Cranfield University

Catarina Henriques

Hydrology and water resources management in East Anglia and North West England in the context of climate and socio-economic change

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Supervisor: Dr. Ian Holman

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Abstract

Future water resource management is of primary importance to society, economy and the environment. Planning for climate change and adapting to those changes, which requires an understanding of the complex consequences of climate change for the hydrology and human and environmental uses of water, is important for a sustainable future. This research study holistically explored possible implications of global climate change and regional socio-economic change on water resource management in the contrasting regions of East Anglia and North West England. A model was developed to estimate the impacts on the catchment hydrology and on the robustness of the regional water resources system as a consequence of future changes. For a range of plausible futures, the hydrological responses are mainly affected by changes in climate, whereas the impacts on water resources are primarily determined by socio-economic factors that can exacerbate or ameliorate the impacts of climate. Under economically-focused futures, water demand increases at the expense of the environment's allocation of water, and the water quality is deteriorated, which compromises current environmental legislative requirements. Under environmentally-focused futures the environment is protected but at the expense of society and the economy. East Anglia is generally more vulnerable than North West England because water supply is scarcer, river flows are lower and it has a much larger arable agricultural area; *e.g.* under most futures there is a deficit between the water supply and demand. Anticipatory adaptation options within the context of the storylines of each socio-economic scenario were generally successful in managing water demand and supply and avoiding conflicts between the water users. This study illustrates the importance of regional integrated assessments which allow for future socio-economic changes in evaluating the impacts of climate change on the hydrology, water environment and water resources.

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Above all, I want to express my most cordial gratitude to my family and friends for their love.

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List of acronyms

CAMS	Catchment Abstraction Management Strategies
Defra	Department for Environment, Food and Rural Affairs
DPSIR	'Drivers-Pressure-State-Impact-Response' framework
ETa	Actual evapotranspiration, mm
ETp	Potential evapotranspiration, mm
FDC	Flow Duration Curve
FEH	Flood Estimation Handbook
f.s.e.	Factorial standard error
GCM	Global Circulation Model
GM	'Global Markets' socio-economic scenario
GS	'Global Sustainability' socio-economic scenario
HOST	'Hydrology Of Soil Types' classification
IPCC	Intergovernmental Panel on Climate Change
LOSSES	Catchment losses due to evapotranspiration, mm
MAM(7)	Mean annual minimum seven day flow, m^3/s
MF	Mean flow, m^3/s
PREC	Adapted climatological precipitation descriptor for estimating QMED
Q5	Discharge with a 5 percentile exceedance probability from one day flow, m^3/s
Q95	Discharge with a 95 percentile exceedance probability from one day flow, m^3/s
QMED	Median Annual Flood, m^3/s
RAM	'Resource Assessment Management' framework
RE	'Regional Enterprise' socio-economic scenario
RegIS2	Second phase of the 'Regional Climate Change Impact and Response studies in East Anglia and North West England' project
REP	Regional Environmental Priority
RFO	River Flow Objective

RS	‘Regional Stewardship’ socio-economic scenario
SAAR	Standard Average Annual Rainfall, mm
SRES	Special Report on Emissions Scenarios
UKCIP	UK Climate Impacts Programme
UNFCCC	United Nation Framework Convention on Climate Change
URBAN	Urbanisation parameter (Urban + Suburban land classes)
URBEXT	Urbanisation parameter (Urban + Suburban/2 land classes

1 Introduction

1.1 Background

1.1.1 Climate is changing

The average climate experienced over long periods, such as temperature, wind and rainfall patterns, has changed many times in response to natural variability and natural causes such as volcanic activity. However, according to the Intergovernmental Panel on Climate Change (IPCC, 2001b), since the industrial revolution, anthropogenic causes are playing an important role primarily due to the combustion of fossil fuels, agriculture and land-use changes (*e.g.* deforestation), which has increased the atmospheric concentration of aerosols and greenhouse gases. New evidences suggest that most of the warming observed over the last 50 years is attributable to human activities (IPCC, 2001b).

