urbanisation; protection afforded to designated areas
Rural land management	Drive for catchment-sensitive farming
Floodplain management	New development restricted unless protected by existing defences, behind which development continues
Urban storm water management	Attenuation in new development
Standard of protection	Variable but typically to 1.0% to 1.3% APE for urban areas (fluvial)
Value of agricultural production or land	Volatile, a reaction to competing issues e.g. food security, biofuels and GM crops
Value of urban and infrastructure assets and disruption costs	Increases, as assets become more valuable
Social impacts	Aging population increasingly vulnerable; insurance issues for some in high risk areas
Stakeholder behaviour	Insurance as primary mechanism, but based on fragile agreement with Government
Public attitudes	Preference for risk reduction with minimal disruption; environmental protection important
Governance	Hierarchy of plans, but somewhat re-active response to flood events; re-organisation to improve coordination

A1.2 Method for developing future socio-economic scenarios

A variety of methods are used in the development of socio-economic scenarios. A brief review of those developed for use with climate change scenarios is provided here. Most methods rely on expert judgement to develop exploratory or descriptive scenarios of how the future may unfold, typically involving downscaling of pre-existing global or national socio-economic scenario sets. Jacques (2006) calls for more social science research on downscaling to balance the extensive climate change literature on this topic (reviewed in Chapter 3). Downscaling is often followed by the quantification of certain parameters for use in modelling (see Figure 4-3).

Examples of studies include Arnell *et al*. (2004) who downscale the SRES socio-economic scenarios (IPCC, 2000) for each region of the world for use in global-scale impact assessments, whilst Turner (2005) uses a variety of scenarios including the UK Government's Foresight work (OST, 1999) to develop scenarios of European coastal futures. The RegIS project (see Holman *et al.*, 2005b) involved stakeholder engagement to understand driving pressures and to evaluate socio-economic scenarios. The EU ACCELERATES[45] project (Abildtrup *et al.*, 2006) developed narrative storylines of agricultural land use and then quantified various parameters using a stepwise downscaling procedure. This involved the expert judgement of stakeholders and a technique called pairwise comparison, in which qualitative judgements between two storylines (at a time) are converted into numbers. A top-down approach utilising passive stakeholder engagement is suitable for exploratory studies where a range of perspectives is important (Kloprogge and Van der Sluijs, 2006). However, social learning participatory approaches go a step further, involving stakeholders in the design of scenarios. In the EU SIRCH[46] project it was concluded that participatory scenarios are more insightful than 'imposed' scenarios, with the latter being difficult to downscale (Paul-Wostl, 2002). EEA (2001) proposes a Story-and-Simulation Approach involving a stakeholder panel that provides the creative input and evaluates the storylines and their quantification. Tansey *et al*. (2002) conducted workshops in which stakeholders completed scenario narratives, under a finite set of choices that reflected the limitations of the modelling process.

As described above, most scenarios rely on pre-existing global or national socio-economic scenario sets that provide a broad coverage of the economy, society and environment. The SRES scenarios (IPCC, 2000) are particularly important, along in the UK with the OST/Foresight/UKCIP/BESEECH family, although others exist[47] at global and national

[45] Assessing Climate Change Effects on Land use and Ecosystems from Regional Analysis to The European Scale.
[46] Social and Institutional Responses to Climate Change and Climatic Hazards: Drought and Floods.
[47] For a review of early futures literature see Hughes (1985) and for a review of global and regional scenario sets see EEA (2000).

scales, for example the 2050 project (see Hammond, 1998) and Environment Agency scenarios 2030 (Burdett *et al.*, 2006). The IPCC SRES scenarios, described in Section 4.2.1, provide global socio-economic scenarios and related greenhouse gas emissions for use in climate change modelling (and therefore impact assessment) and in the design of options to mitigate climate change. The original UK OST *Environmental Futures* scenarios (OST, 1999) were developed on a similar basis using a two dimensional framework (see Section 4.2.1) and this has been extended to provide regional information, quantification and to cover non-environmental sectors (Berkhout *et al.*, 1999; UKCIP, 2001; OST, 2002). Most recently, the BESEECH[48] project (see Dahlström and Salmons, 2005) has enhanced the scenarios, with a particular emphasis on including adaptive capacity, and has provided a detailed set of quantitative demographic, economic and social data at national and regional levels.

It is recommended that the socio-economic scenarios are developed based on a desk-based downscaling of global and national socio-economic scenarios, combined with a review of local documents and knowledge of the case study catchments. The BESEECH project is a useful source of quantified data. As the global and national level scenarios are already established, and the scenarios are exploratory rather than normative, it is feasible not to involve consultation. However, given the subjective nature of the method and the potentially contentious nature of the scenarios, engagement with a variety of stakeholders is strongly recommended. Such engagement will help ensure the scenarios are robust by being internally consistent and locally valid.

It is possible to add to or rationalise the four conventional socio-economic scenarios (see Chapter 4). The BAU scenario (described above) is akin to conventional development, which is dominated by World Markets, but with important elements of other scenarios, for example the move towards sustainable catchment management. Therefore this scenario could be contrasted with three other scenarios, for example (see also Figure A1-1):

- A world markets scenario, which is similar to BAU, but more economically led.
- A national security scenario, which is similar to the conventional provincial enterprise scenario and is concerned with the protection of UK interests.
- A green scenario, similar to 'Scenario 3' in Turner (2005), which combines strong international policies embodying sustainability with attitudinal and lifestyle changes in society that alter local environments.

Although the use of three (future) scenarios is often cautioned (as it leads to selection of a middle ground), this number is probably adequate for testing the sensitivity of future flood risk and strikes a pragmatic balance between parsimony for tractability of the analytical task and comprehensiveness for realism (Duinker and Greig, 2007).

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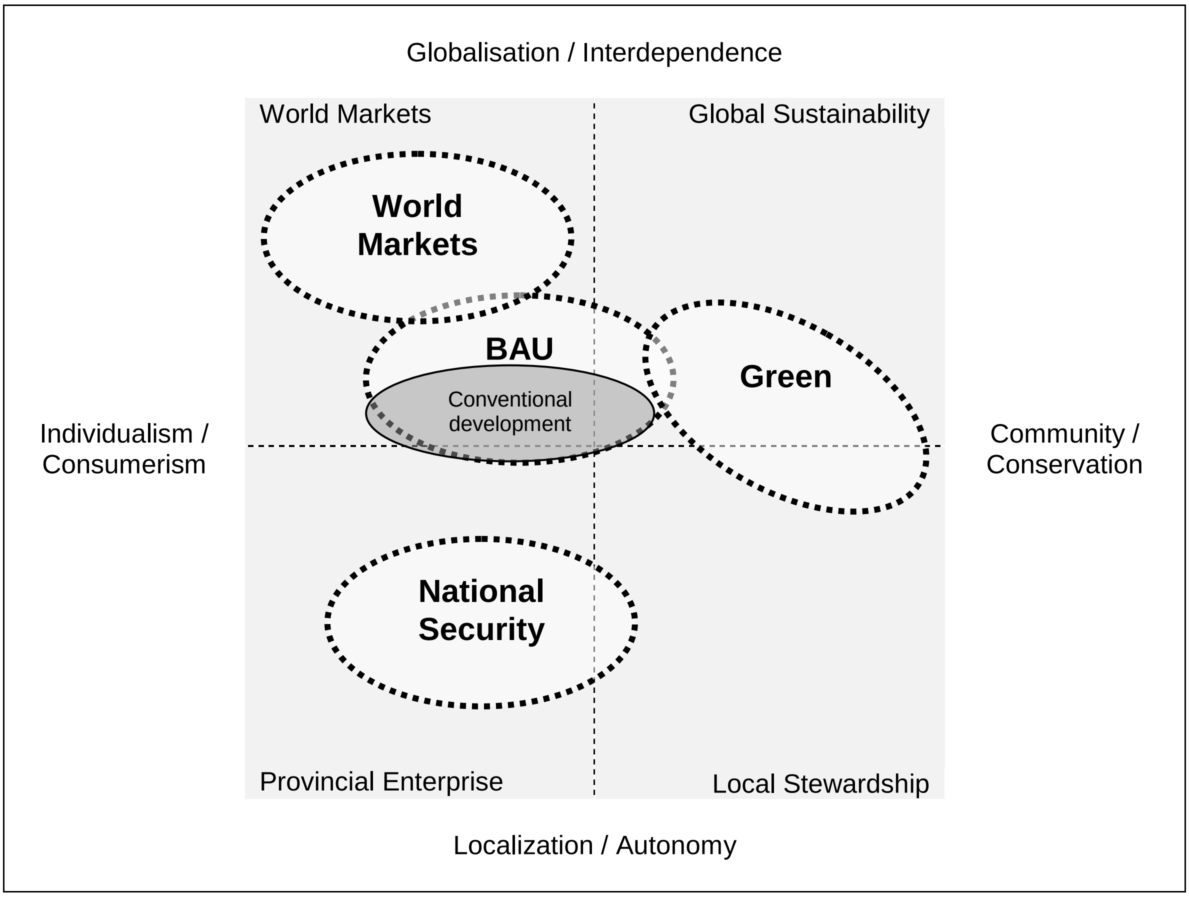
Further detail regarding each of the three scenarios is provided in Table A1-3, in relation to the key scenario elements identified in Table A1-1. This is based on UK-level descriptions from UKCIP (2001), OST (2002) and Dahlström and Salmons (2005), supplemented with the judgement of the author, particularly for the green scenario, which does not map directly to a single national scale scenario.

Figure A1-1 Possible socio-economic scenarios



Adapted from OST (2002) and Turner (2005).

Catchment-specific scenarios would contain qualitative overviews and quantitative data, the latter include drive parameterisation for use in catchment modelling (see Figure 4-3). The qualitative overviews would be developed using the scenario settings from Table A1-3, along with a review of local documents and knowledge of the case study catchments, including that of stakeholders. The quantitative information would be used to perturb the fluvial modelling (if such models exist or can be developed) and as an input to the risk assessments for important receptors (e.g. those identified in Sections 5.2.2 and 5.2.3). Scenario interactions will need to be incorporated (see Section 4.2.3.2)

Table A1-3 Generic overview of key elements of socio-economic scenarios

Scenario element	BAU (from Table A1-2)	World Markets	National Security	Green
Land use	Development on brownfield land, but pressure leads to creeping urbanisation; protection afforded to designated areas	Some agricultural land converted to recreational use or development	Housing and industrial development to support economy; reduction in agricultural land due to intensification; habitat fragmentation	Stable area of arable land, with decline in grazing; habitat recreation; urban growth focused on brownfield sites.
Rural land management	Drive for catchment-sensitive farming	Intensification of agriculture; increase in runoff in agricultural areas	Intensification of agriculture, habitat fragmentation; increase in runoff	High yield, low-input; environmental stewardship; retention of water
Floodplain management	New development restricted unless protected by existing defences, behind which development continues	Development by high-income groups with private defences	Some new development around existing settlement	Floodplain restoration including improving connectivity and floodplain woodlands
Urban storm water management	Attenuation in new development	High price for water leads to some rainwater capture; otherwise little concern	No attenuation as little innovation or concern for environment	Separation of storm and waste water with re-use and local treatment respectively
Standard of protection	Variable but typically to 1.0% to 1.3% APE for urban areas (fluvial)	Highly variable with private defences offering excellent protection, limited elsewhere	All economically significant areas of floodplains protected	Remains for urban areas but greater emphasis on resilience and withdrawal; strong planning controls
Value of agricultural production or land	Volatile, a reaction to competing issues e.g. food security, biofuels and GM crops	Declines, as productivity increases and food prices fall	Stable, balanced between increased food security and increased productivity	High in most fertile areas, declines in areas of livestock production
Value of urban and infrastructure assets and disruption costs	Increases, as assets become more valuable	Increases significantly, with huge investments in infrastructure and mobility more important	Declines, as investment reduces, although disruption effects large due to congestion	Declines as greater emphasis on resilient systems

Scenario element	**BAU (from Table A1-2)**	**World Markets**	**National Security**	**Green**
Social impacts	Aging population increasingly vulnerable; insurance issues for some in high risk areas	Aging population increasingly vulnerable; withdrawal or high cost of insurance and flood defences produces floodplain ghettos	Aging population and lower income groups increasingly vulnerable especially as welfare is increasingly restricted	Aging population but more mixed communities with a range of public and third sector services
Stakeholder behaviour	Insurance as primary mechanism, but based on fragile agreement with Government	Divergent: wealthy will pay to avoid disruption and loss; lower income groups left to cope with events	Insurance available, but at high cost in at risk areas, leading to patchy uptake and some left to bear losses	Attempts to minimise risk including through resilience; community sharing of risks
Public attitudes	Preference for risk reduction with minimal disruption; environmental protection important	No point in specific risk prevention, although expensive assets protected; environmental protection directed by economic instruments	Risk is personal responsibility; little concern about environmental protection beyond local area	Continued protection in high-risk areas, although risk viewed in the context of the community; strong interest in environmental protection
Governance	Hierarchy of plans, but somewhat re-active response to flood events; re-organisation to improve coordination	Weakens, with a range of competing interests and decisions made more locally to benefit economy	Strengthened and centralised nationally; generally re-active to events; lack of cooperation between parties	Combination of decision making for local issues at local levels and for ‘commons’ issues at supra-national levels, but decision-making slow due to inclusivity; anticipatory and equitable.

Appendix 2. Stochastic baseline: selection of flood-producing rainfall periods for the upper Bedford Ouse

A2.1 Introduction

This appendix presents the work undertaken to identify adequate relationships for selecting likely periods of flood-producing rainfall from the stochastic weather generator output.

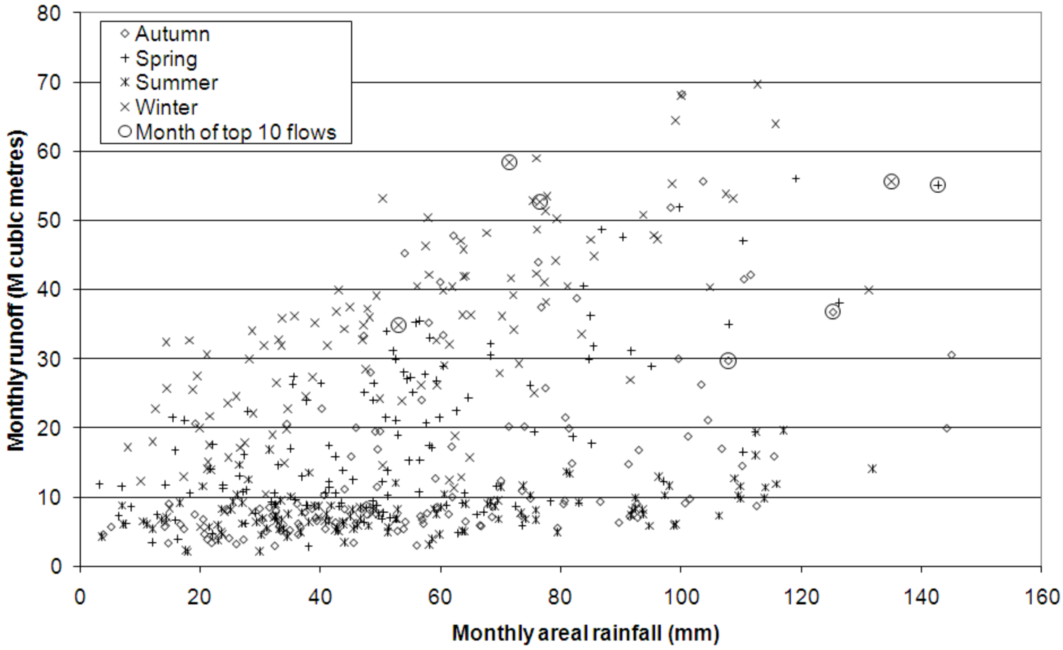
A2.2 Analysis

Initially, the ranking analysis described in Section 8.2.2 was used for the 5 catchments above Newport Pagnell, which ranked the months of peak flows (repeats within the month were excluded). The months in which the highest flows occurred generally coincided with high monthly or seasonal rainfall, the exceptions relating to high flows in one of the catchments. However, there were many months and seasons of high rainfall that did not result in such high flows.

In order to provide a more accurate analysis based on actual flows rather than ranks, which take no account of the relative contribution to flow from each catchment, flows from an initial hydrological run (the 'Blue' run of Table 6-4) were used. Flows were extracted at 6 hour intervals (the model timestep was 15 minutes) and converted to approximate volumes (based on the assumption that flow had been the same for the previous 6 hours). The flows for the 5 catchments were summed. This provided a crude measure of runoff at Newport Pagnell, ignoring attenuation and the relative timing of inputs from different catchments.

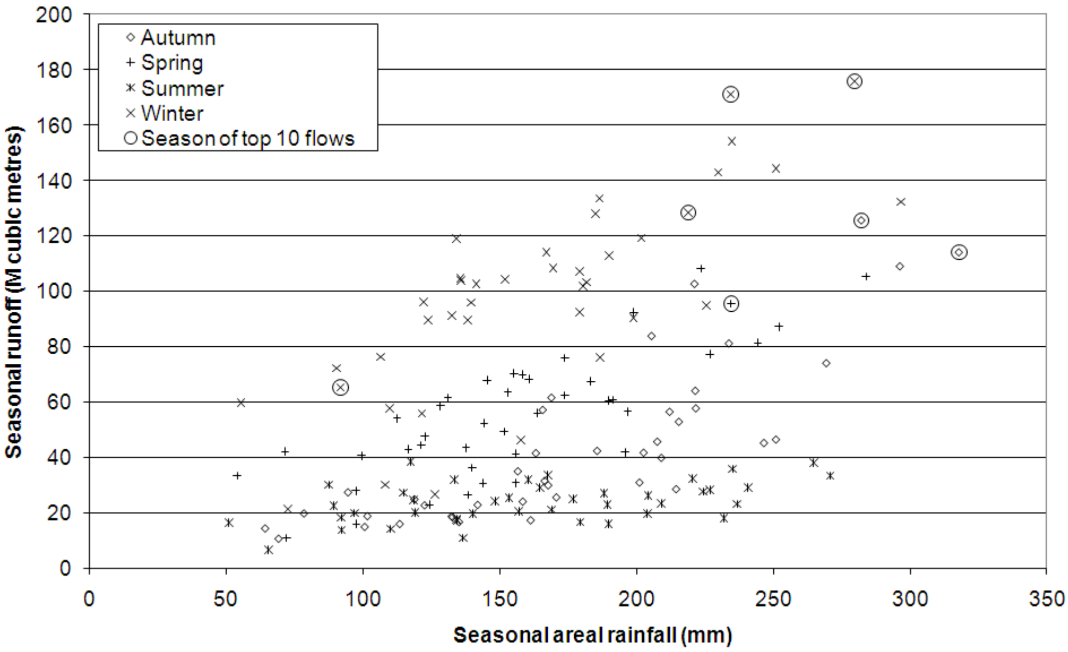
First, a comparison was made of fixed monthly and seasonal rainfall and flow totals and moving weekly rainfall and flow totals. All the results have been stratified by season, as there are distinct differences between seasons. At the all time periods (see Figures A2-1 to A2-3 respectively), a range of summer rainfall totals are all associated with low flows in summer, whereas in winter, greater rainfall totals are associated with greater flows. This is to be expected as summer flows may infiltrate first, whereas winter rainfall is more likely to runoff. Intuitively, the relationships in spring and autumn fit between those in summer and winter, with rainfall and flows more strongly correlated (visually) at the seasonal level. However, high monthly and seasonal rainfall flow totals do not necessarily correlate with shorter duration flood peaks (see the circles in Figures A2-1 and A2-2). Similarly, the day of the peak 7-day flow totals tend to lag the day of highest peaks (black dots in Figure A2-3) by 4 to 5 days, which relates to the wetting up of the catchment and the event time to peak.

Figure A2-1 Relationship between monthly areal rainfall and monthly runoff from the Bedford Ouse above Newport Pagnell (1961–2001)



Note: some months have more than one of the top 10 flows.