The global-average surface temperature is the dimension which is changing most clearly (Hulme e*t al.*, 2002) and globally, 1990s was the warmest decade and 1998 the warmest year on record (IPCC, 2001b). Observed changes in regional climate have affected many physical and biological systems such as shrinkage of glaciers, changes in sea level (IPCC, 2001b) and decline of some plant and animal populations (IPCC, 2001; Parmesan and Yohe, 2003; Root *et al.*, 2003). There are also preliminary indications that social and economic systems have been affected (IPCC, 2001); some examples include:

- heavy loss of human life and property and environmental damage recorded during El Niño event of the years 1997-1998;
- the number of people affected by floods worldwide has already risen from 7 million in the 1960s to 150 million today;
- 2003's heat-wave was linked to 26,000 premature deaths and cost 13.5 billion US dollars.

Climate is expected to continue to change in the future in spite there are still many uncertainties, which will affect natural and human systems such as forestry, fisheries, water resources, human settlements and human health (IPCC, 2001). Climate models project that in the next 100 years global average temperature could warm 1.4 to 5.8ºC (IPCC, 2001) rising more rapidly than in the last 10,000 years (National Assessment Synthesis Team, 2001). The impacts of climate can be positive (*e.g.* increased tourism and leisure in some regions; and increase in potential crop yields in some regions at mid-latitudes; IPCC, 2001) or negative (*e.g.* increase in the number of people exposed to vector-borne and water-borne diseases; and decreased water availability for populations in some water scarce regions, particularly in the sub-tropics; IPCC, 2001). However, the adverse effects will outweigh the benefits, particularly as climate change increases (HM Government, 2006; Stern Review, 2006).

1.1.2 Mitigation and adaptation options to tackle climate change

Important international roles are being played through European Union (*e.g.* the European Union Emissions Trading Scheme), G8 (*e.g.* 2005 Gleneagles Summit) and United Nation Framework Convention on Climate Change (UNFCCC) processes (*e.g.* 1997 Kyoto Protocol) in order to secure global action to tackle the global problem of climate change.

In order to avoid future dangerous levels of climate change, *i.e.* allowing ecosystems to adapt naturally to climate change, ensuring that food production is not threatened and enabling economic development to proceed in a sustainable manner (http://unfccc.int), the world has agreed to stabilise greenhouse gas concentrations in the atmosphere at the Earth Summit in 1992. Moreover, *the benefits of strong, early action considerable outweigh the costs* and *ignoring climate change will eventually damage economic growth* (Stern Review, 2006). Some of the options to mitigate global warming include reducing the energy use, shifting from carbon-based fossil fuels to alternative energy sources, storing and capturing carbon (*e.g.* forest and cropland management, re-vegetation) and even geo-engineering not yet advocated by police makers (Pielke Jr., 1998) such as seeding oceans with iron to generate algal blooms.

Industrialised countries have mandatory limits on greenhouse gas emissions imposed by the Kyoto Protocol that came into force during 2005. Mechanisms under Kyoto Protocol agreed in Bonn 2001, allow these countries to trade their carbon emissions and to invest in emission reducing projects in another industrialised country (Joint Implementation) or in developing countries (Clean Development Mechanism) as alternative to emission reductions in their own countries. United States and Australia that did not ratify the Kyoto Protocol and China, India, Japan and South Korea have agreed in 2005 the Asia-Pacific Partnership for Clean Development and Climate, which allows member countries to set their goals for reducing emissions individually.

However, mitigation cannot be the entire response to the threat of climate change. Firstly, societies might not be able to institute the mitigation activities needed to reduce increases in greenhouse gases. The 5% average reduction in greenhouse gas emission by around 2010 (relative to 1990) target set in Kyoto Protocol is related to the nations that account for about 55% of present global carbon emission, but will produce only 25% of the emission growth over the next 20 years (Parry *et al.*, 1998).

- Even assuming that Kyoto is fully implemented, estimates suggest that this would reduce global warming by 2050s only by about 0.05ºC (Parry *et al.*, 1998) therefore resulting in only small reduction in the climate changes to be expected over the next century (Pittock and Jones, 2000).
- Most of future growth in emissions is expected to occur in the fast developing countries that view the industrialised world as the cause of the climate change problem and, due to equity reasons, have no mandatory enforcement mechanism to control their greenhouse gas emissions.

Secondly, a reduction in greenhouse gases might not mean less change in climate. Much of the change in climate over the next 30 to 40 years has already been determined by historical emissions and because of inertia in the climate system (Hulme e*t al.*, 2002). Moreover, natural climate variability might change in surprising and unpredictable ways. Therefore, complementing mitigation, we will have to adapt finding sustainable solutions to cope with a degree of inevitable climate change irrespective of whether global future emissions are reduced (Pielk Jr., 1998; Hulme e*t al.*, 2002). Besides, in order to assess the need for mitigating global long-term change, research is identifying the limits of adaptation, or the *dangerous levels* of climate change (Yohe, 2000; Pittock and Jones, 2000).