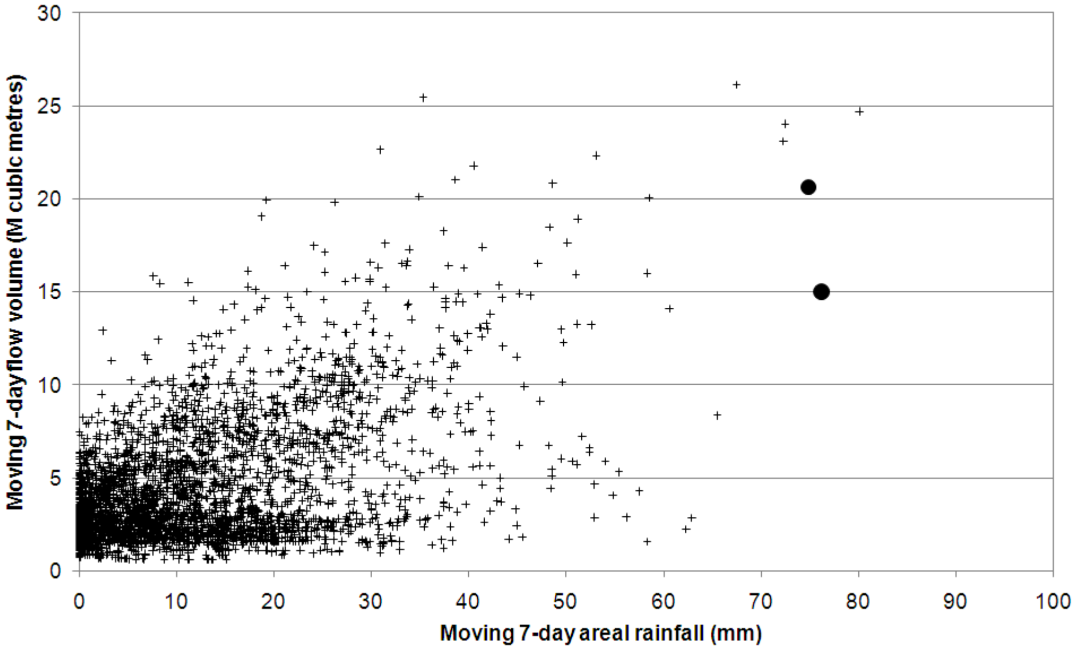
Figure A2-2 Relationship between seasonal areal rainfall and seasonal runoff from the Bedford Ouse above Newport Pagnell (1961–2001)



Note: some seasons have more than one of the top 10 flows.

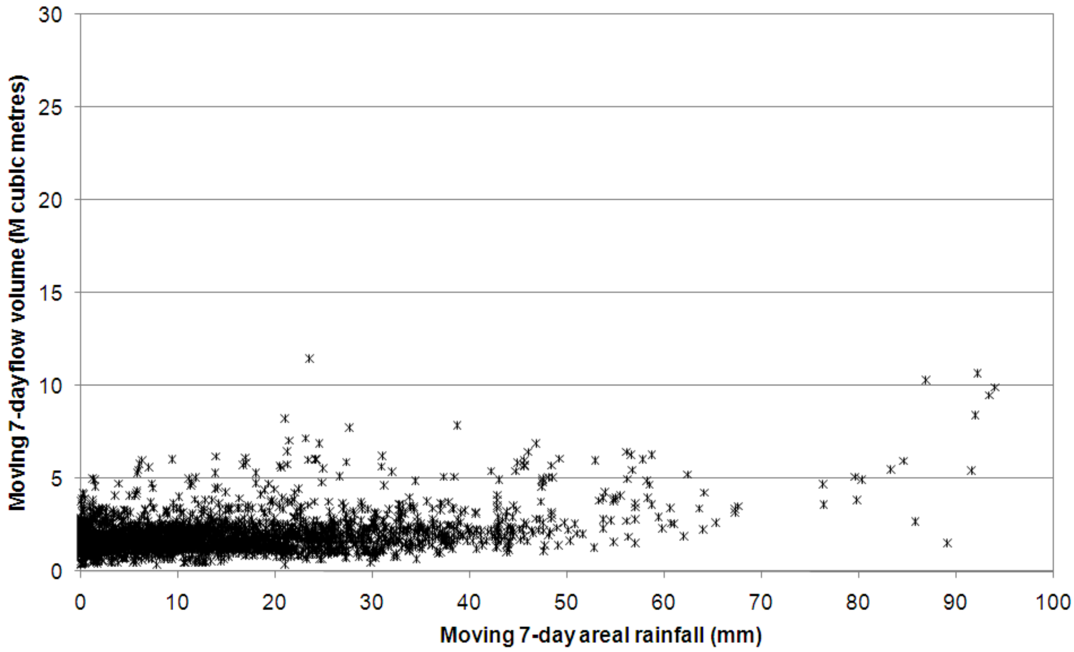
Figure A2-3 Relationship between moving 7-day areal rainfall and moving 7-day runoff from the Bedford Ouse above Newport Pagnell (1961–2001)

A Spring

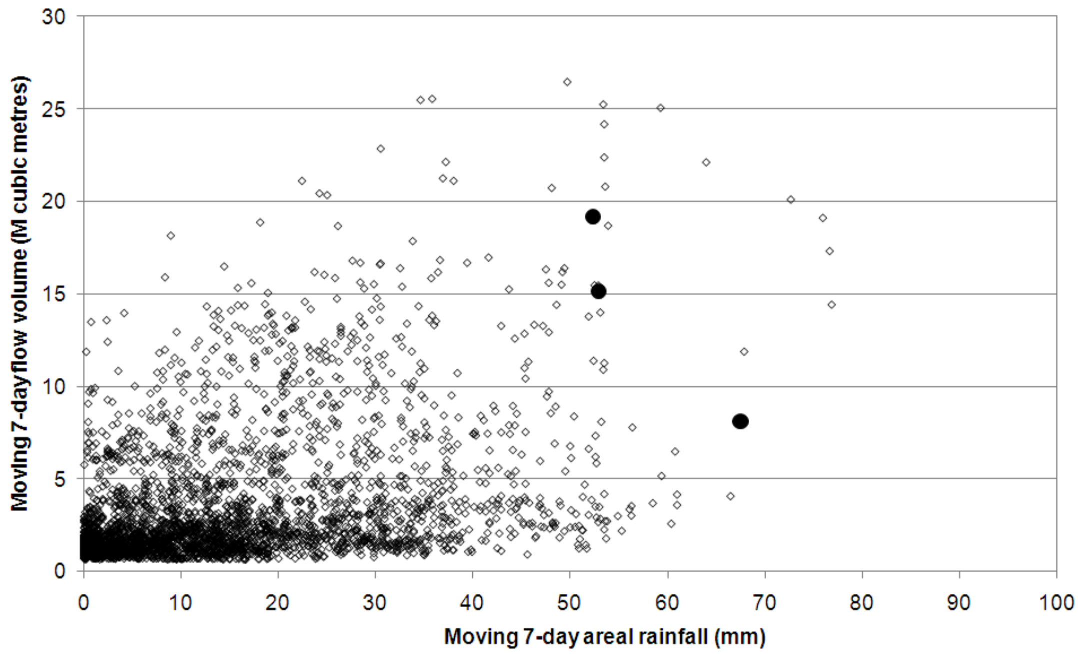


Large black dots =days of top 10 flows (2 occurred in spring).

B Summer

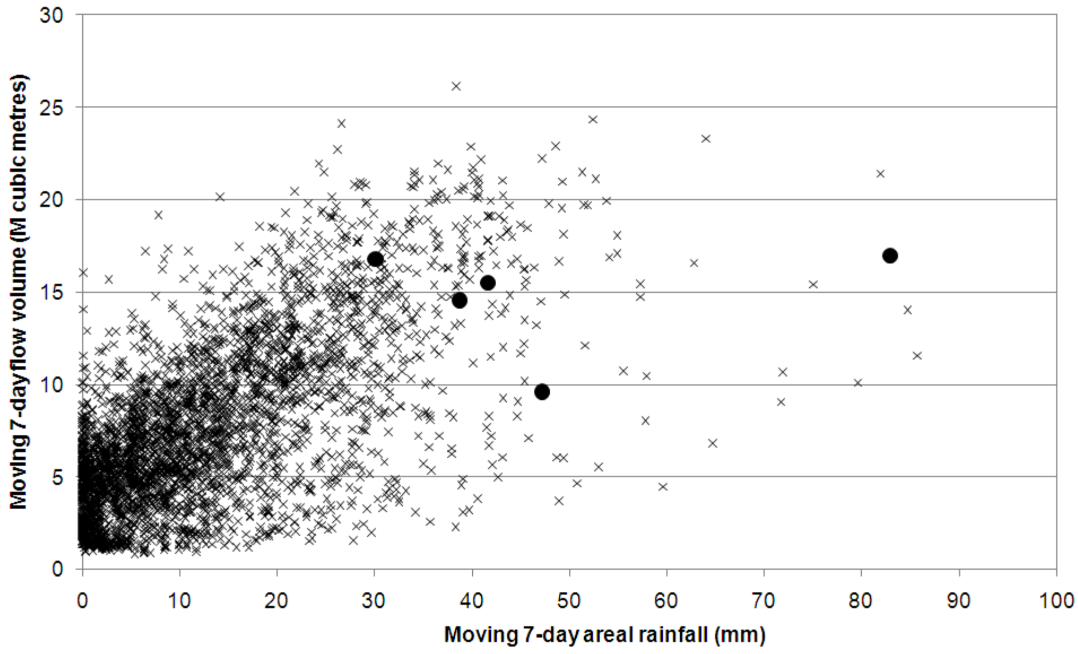


C Autumn



Large black dots = days of top 10 flows (3 occurred in autumn).

D Winter



Large black dots = days of top 10 flows (5 occurred in winter).

Secondly, a method was used to better capture rainfall antecedent to flow on individual days, and flow over 7 days. Moving 1-day flow totals were compared to rainfall on the previous 7, 30 and 90 days, and moving 7-day flow totals were compared with the same rainfall totals, but with flow lagging by 1 day. The patterns (not shown) were similar to the moving 7-day plots in Figure A2-3 above, with a widening sideways 'V' shape appearing as antecedent rainfall time lengthened. The best relationships (visually) were those associated with the 7-day rainfall and flow totals; these were very similar to the moving 7-day plots above, but slightly better at the extremes.

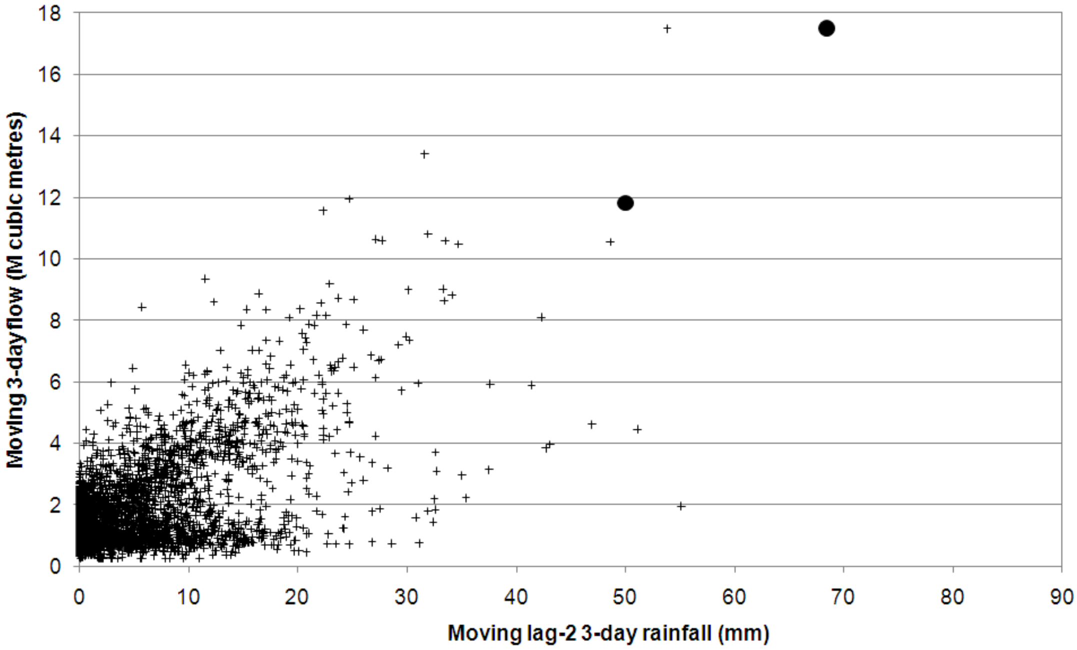
Finally, a third method was used to better represent rainfall and flow characteristics in the catchment, based on 3-day rainfall and 3-day flow, with flow lagging behind rainfall by 2 days. The results (see Figure A2-4) show a slight improvement on the 7-day rainfall and flow relationships. The black dots depict the days which fall 2 days after the peak flow for the 10 highest flows during the period 1961-2001; these are not always the highest 3-day flows.

A2.3 Conclusion

Overall, it was difficult to find any single metric that adequately defined the amount of rainfall that would likely lead to flooding (note that combined metrics, for example 3-day rainfall plus 90-day rainfall, were not evaluated).

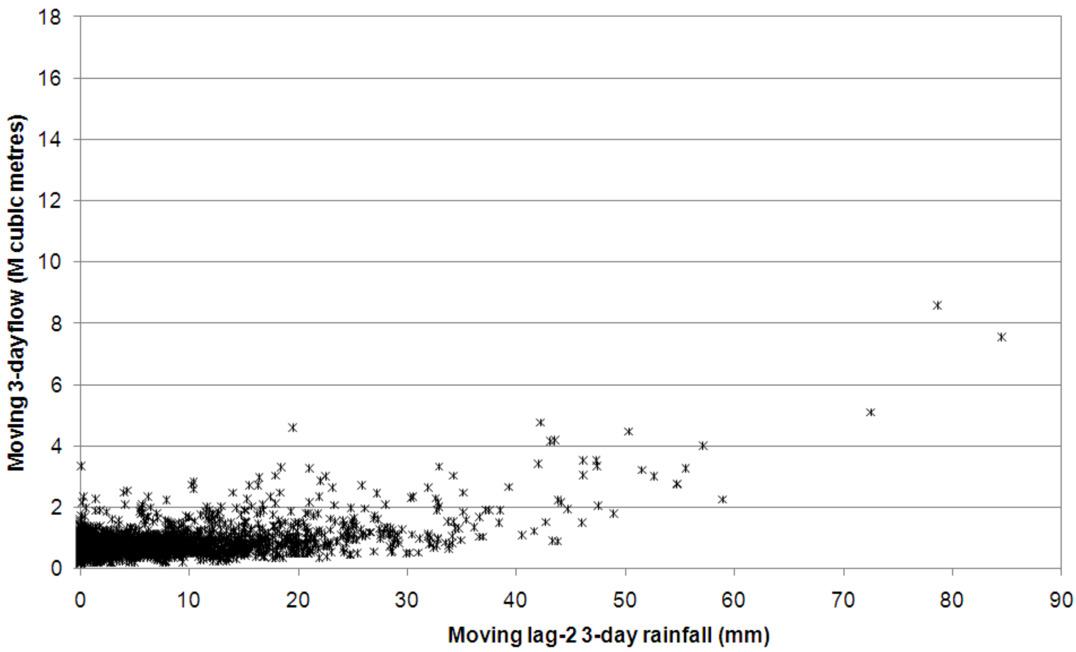
Figure A2-4 Relationship between moving lag-2 3-day areal rainfall and moving 3-day runoff from the Bedford Ouse above Newport Pagnell (1961–2001)

A Spring

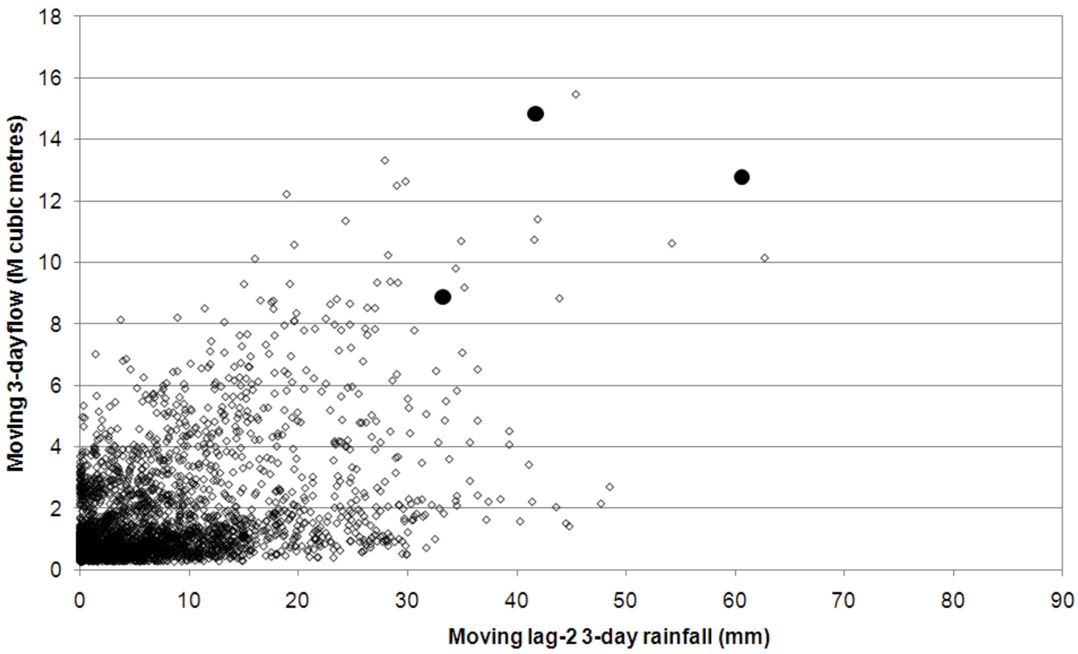


Large black dots = 2 days after the days of top 10 flows (2 occurred in spring).

B Summer

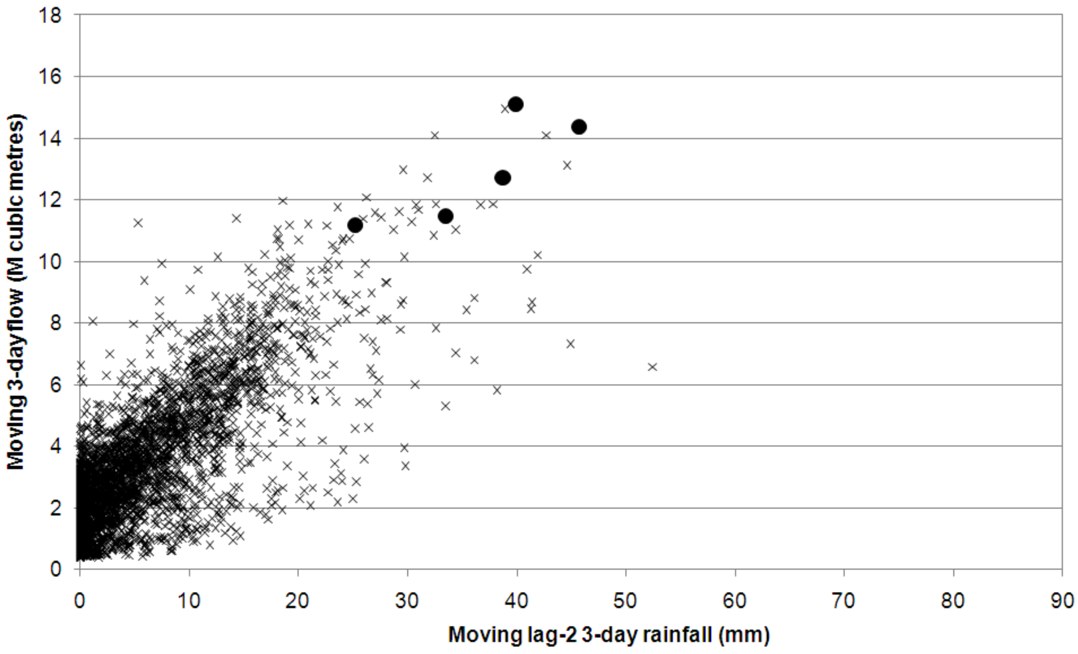


C Autumn



Large black dots = 2 days after the days of top 10 flows (3 occurred in autumn).

D Winter

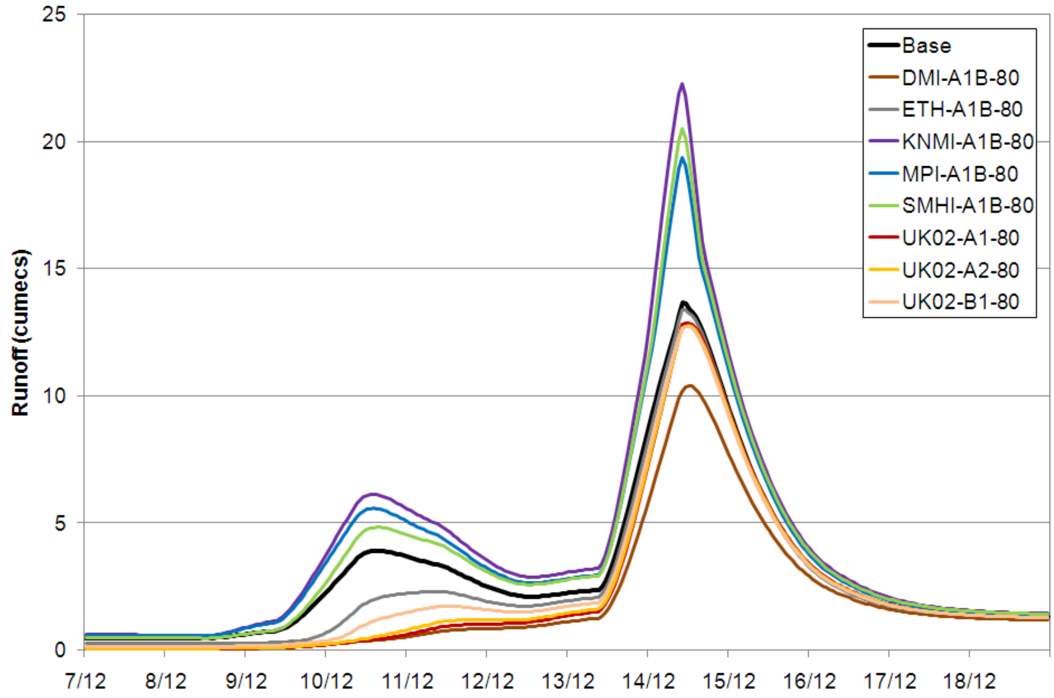


Large black dots = 2 days after the days of top 10 flows (5 occurred in winter).

Appendix 3. Further graphs from the Bedford Ouse results

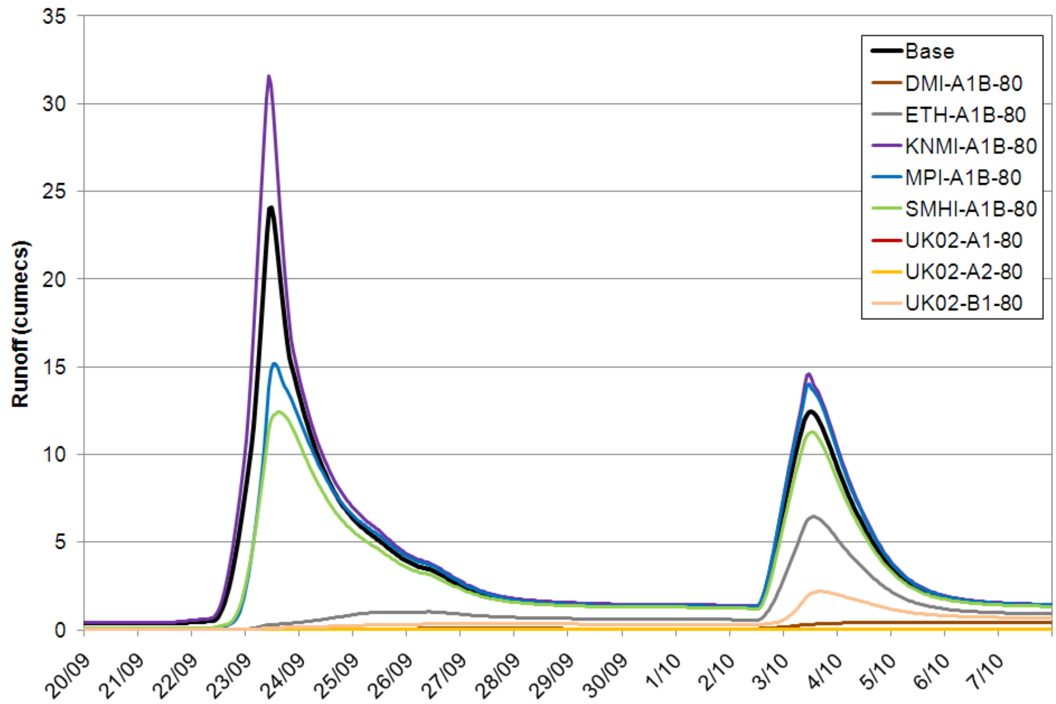
A3.1 Runoff for the four selected flood events for the three response type exemplar catchments

Figure A3-1 Modelled runoff from the Alconbury Brook catchment for the December 1979 event and under different scenarios for the 2080s



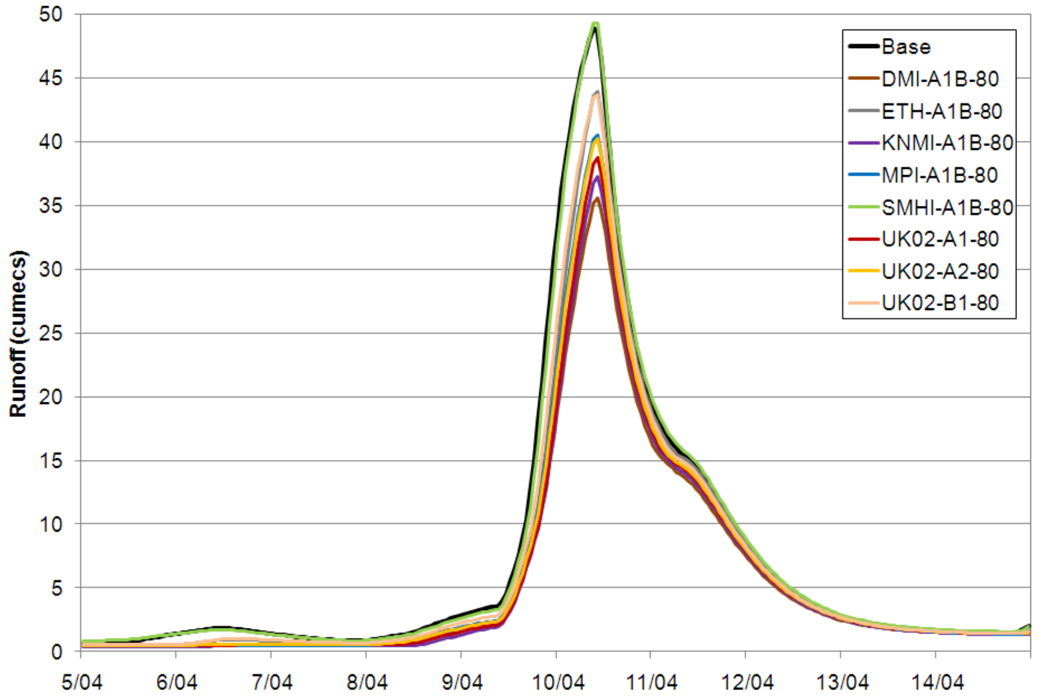
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-2 Modelled runoff from the Alconbury Brook catchment for the September 1992 event and under different scenarios for the 2080s



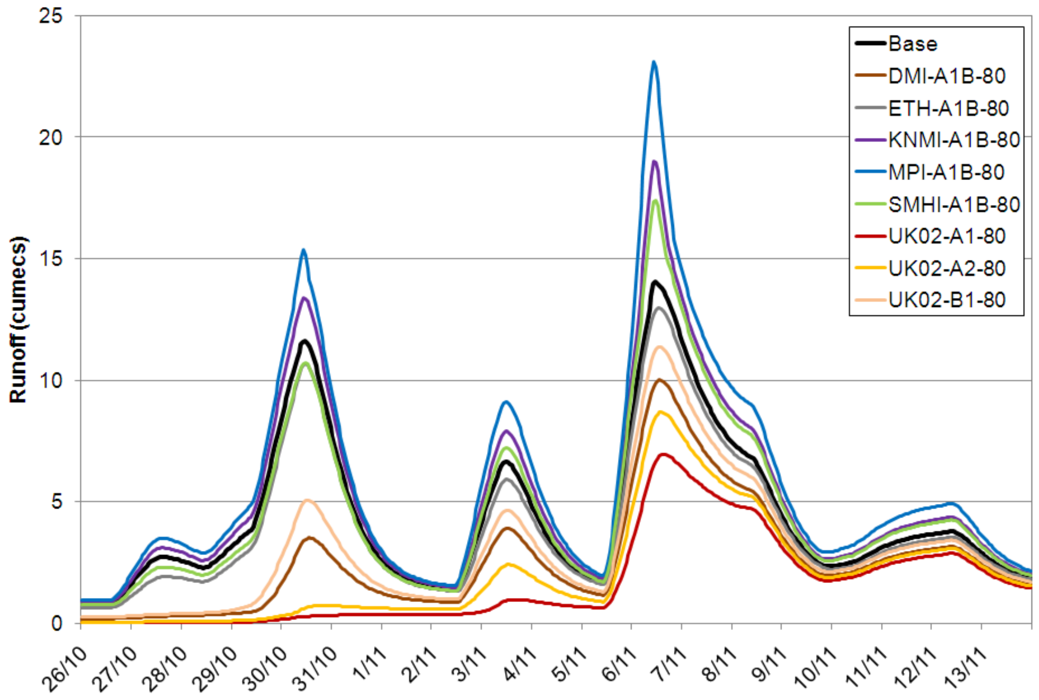
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-3 Modelled runoff from the Alconbury Brook catchment for the Easter 1998 event and under different scenarios for the 2080s



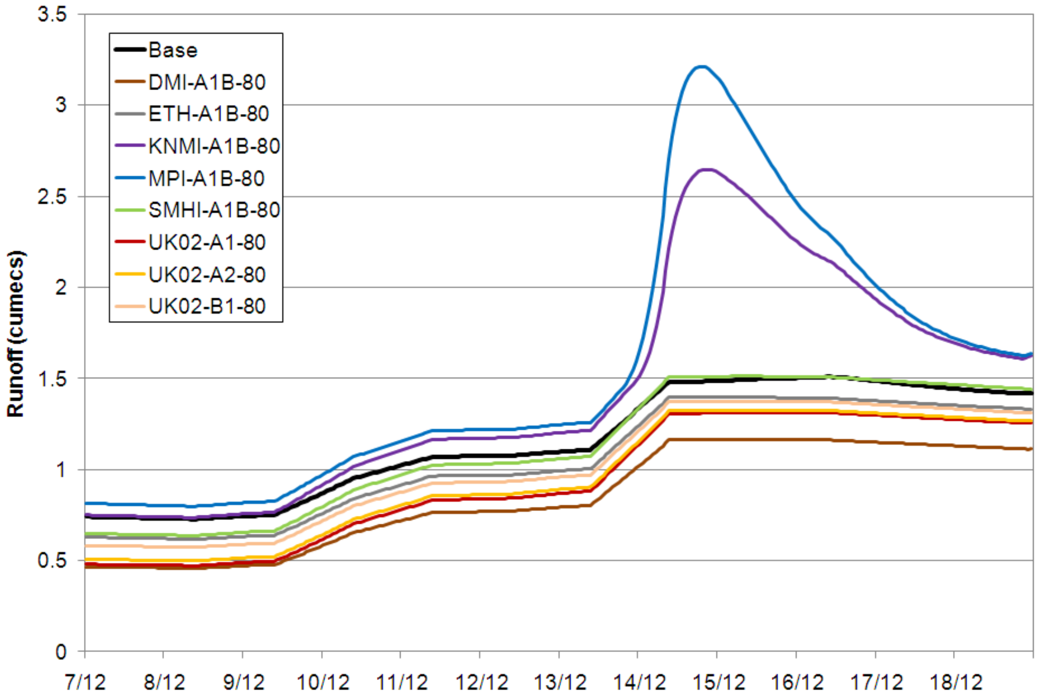
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-4 Modelled runoff from the Alconbury Brook catchment for the Autumn 2000 event and under different scenarios for the 2080s



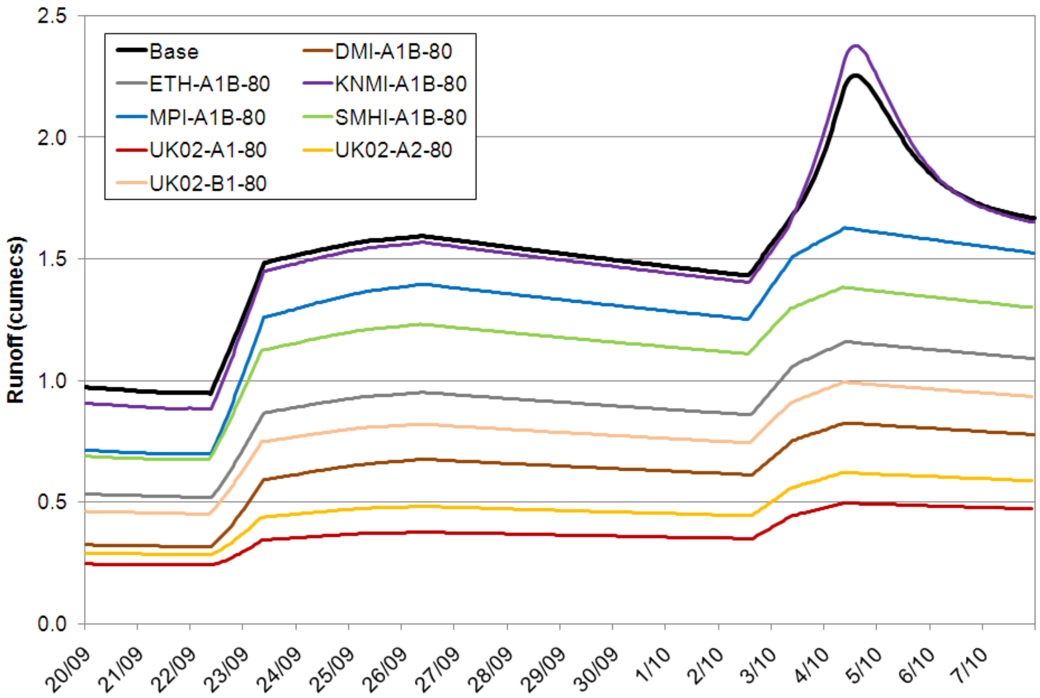
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-5 Modelled runoff from the Flit catchment for the December 1979 event and under different scenarios for the 2080s



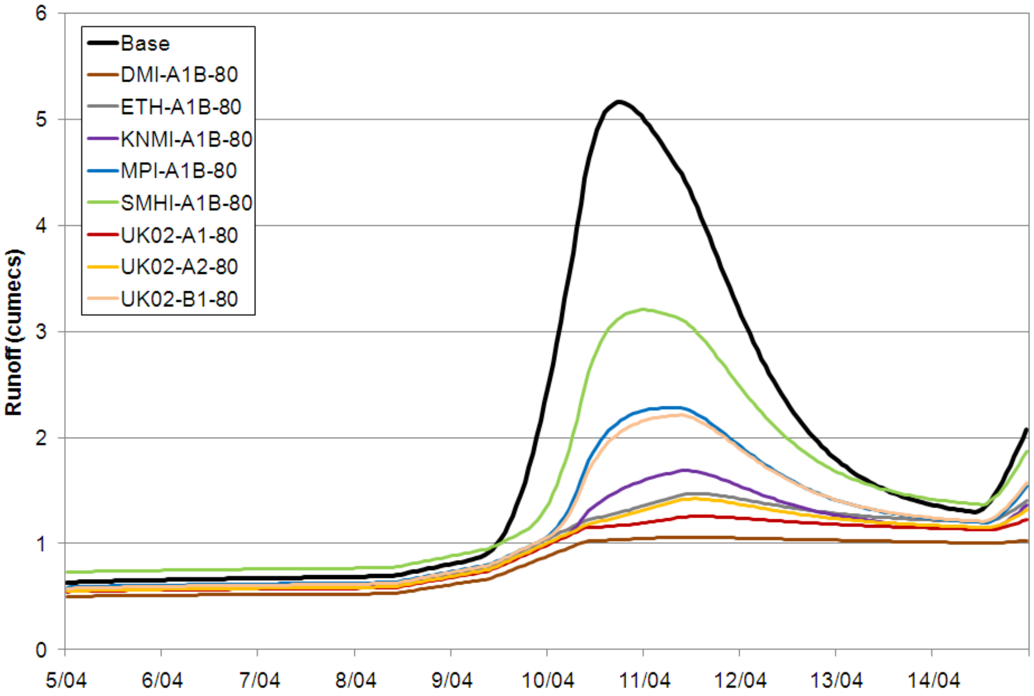
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-6 Modelled runoff from the Flit catchment for the September 1992 event and under different scenarios for the 2080s



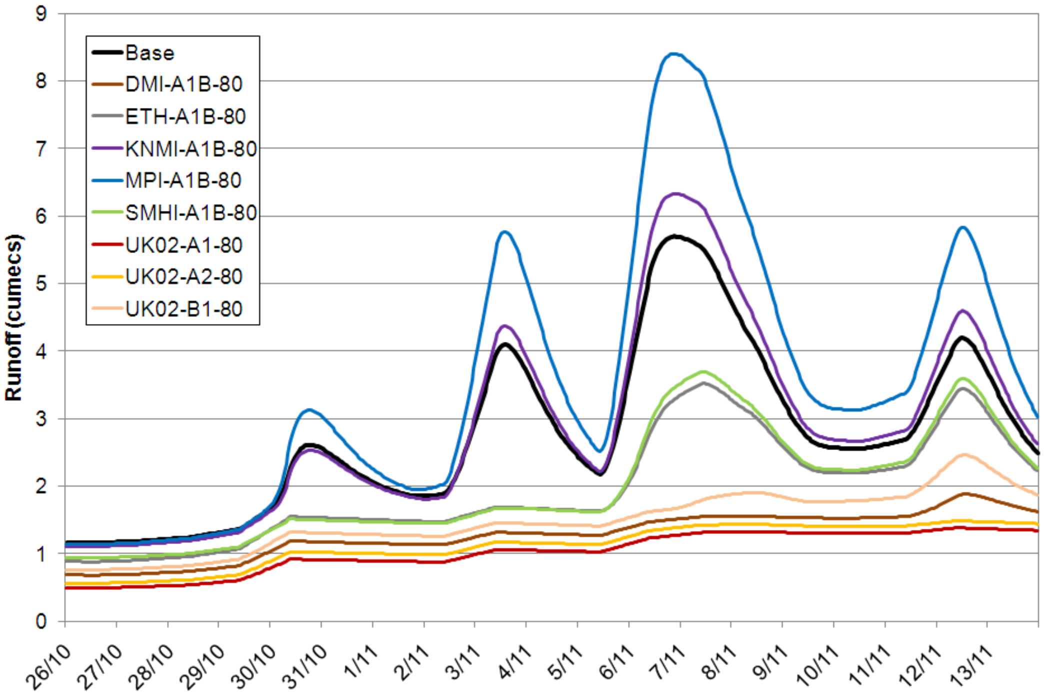
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-7 Modelled runoff from the Flit catchment for the Easter 1998 event and under different scenarios for the 2080s



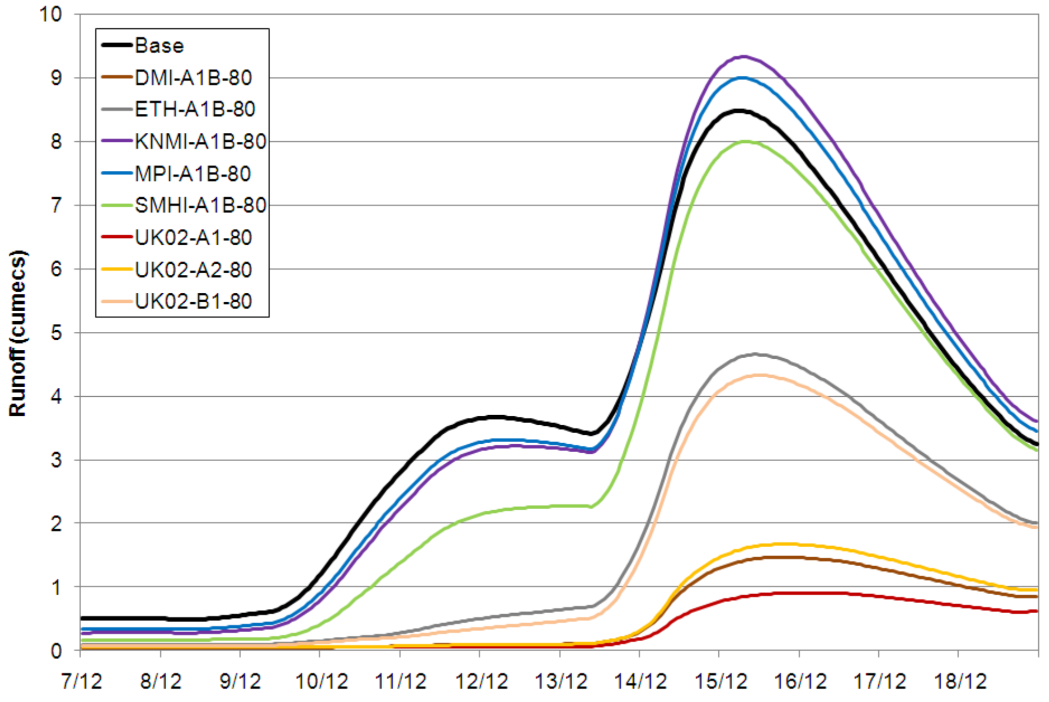
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-8 Modelled runoff from the Flit catchment for the Autumn 2000 event and under different scenarios for the 2080s



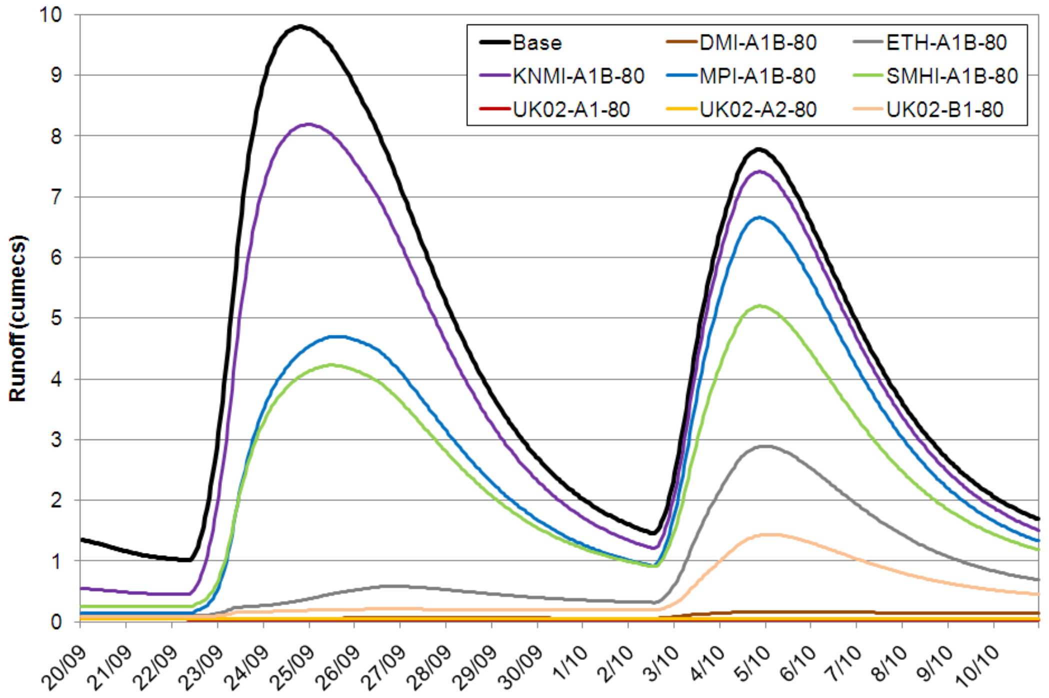
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-9 Modelled runoff from the tributaries of the Bedford Ouse between Bedford and Roxton for the December 1979 event and under different scenarios for the 2080s



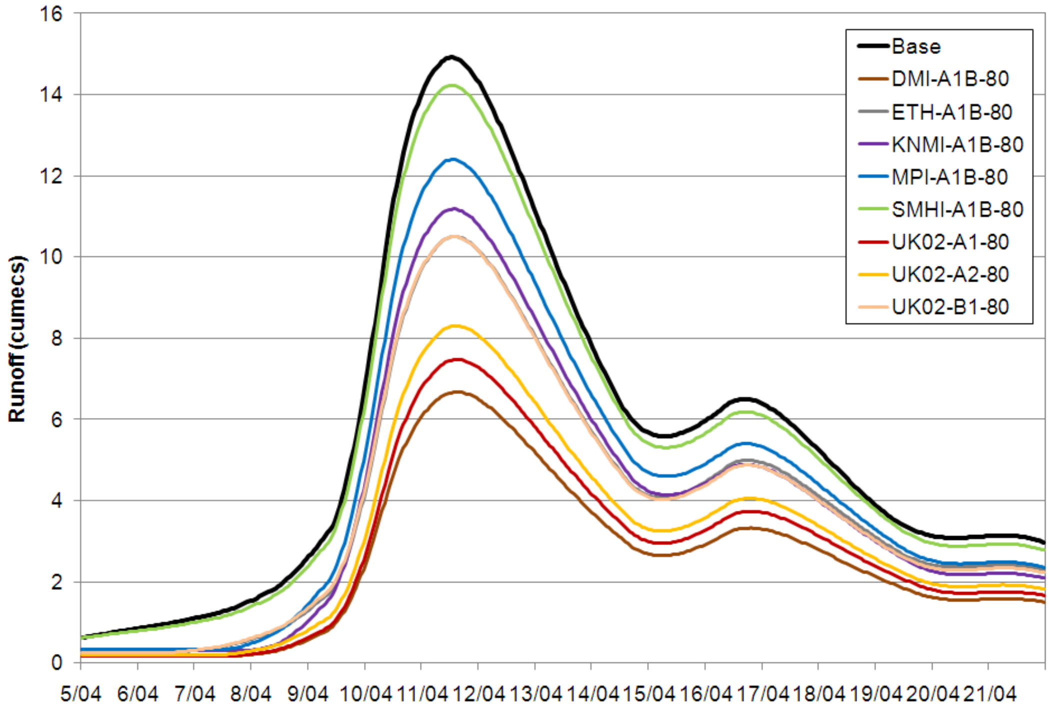
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-10 Modelled runoff from the tributaries of the Bedford Ouse between Bedford and Roxton for the September 1992 event and under different scenarios for the 2080s



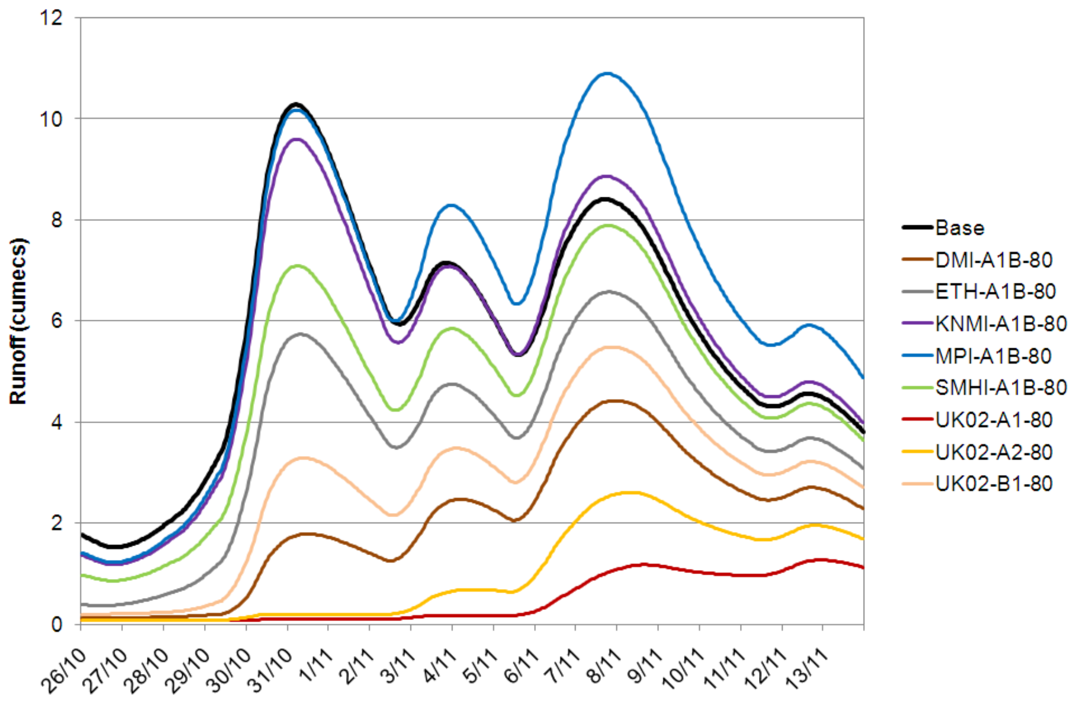
For details of scenarios, see Table 8-1. Original in colour.

Figure A3-11 Modelled runoff from the tributaries of the Bedford Ouse between Bedford and Roxton for the Easter 1998 event and under different scenarios for the 2080s



For details of scenarios, see Table 8-1. Original in colour.

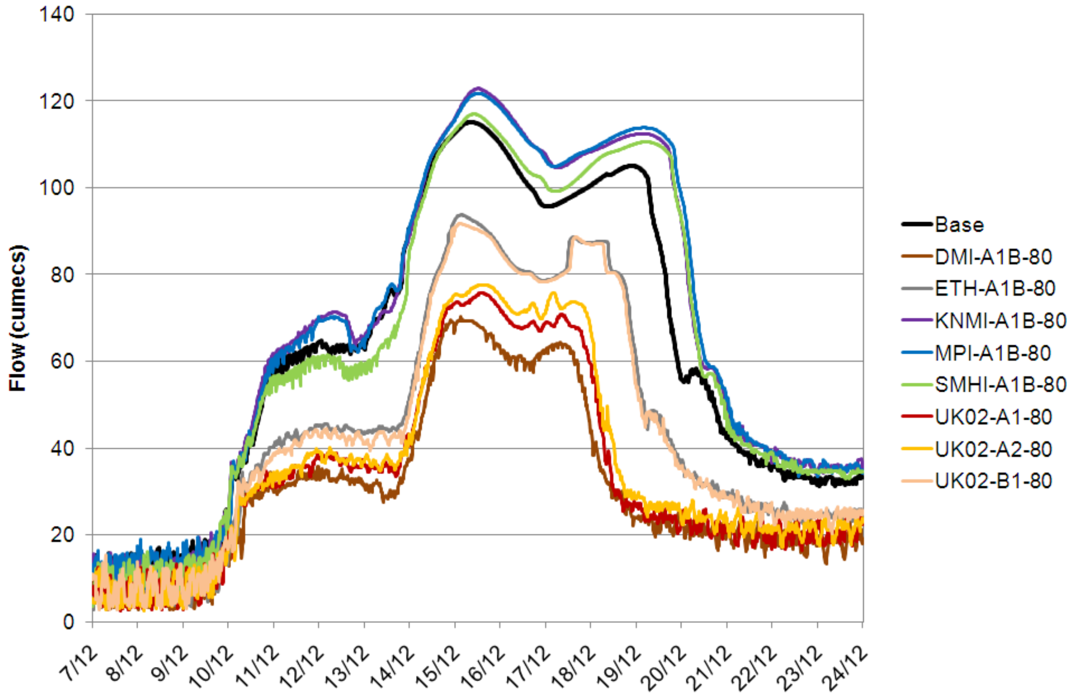
Figure A3-12 Modelled runoff from the tributaries of the Bedford Ouse between Bedford and Roxton for the Autumn 2000 event and under different scenarios for the 2080s



For details of scenarios, see Table 8-1. Original in colour.

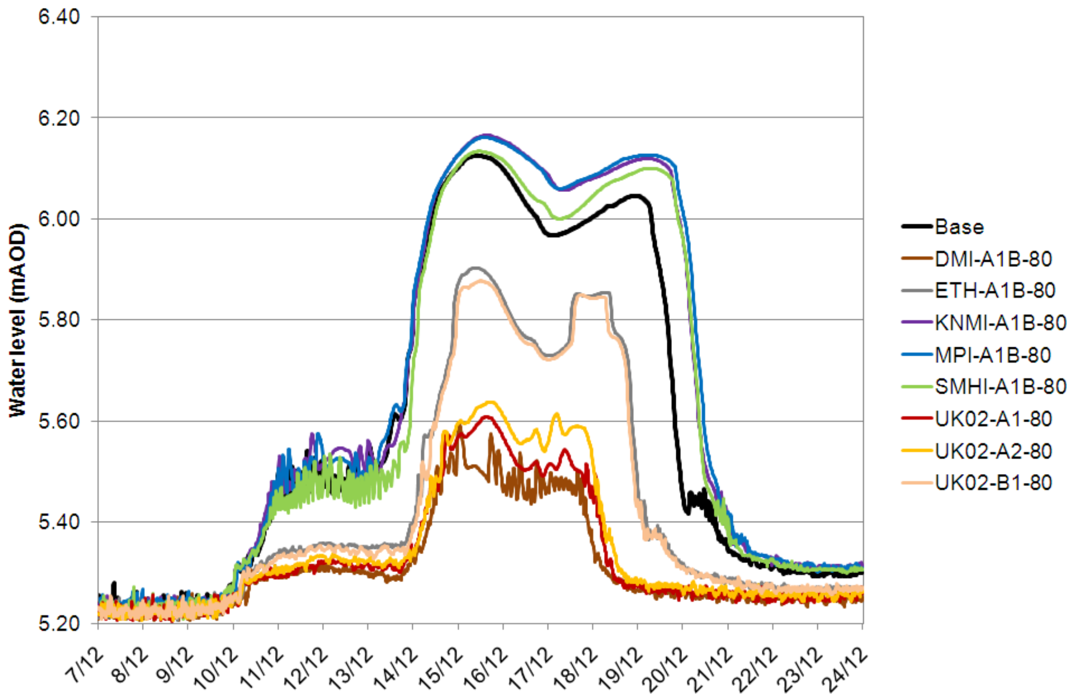
A3.2 Flow and water level for four key flood events for the Great Ouse at St Ives

Figure A3-13 Modelled flow on the Great Ouse at St Ives for the December 1979 event and under different scenarios for the 2080s



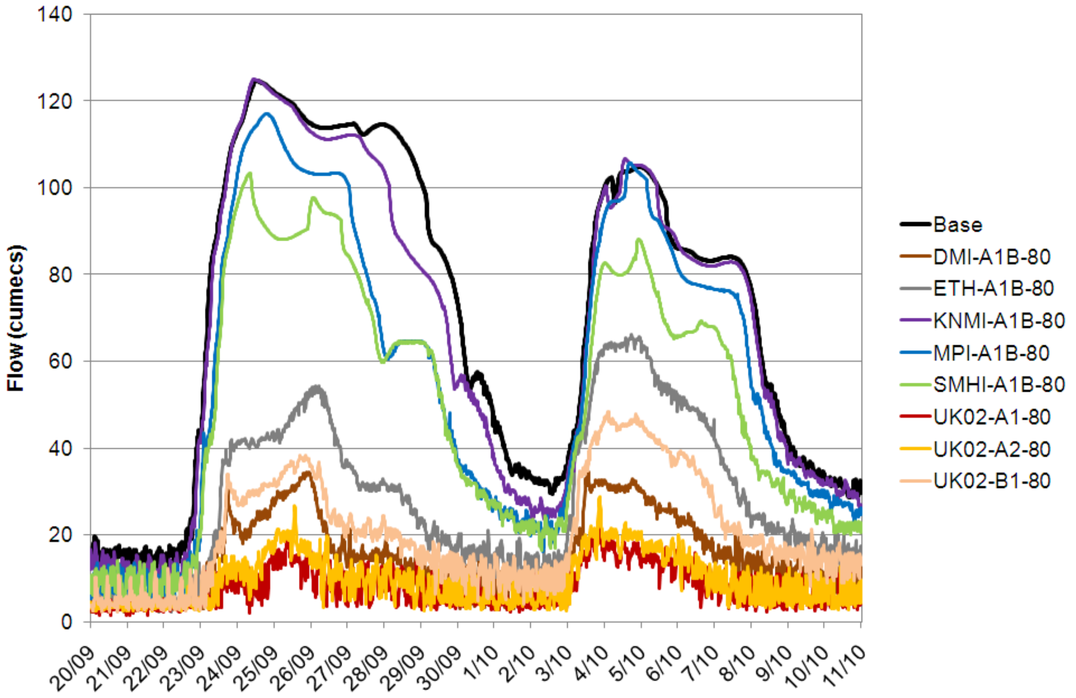
Results for model node at chainage 'GREAT OUSE 172034.94'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-14 Modelled water levels on the Great Ouse at St Ives for the December 1979 event and under different scenarios for the 2080s



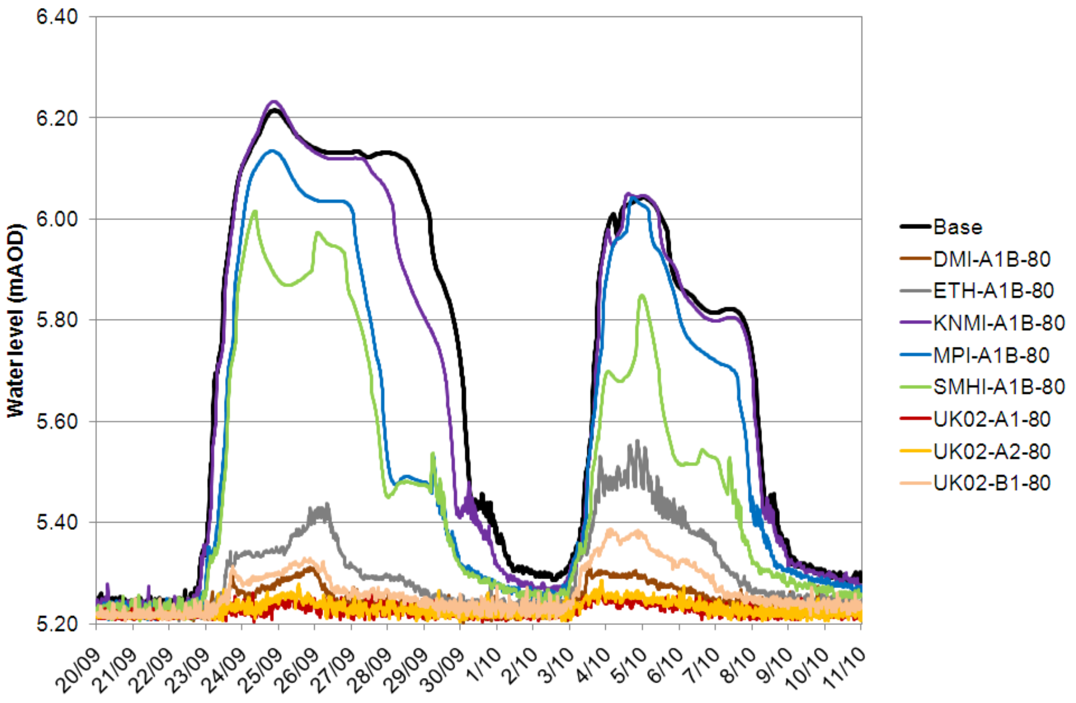
Results for model node at chainage 'GREAT OUSE 172094.86'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-15 Modelled flow on the Great Ouse at St Ives for the September 1992 event and under different scenarios for the 2080s



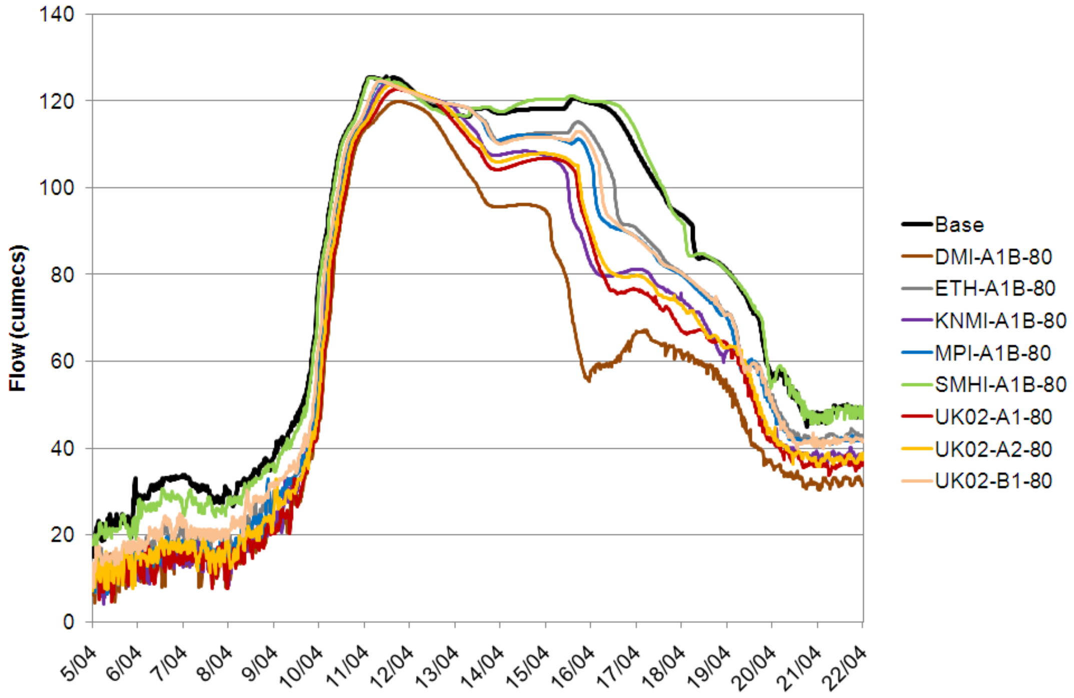
Results for model node at chainage 'GREAT OUSE 172034.94'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-16 Modelled water levels on the Great Ouse at St Ives for the September 1992 event and under different scenarios for the 2080s



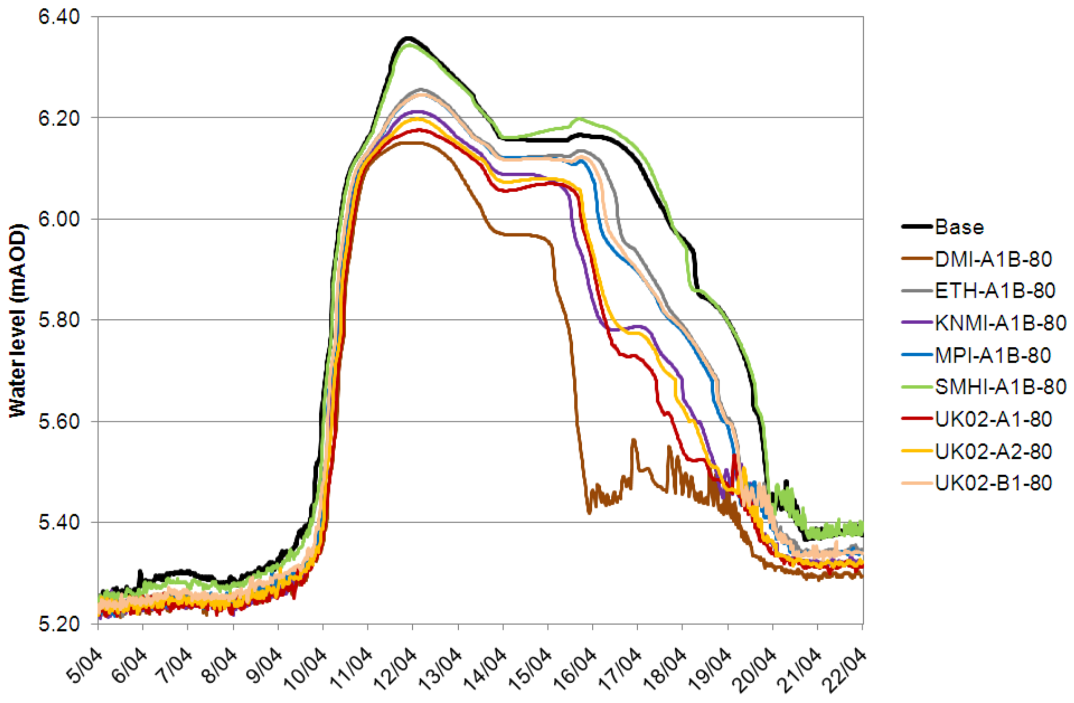
Results for model node at chainage 'GREAT OUSE 172094.86'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-17 Modelled flow on the Great Ouse at St Ives for the Easter 1998 event and under different scenarios for the 2080s



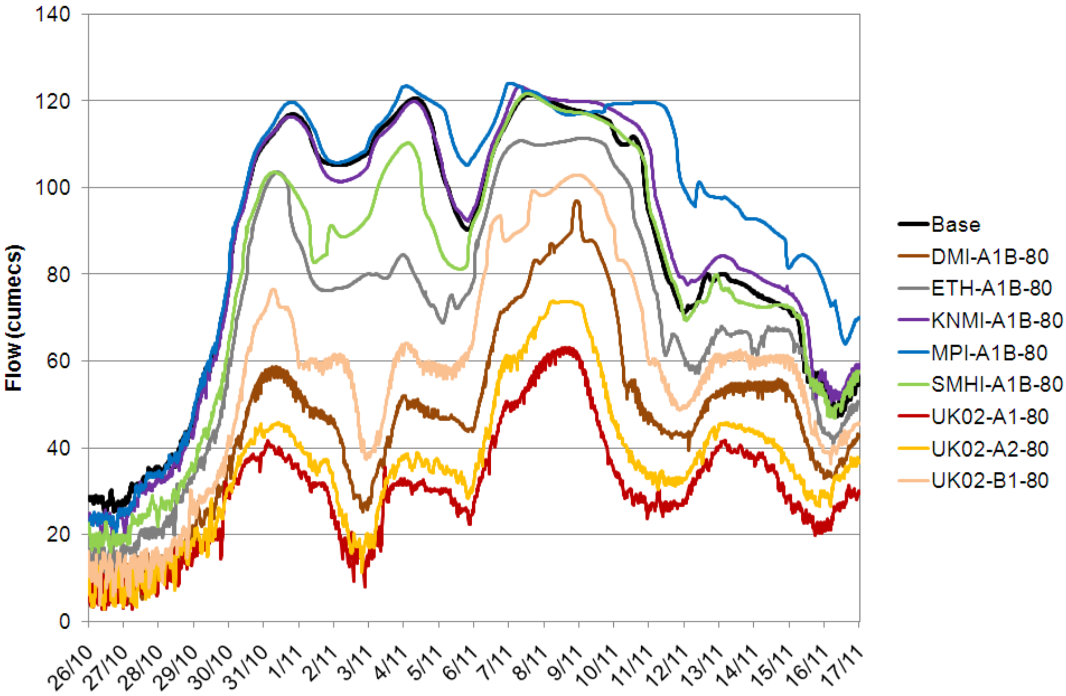
Results for model node at chainage 'GREAT OUSE 172034.94'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-18 Modelled water levels on the Great Ouse at St Ives for the Easter 1998 event and under different scenarios for the 2080s



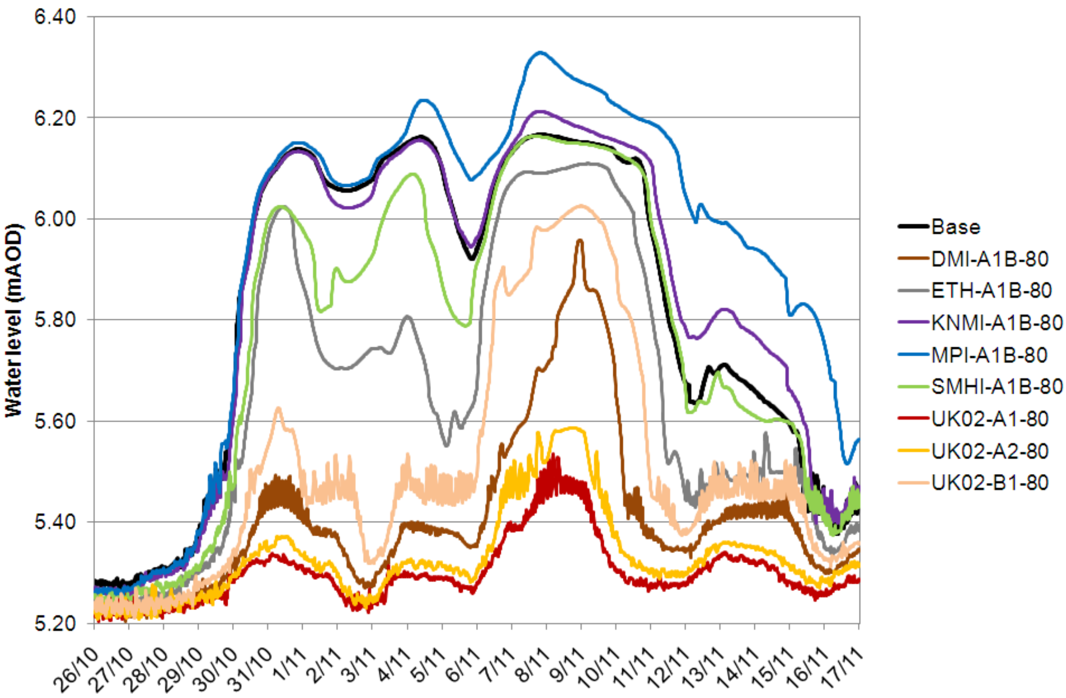
Results for model node at chainage 'GREAT OUSE 172094.86'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-19 Modelled flow on the Great Ouse at St Ives for the Autumn 2000 event and under different scenarios for the 2080s



Results for model node at chainage 'GREAT OUSE 172034.94'. For details of scenarios, see Table 8-1. Original in colour.

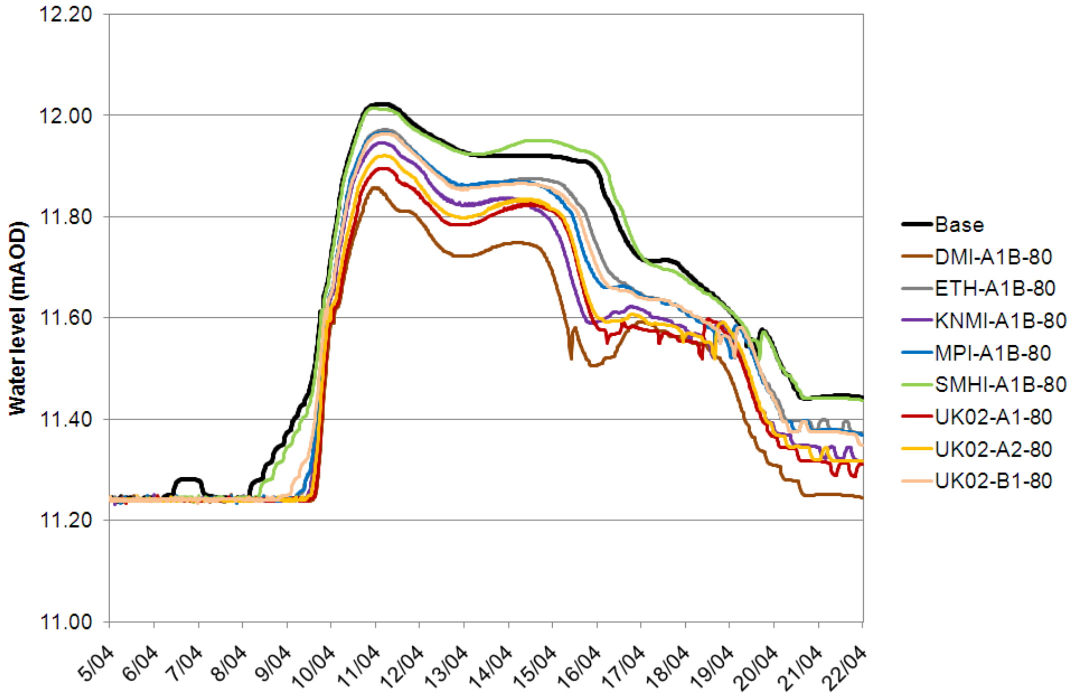
Figure A3-20 Modelled water levels on the Great Ouse at St Ives for the Autumn 2000 event and under different scenarios for the 2080s



Results for model node at chainage 'GREAT OUSE 172094.86'. For details of scenarios, see Table 8-1. Original in colour.

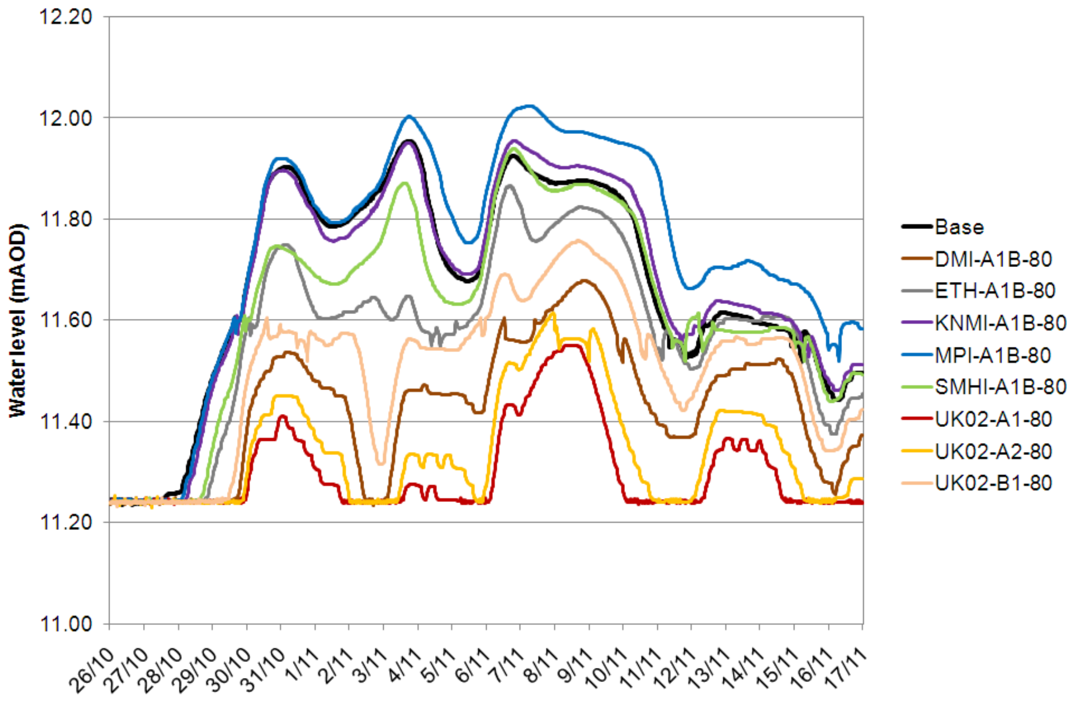
A3.3 Water levels for the Easter 1998 and Autumn 2000 events at other extracted model nodes

Figure A3-21 Modelled water levels on the Great Ouse at Offord for the Easter 1998 event and under different scenarios for the 2080s



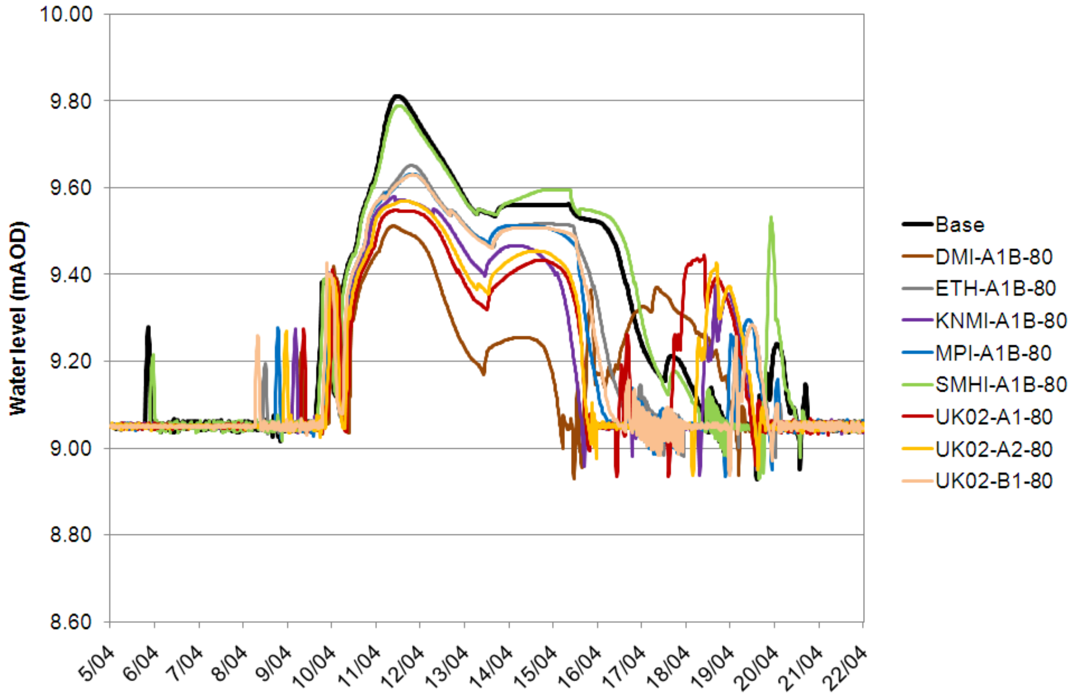
Results for model node at chainage 'GREAT OUSE 156385.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-22 Modelled water levels on the Great Ouse at Offord for the Autumn 2000 event and under different scenarios for the 2080s



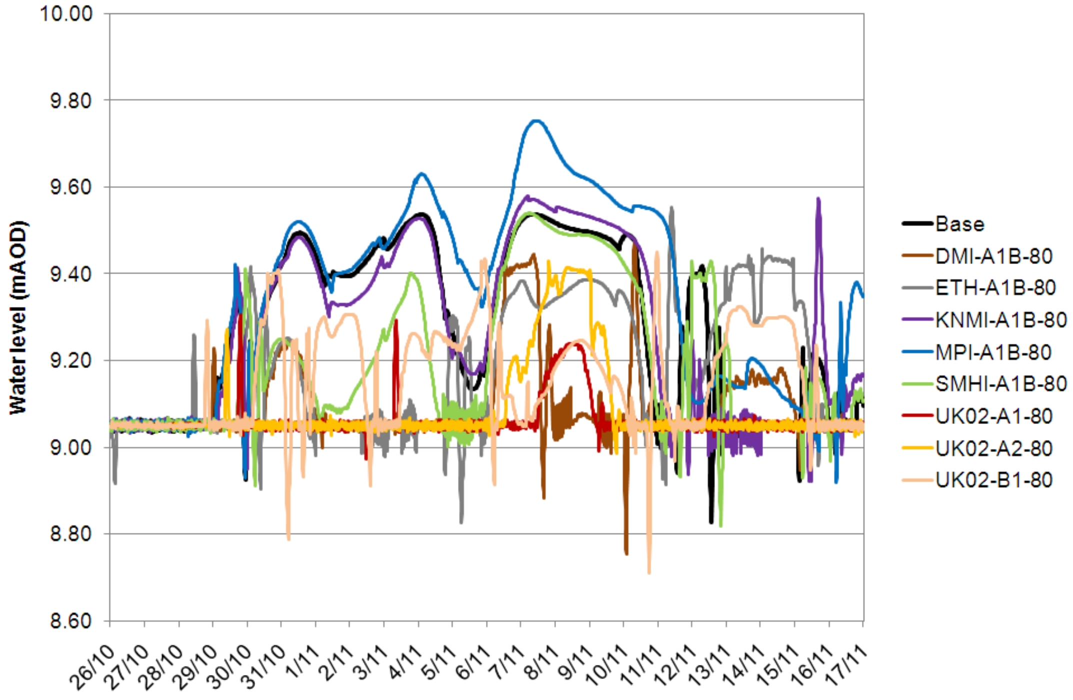
Results for model node at chainage 'GREAT OUSE 156385.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-23 Modelled water levels on the Mill Channel at Godmanchester for the Easter 1998 event and under different scenarios for the 2080s



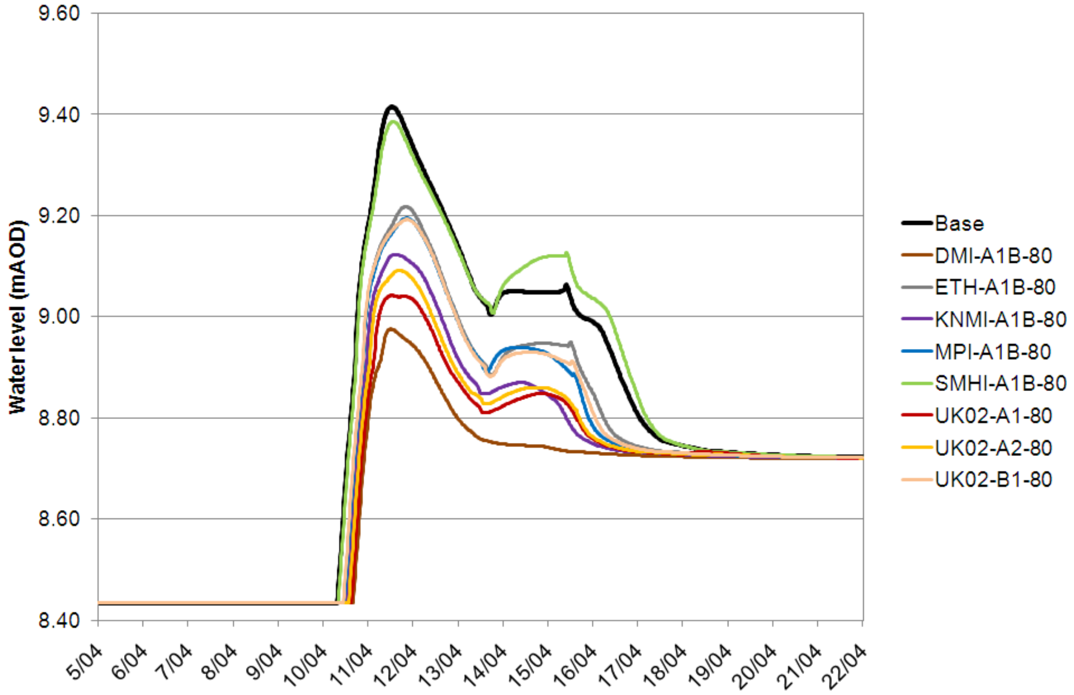
Results for model node at chainage 'MILL CHANNEL 250.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-24 Modelled water levels on the Mill Channel at Godmanchester for the Autumn 2000 event and under different scenarios for the 2080s



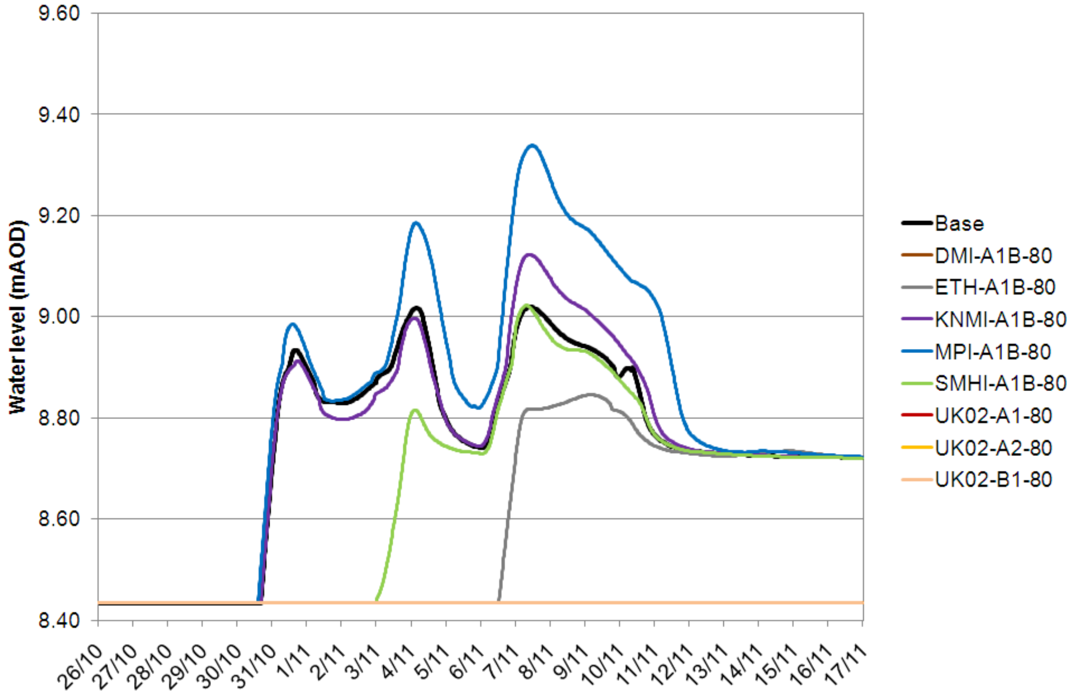
Results for model node at chainage 'MILL CHANNEL 250.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-25 Modelled water levels on Portholme Meadow for the Easter 1998 event and under different scenarios for the 2080s



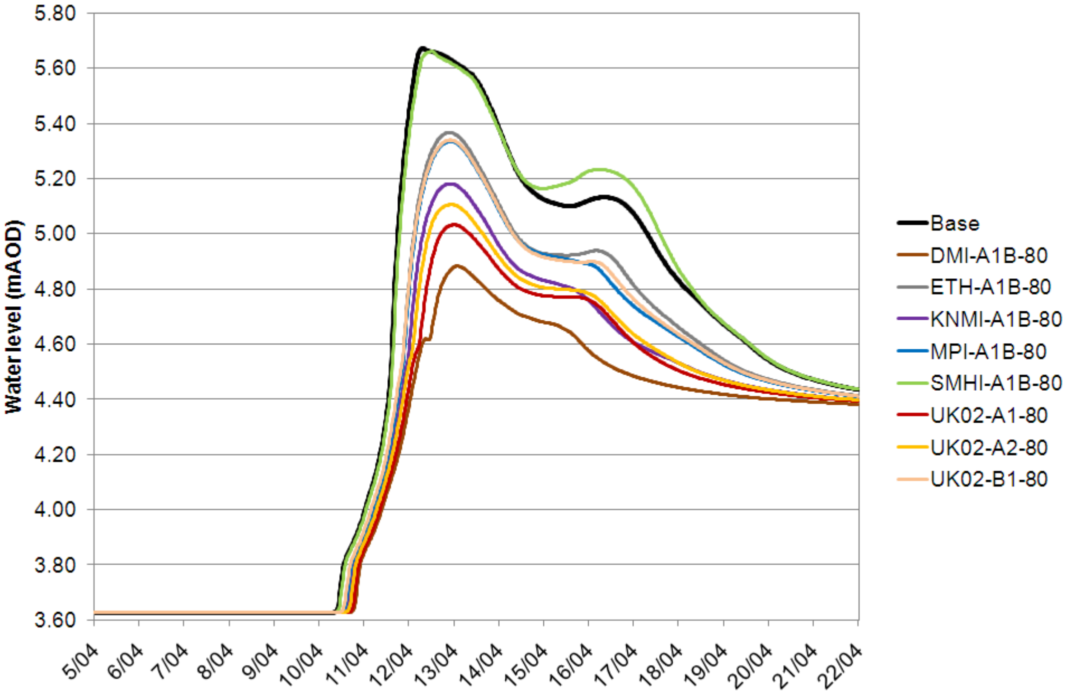
Results for model node at chainage 'GM_FP_CLOW 2400.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-26 Modelled water levels on Portholme Meadow for the Autumn 2000 event and under different scenarios for the 2080s



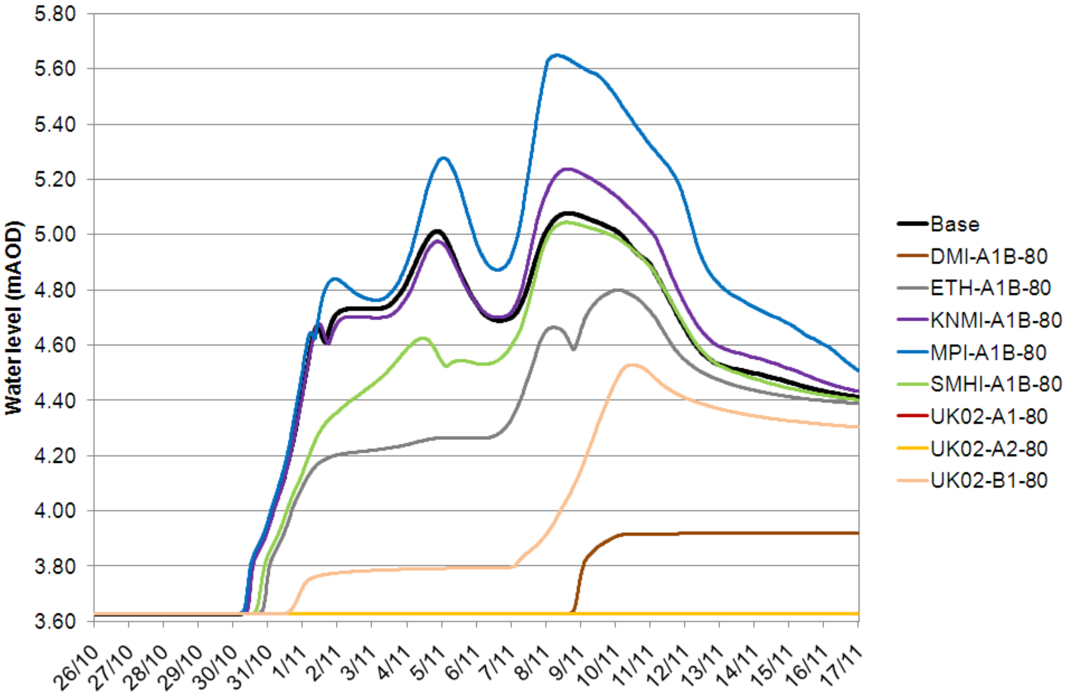
Results for model node at chainage 'GM_FP_CLOW 2400.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-27 Modelled water levels at Fen Drayton Lakes for the Easter 1998 event and under different scenarios for the 2080s



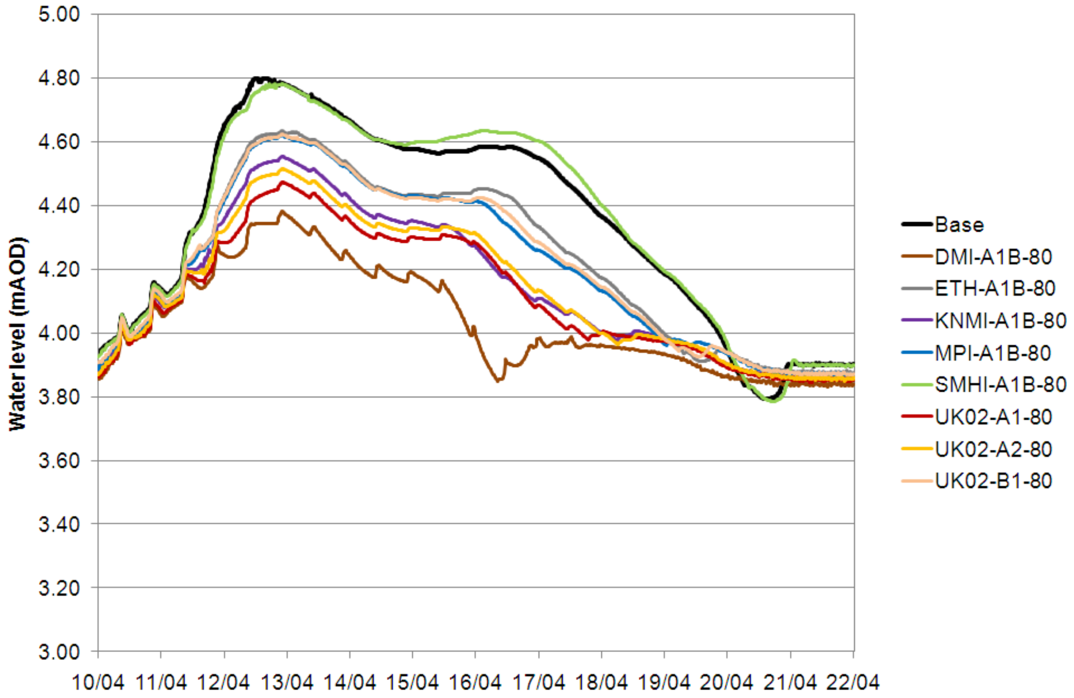
Results for model node at chainage 'FEND_SE 7600.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-28 Modelled water levels at Fen Drayton Lakes for the Autumn 2000 event and under different scenarios for the 2080s



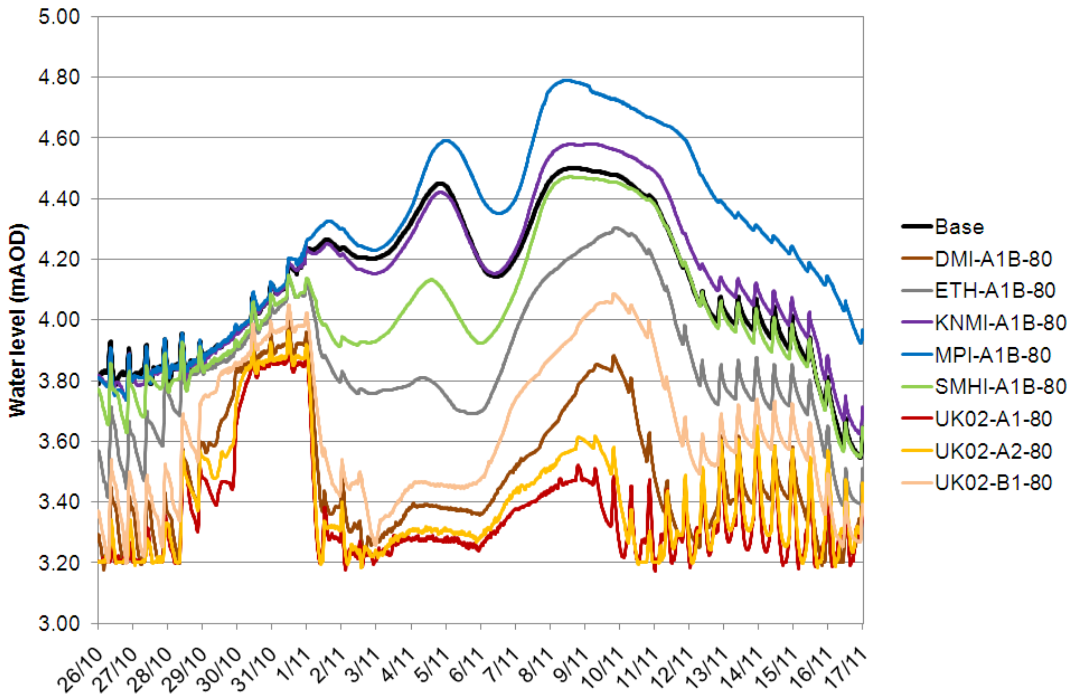
Results for model node at chainage 'FEND_SE 7600.00'. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-29 Modelled water levels on the Great Ouse just upstream of Brownshill Staunch for the Easter 1998 event and under different scenarios for the 2080s



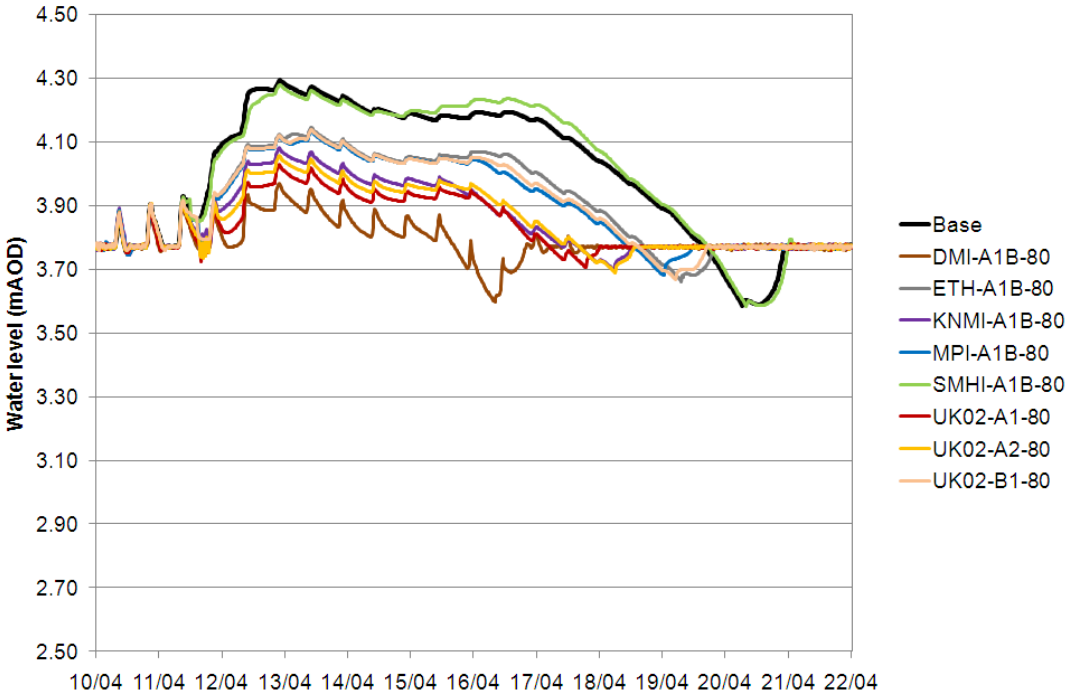
Results for model node at chainage 'GREAT OUSE 181530.00'. Note that the saw-tooth pattern relates to the tides. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-30 Modelled water levels on the Great Ouse just upstream of Brownshill Staunch for the Autumn 2000 event and under different scenarios for the 2080s



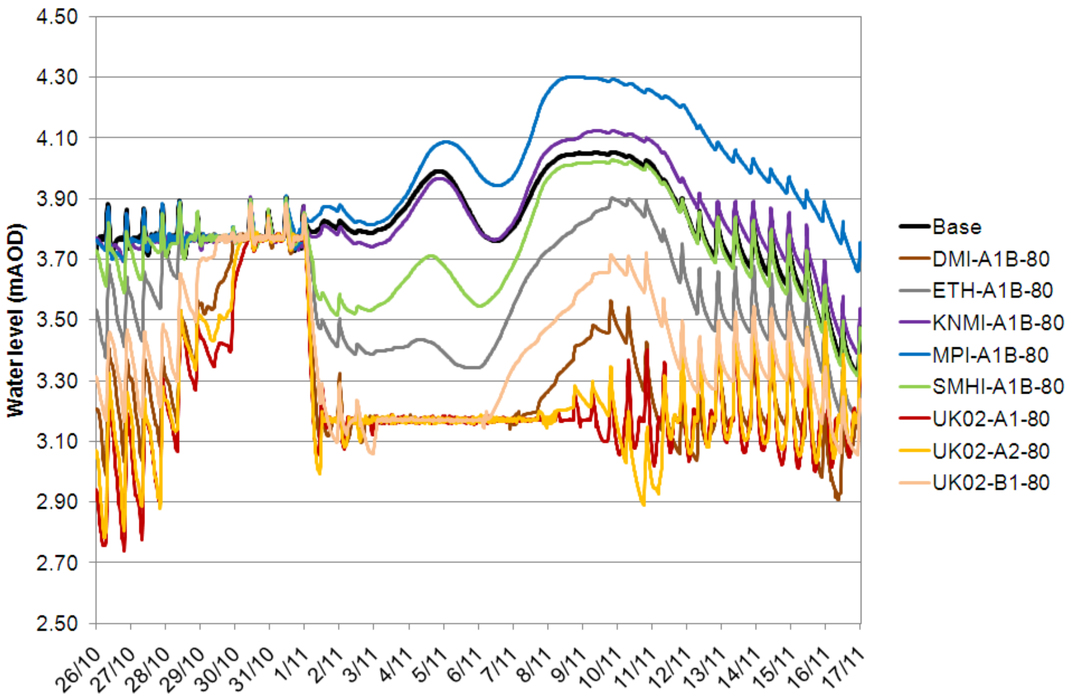
Results for model node at chainage 'GREAT OUSE 181530.00'. Note that the saw-tooth pattern relates to the tides. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-31 Modelled water levels on the Great Ouse at the inflow to the Ouse Washes for the Easter 1998 event and under different scenarios for the 2080s



Results for model node at chainage ‘GREAT OUSE 184701.61’. Note that the saw-tooth pattern relates to the tides. For details of scenarios, see Table 8-1. Original in colour.

Figure A3-32 Modelled water levels on the Great Ouse at the inflow to the Ouse Washes for the Autumn 2000 event and under different scenarios for the 2080s

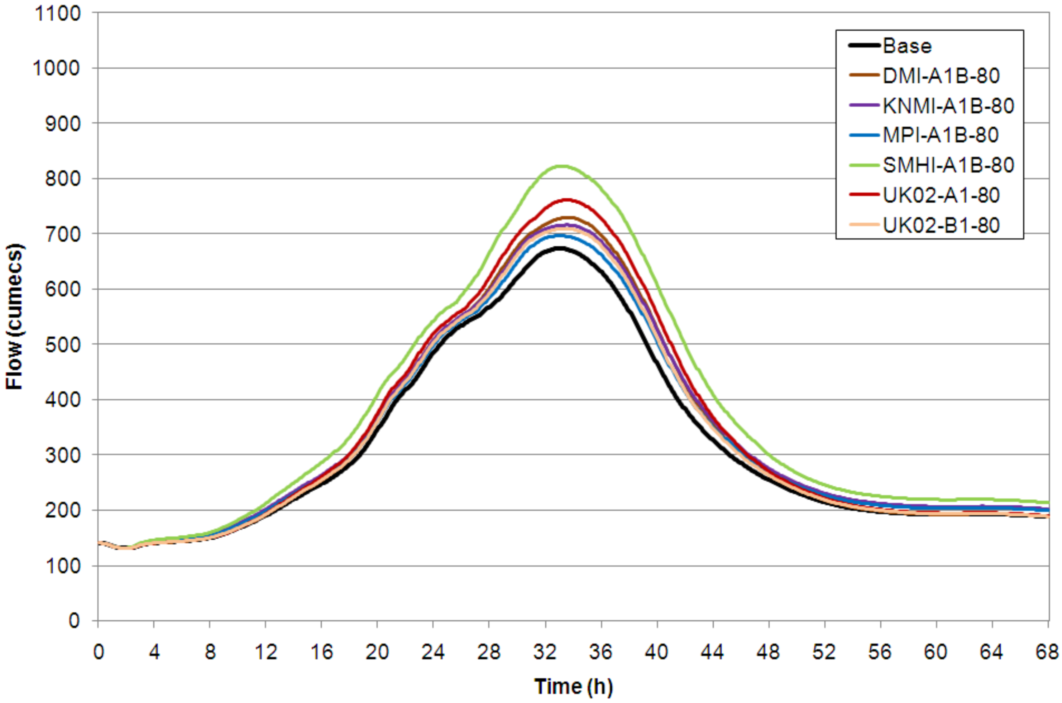


Results for model node at chainage ‘GREAT OUSE 184701.61’. Note that the saw-tooth pattern relates to the tides. For details of scenarios, see Table 8-1. Original in colour.

Appendix 4. Further graphs from the Eden results

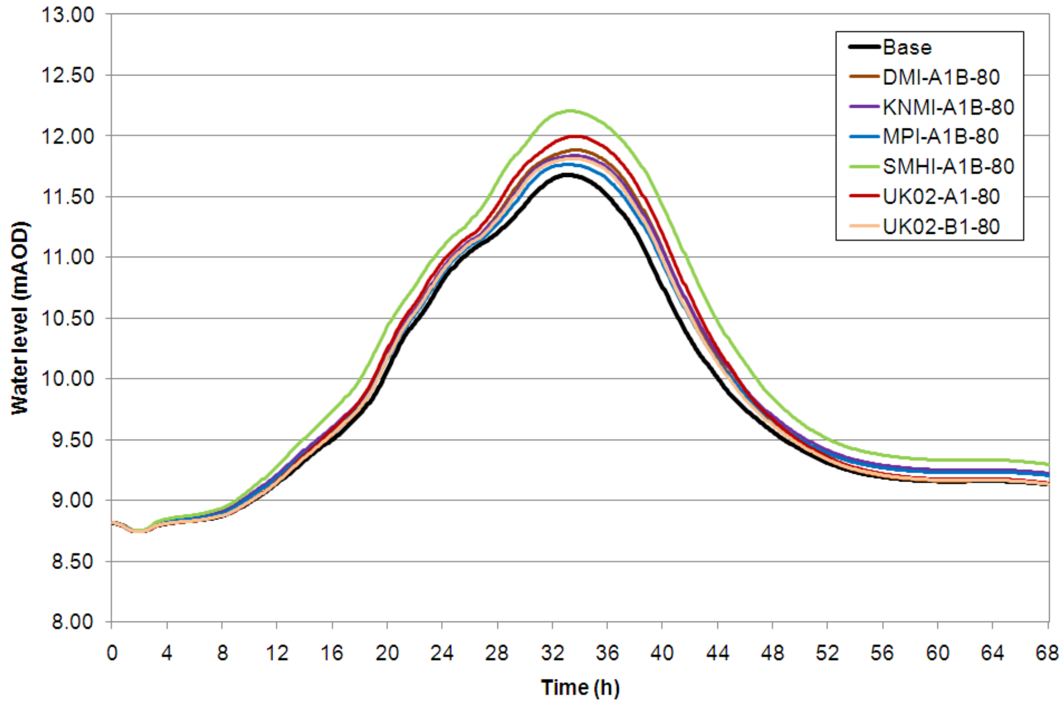
A4.1 Flow and water level for the three modelled events for the Eden at Sheepmount, Carlisle

Figure A4-1 Modelled flow on the Eden at Sheepmount for the February 1990 event and under different scenarios for the 2080s



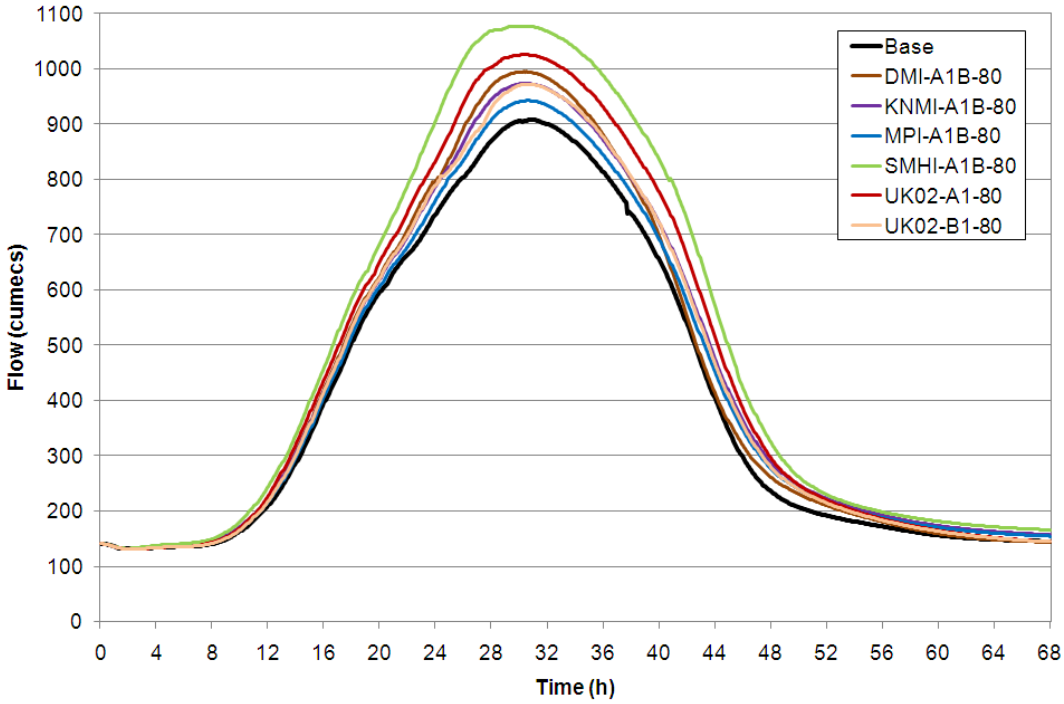
Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-2 Modelled water levels on the Eden at Sheepmount for the February 1990 event and under different scenarios for the 2080s



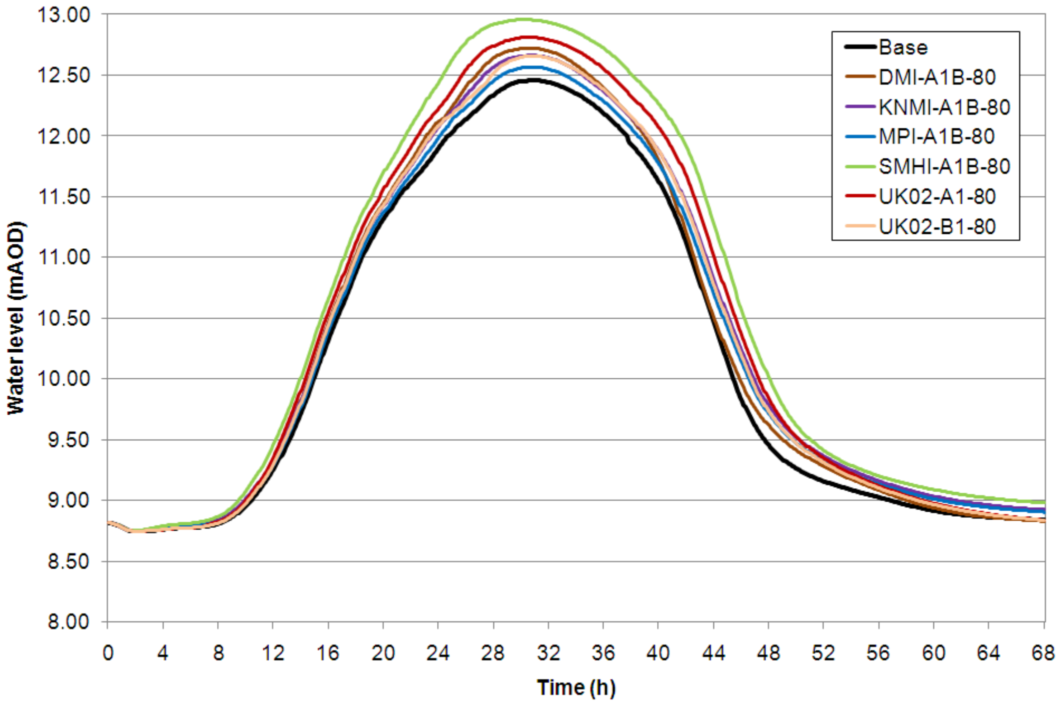
Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-3 Modelled flow on the Eden at Sheepmount for the February 1995 event and under different scenarios for the 2080s



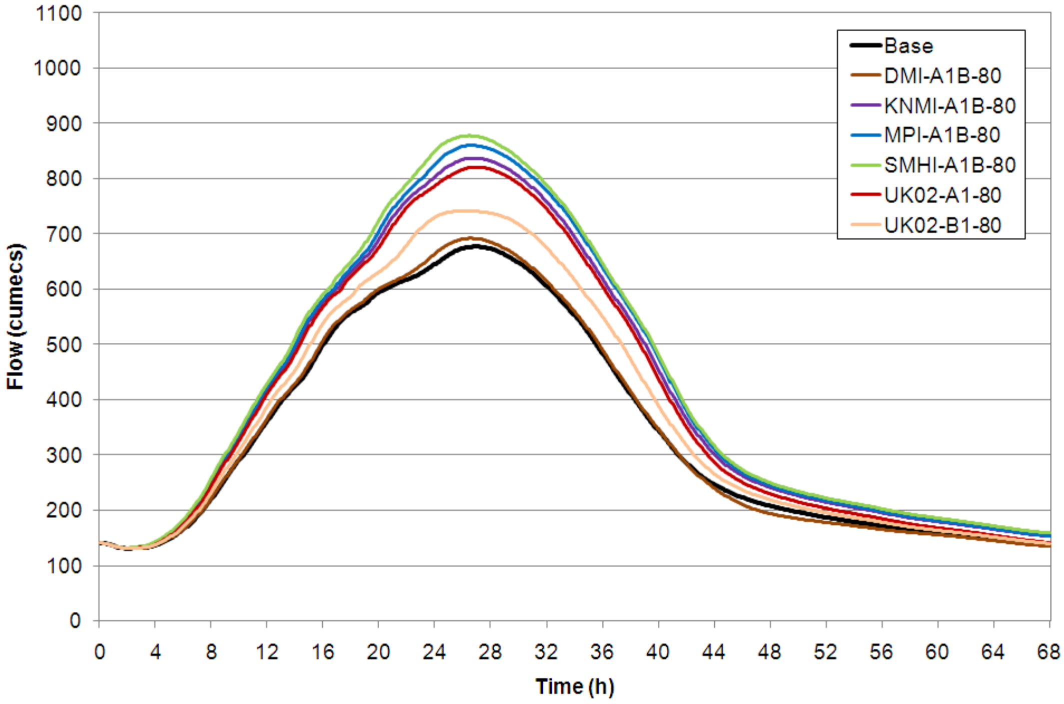
Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-4 Modelled water levels on the Eden at Sheepmount for the February 1995 event and under different scenarios for the 2080s



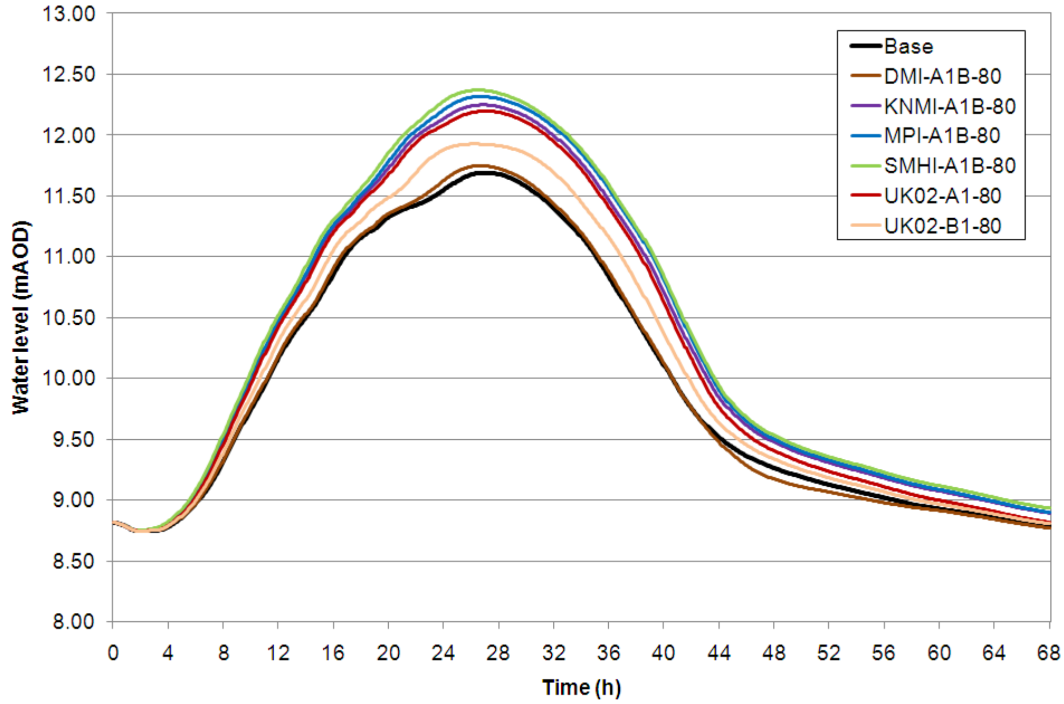
Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-5 Modelled flow on the Eden at Sheepmount for the January 1999 event and under different scenarios for the 2080s



Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-6 Modelled water levels on the Eden at Sheepmount for the January 1999 event and under different scenarios for the 2080s

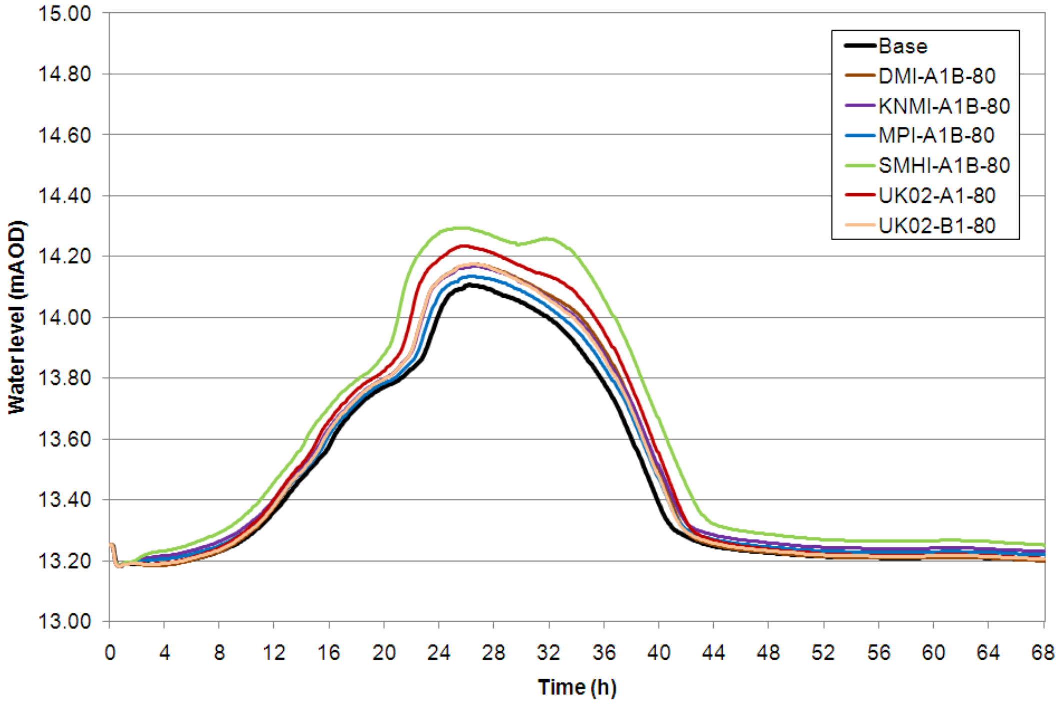


Results for model node 'ED55152'. For details of scenarios, see Table 9-1. Original in colour.

A4.2 Water levels for the three modelled events at other extracted model nodes

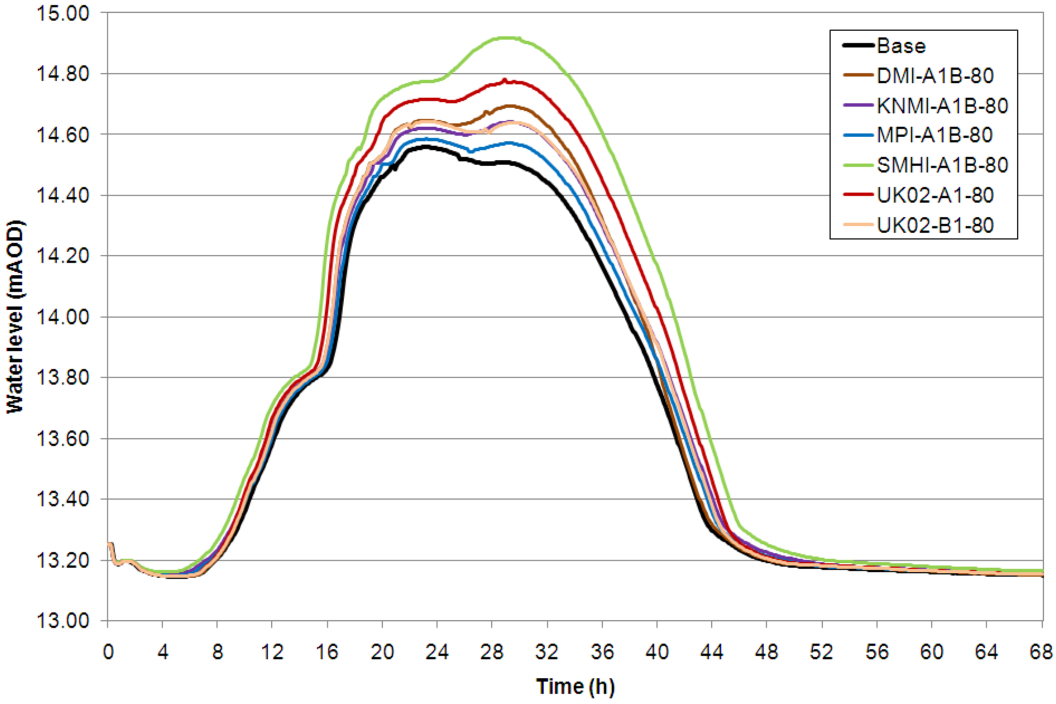
A4.2.1 Petteril at Botcherby Bridge

Figure A4-7 Modelled water levels on the Petteril at Botcherby Bridge for the February 1990 event and under different scenarios for the 2080s



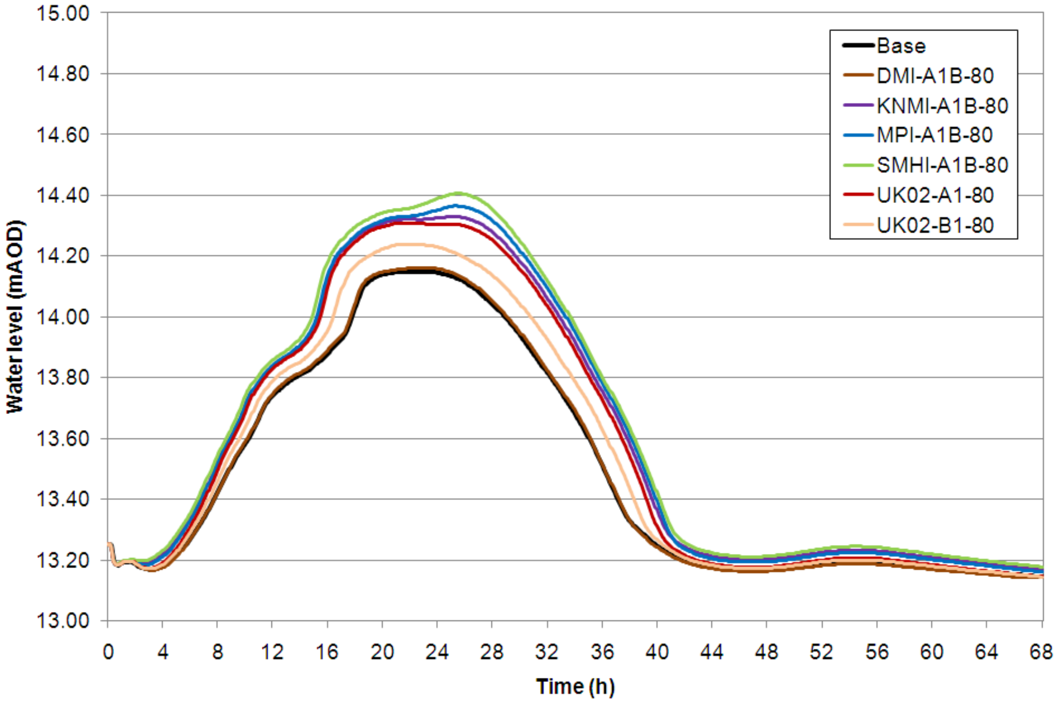
Results for model node 'P11081BU'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-8 Modelled water levels on the Petteril at Botcherby Bridge for the February 1995 event and under different scenarios for the 2080s



Results for model node 'P11081BU'. For details of scenarios, see Table 9-1. Original in colour.

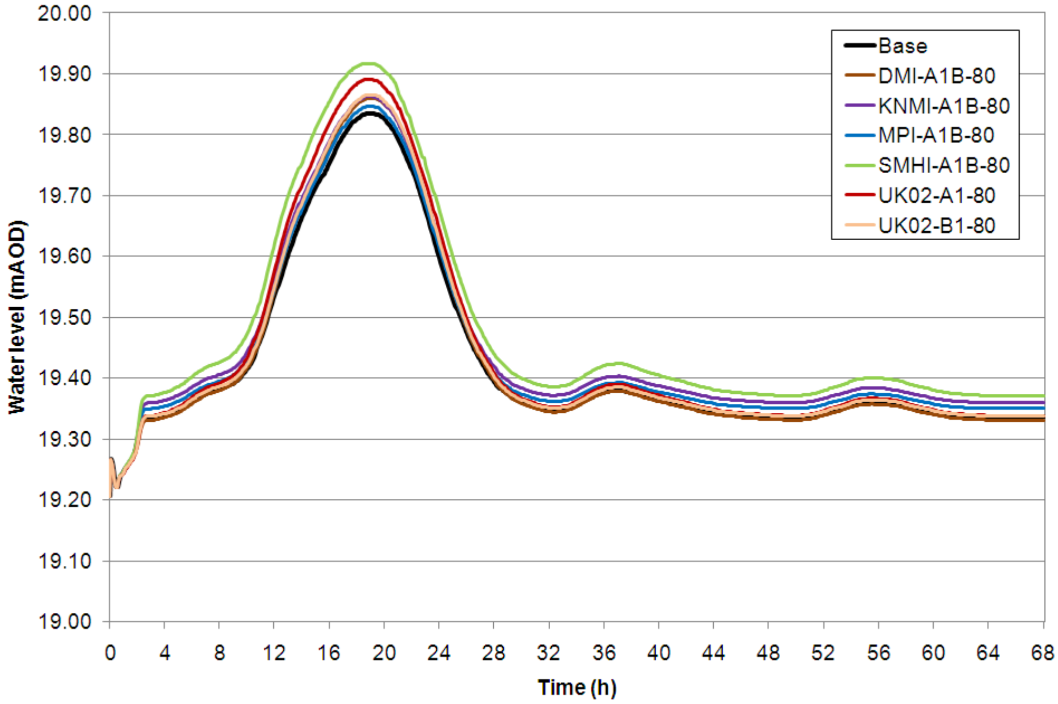
Figure A4-9 Modelled water levels on the Petteril at Botcherby Bridge for the January 1999 event and under different scenarios for the 2080s



Results for model node 'P11081BU'. For details of scenarios, see Table 9-1. Original in colour.

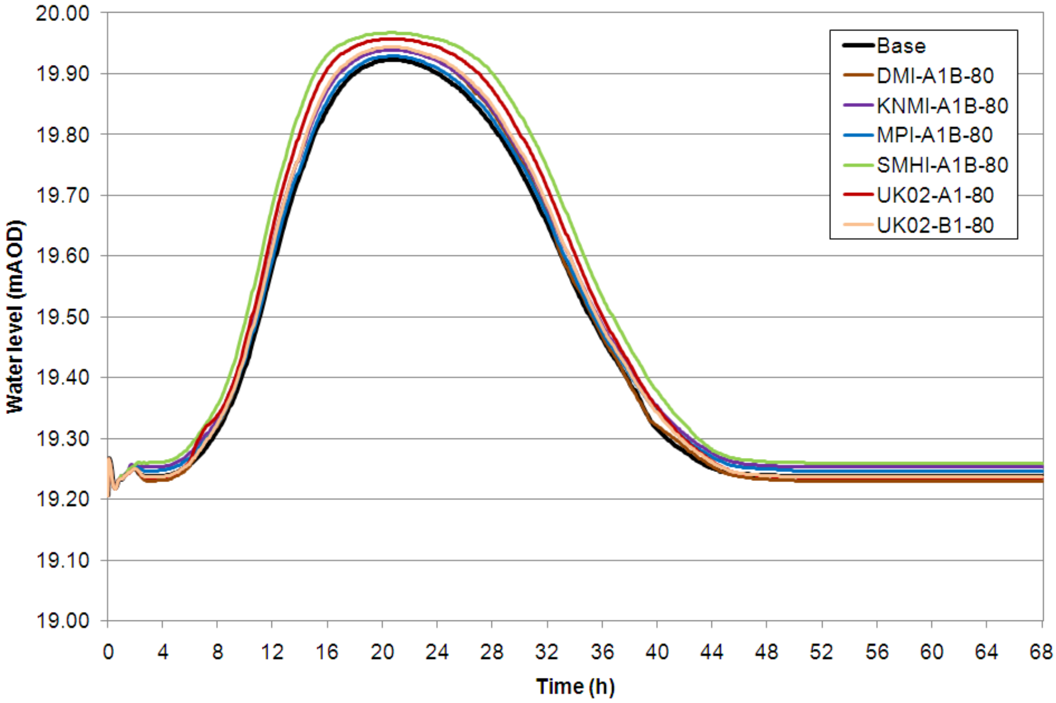
A4.2.2 Caldew just upstream of Holme Head Weir

Figure A4-10 Modelled water levels on the Caldew just upstream of Holme Head Weir for the February 1990 event and under different scenarios for the 2080s



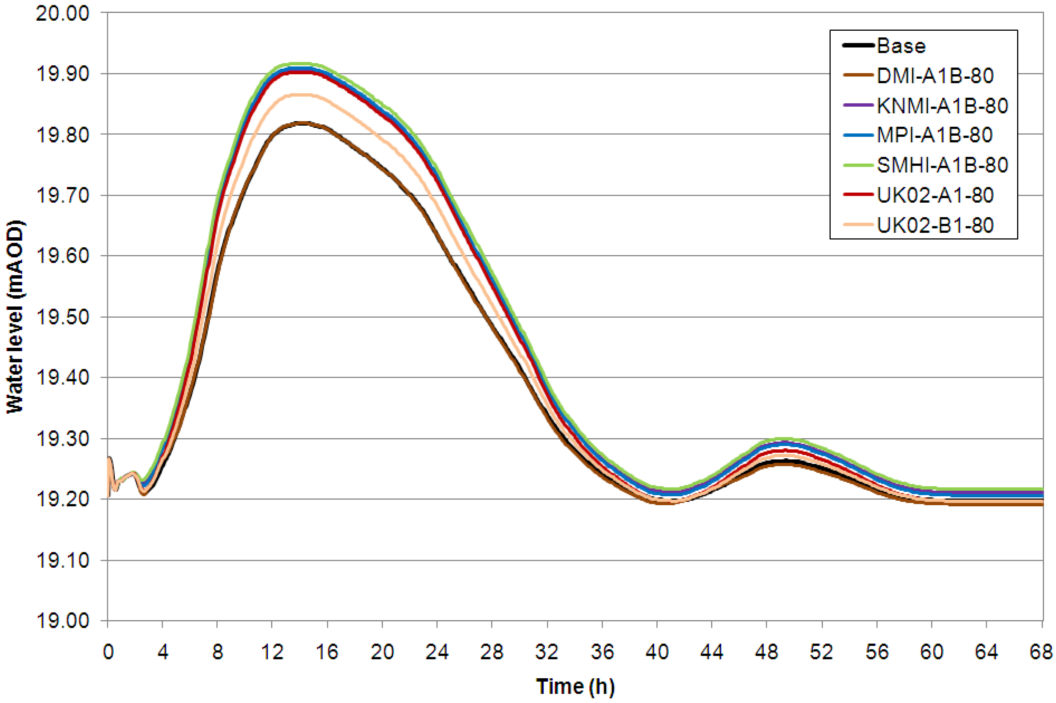
Results for model node 'C20000SU'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-11 Modelled water levels on the Caldew just upstream of Holme Head Weir for the February 1995 event and under different scenarios for the 2080s



Results for model node 'C20000SU'. For details of scenarios, see Table 9-1. Original in colour.

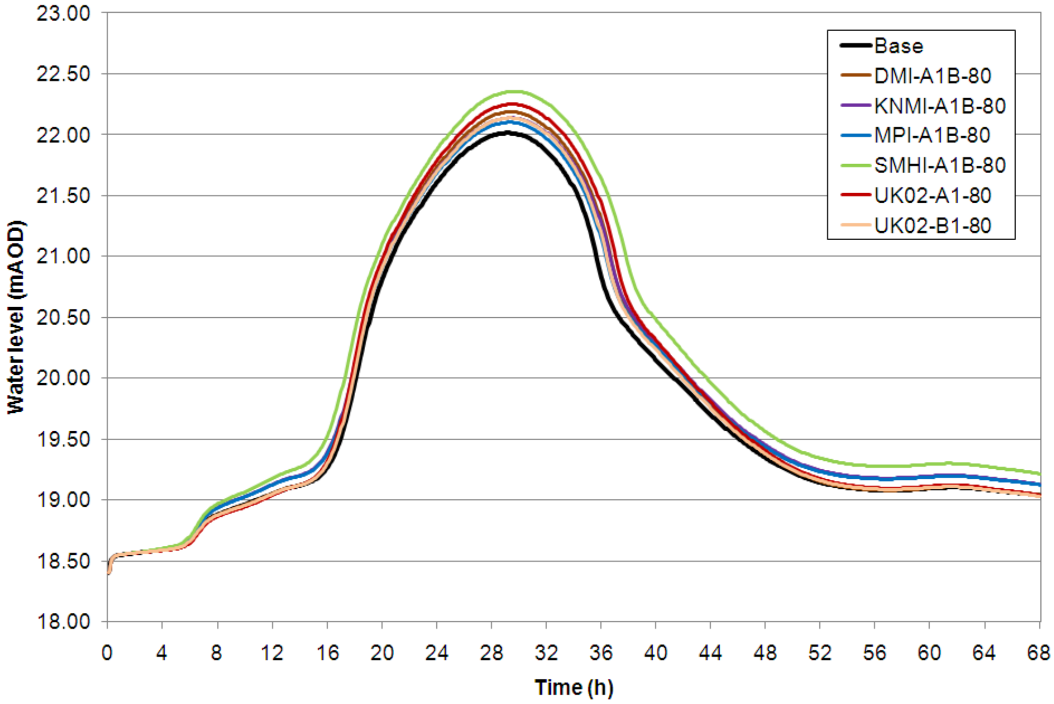
Figure A4-12 Modelled water levels on the Caldew just upstream of Holme Head Weir for the January 1999 event and under different scenarios for the 2080s



Results for model node 'C20000SU'. For details of scenarios, see Table 9-1. Original in colour.

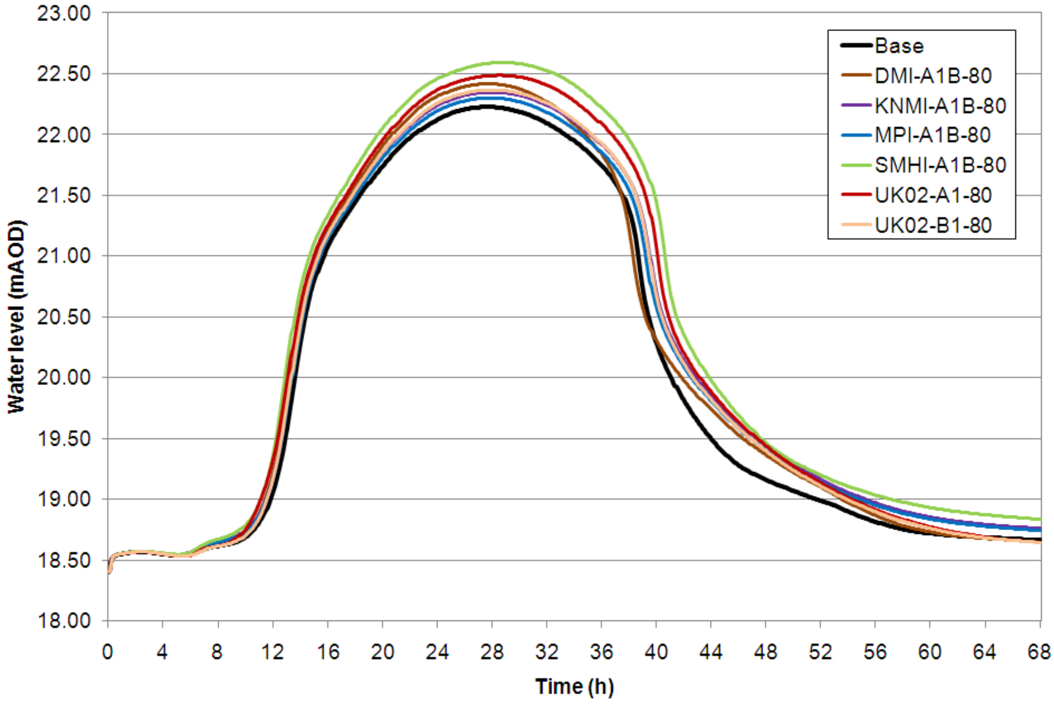
A4.2.3 Eden at Warwick Bridge

Figure A4-13 Modelled water levels on the Eden at Warwick Bridge for the February 1990 event and under different scenarios for the 2080s



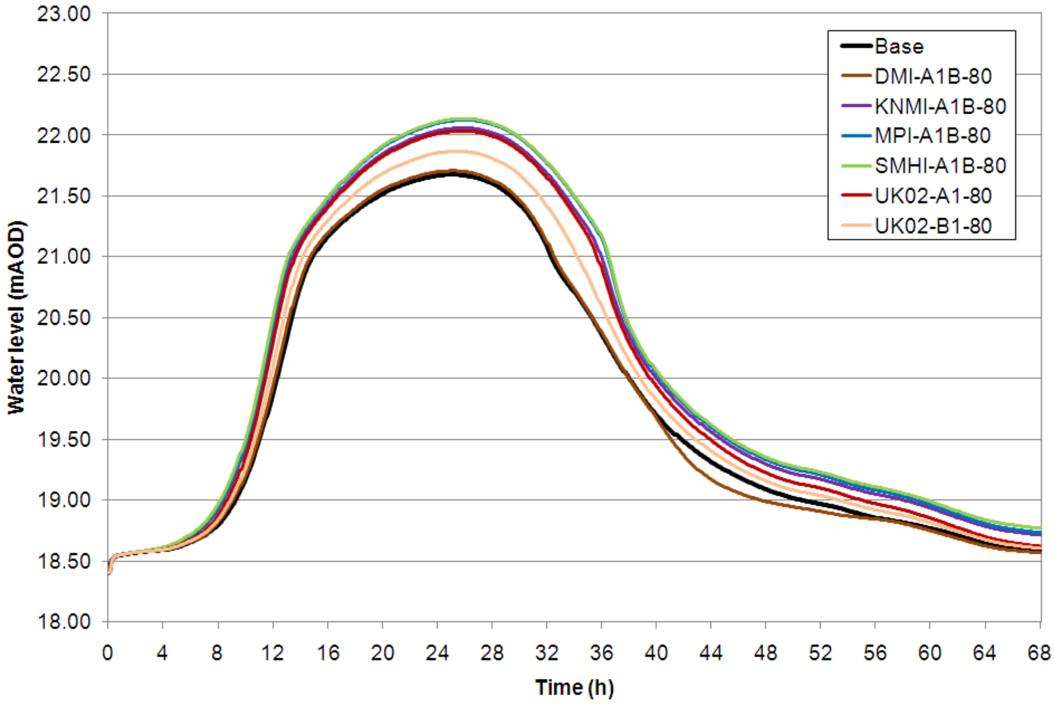
Results for model node 'E77500BU'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-14 Modelled water levels on the Eden at Warwick Bridge for the February 1995 event and under different scenarios for the 2080s



Results for model node 'E77500BU'. For details of scenarios, see Table 9-1. Original in colour.

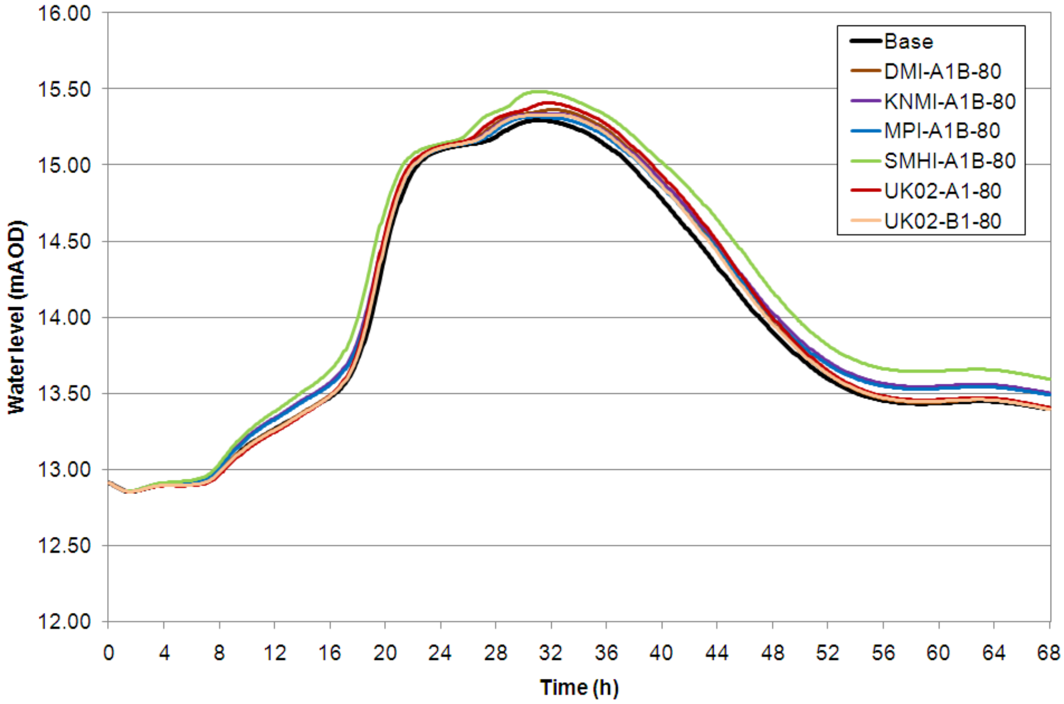
Figure A4-15 Modelled water levels on the Eden at Warwick Bridge for the January 1999 event and under different scenarios for the 2080s



Results for model node 'E77500BU'. For details of scenarios, see Table 9-1. Original in colour.

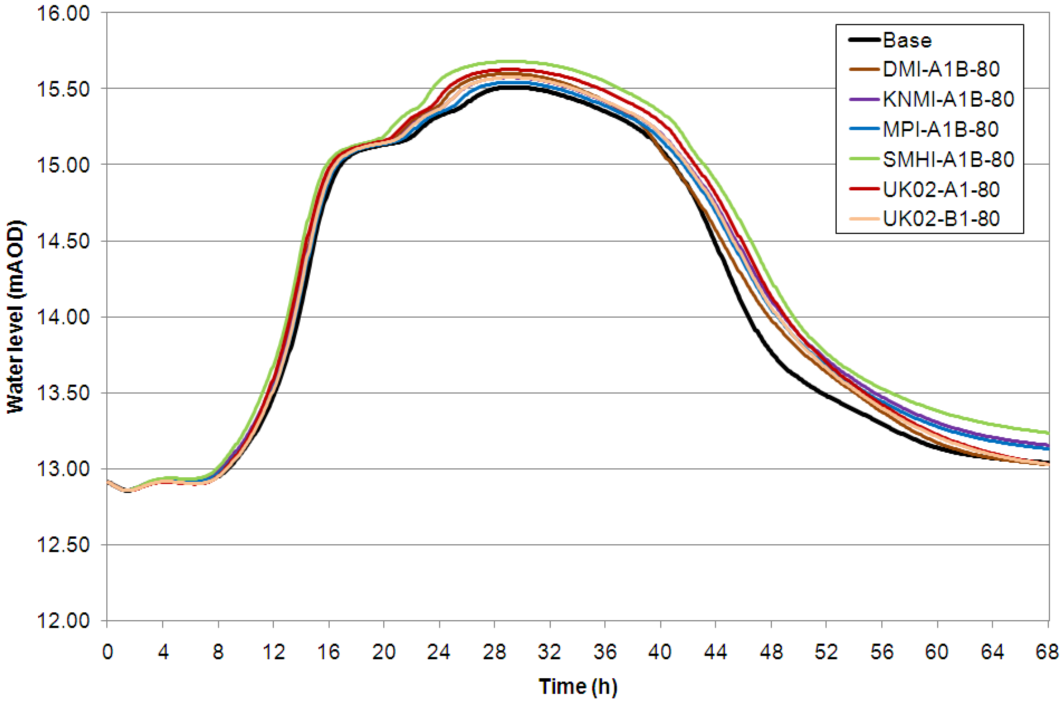
A4.2.4 Eden at the M6 Motorway Bridge

Figure A4-16 Modelled water levels on the Eden at the M6 Motorway Bridge for the February 1990 event and under different scenarios for the 2080s



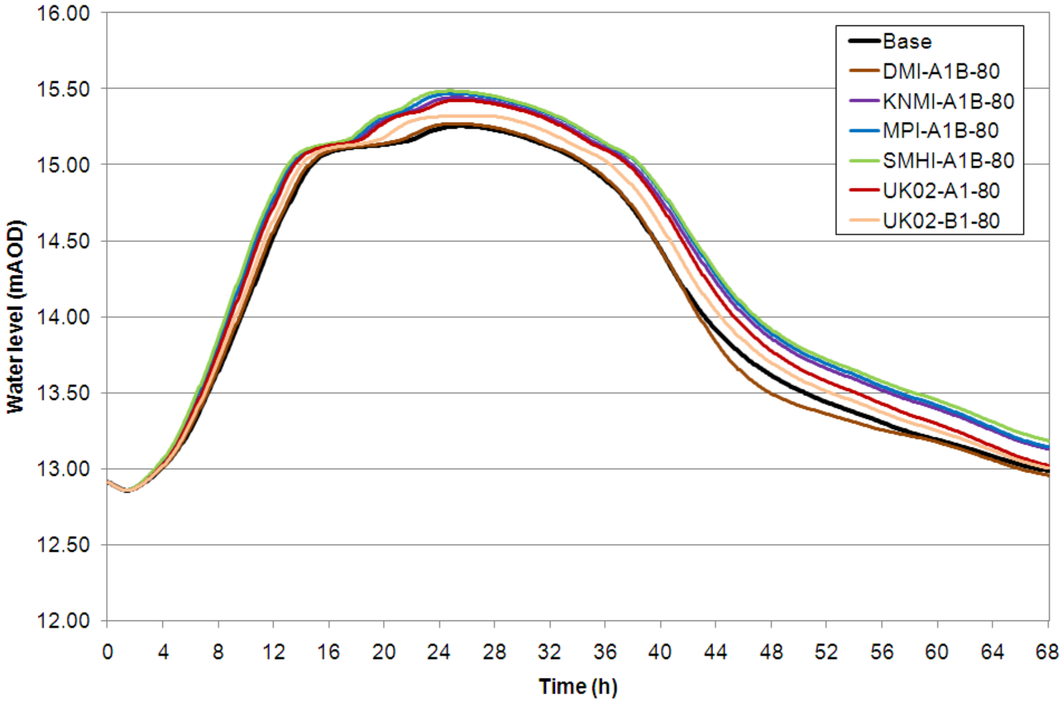
Results for model node 'ED65153U'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-17 Modelled water levels on the Eden at the M6 Motorway Bridge for the February 1995 event and under different scenarios for the 2080s



Results for model node 'ED65153U'. For details of scenarios, see Table 9-1. Original in colour.

Figure A4-18 Modelled water levels on the Eden at the M6 Motorway Bridge for the January 1999 event and under different scenarios for the 2080s



Results for model node 'ED65153U'. For details of scenarios, see Table 9-1. Original in colour.

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