Adaptation refers to *adjustments in ecological-social-economic systems in response to actual or expected climate stimuli, their effect or impacts* (Smit *et al.*, 2000) and involves cascading decisions across individuals, firms and civil society, to public bodies and governments at local, regional and national scales, and international agencies (Adger *et al.*, 2005). There are two dimensions of adaptation (HM Government, 2006 and Adger *et al.*, 2005):

- building adaptive capacity through creating information and conditions (regulatory, institutional and managerial); and
- transforming that capacity into action that help to reduce vulnerability to climate risks and exploit opportunities.

The effects of climate change will most likely be more severe for natural ecosystems than for human systems (Smith, 1997; IPCC 2001) due to their different adaptive capacity. Ecosystems are dynamic, constantly changing and adapting in response to a multitude of factors (*e.g.* migration and behavioural or genetic alteration). Ecologists have high confidence that climate change will produce a shift in species distributions north ward and a range expansion of warm-water and cool-water species into higher latitudes (Gleick and Adams, 2000). However, with climate change, changes may exceed the ability of species to adapt autonomously and natural systems may undergo significant and irreversible damage (IPCC, 2001; Gleick and Adams, 2000). For example, the alpine meadows in the Rocky Mountains are likely to disappear entirely in some U.S. areas (National Assessment Synthesis Team, 2001). The vulnerabilities and adaptability of human systems to climate change vary with geographical location and time, and also depend upon social, economic and environmental conditions (IPCC, 2001). However, because planned adaptation can complement and influence autonomous adaptation of socio-economic systems (Fankhauser, 1999; Smit *et al.*, 2000), human adaptive capacity is high, especially in developed countries (IPCC, 2001).

The importance of adaptation response to climate change has been internationally recognised (*e.g.* by the UNFCCC, Delhi Ministerial Declaration on Climate Change and Sustainable Development and IPCC). Though, adaptation has received very little attention compared with mitigation both by academics and police makers (Parry *et al.*, 1998; Fankhouser, 1999; Scheraga and Grambsch, 1998; and Pielke, Jr. 1998). Some of the reasons to discourage adaptation include the anti-mitigation and therefore anti-environmentalist position (Scheraga and Grambsch, 1998) and the defeat to negotiators (Scheraga and Grambsch, 1998; Pielke, Jr. 1998 and Parry *et al.* 1998). But now the role of adaptation is increasingly considered in academic research and its significance is being recognised in national (*e.g.* 'ADaptation And Mitigation Strategies: Supporting European Climate Policy' ADAM project; http://www.adamproject.eu) and international policy debates on climate change (Smit *et al.*, 2000).

1.1.3 The role of anticipatory adaptation

Societies, organisations and individuals are now contemplating adapting to altered future climatic conditions (Adger *et al*., 2005). The issue for police makers is whether adaptation should be reactive or anticipatory (Smith 1997). To many, it is preferred to react to climate change rather than to try to anticipate it (Smith, 1997; Fankhauser *et al*., 1999; Pittock and Jones, 2000). Often heard statements (Fankhauser *et al*., 1999) are *with a significant change in climate not expected for at least two decades, there is no need for immediate adaptation* and *adaptation to climate change will be largely autonomous and will not require advance strategic policy intervention*. And even for climate influenced decisions, there is a risk that a decision maker may tacitly assume that climate is not an important part of the decision problem (Willows and Connell, 2003).

Anticipatory adaptation is a risk management policy (Scheraga and Grambsch, 1998). It is difficult to assess adaptation options due to the uncertainty about how regional climate and variability will change (Smith, 1997; Scheraga and Grambsch, 1998) and about the long term frame over which climate change may be manifested *i.e.* how soon climate change effects will happen (Smith, 1997; Burton 1997; Smit *et al.*, 2000). Moreover, there are also high uncertainties on the biophysical changes resulting from a change in climate and on how nature and society will adapt (Pielke, Jr., 1998; Smith, 1997; Scheraga and Grambsch, 1998; Pittock and Jones, 2000; Willows and Connell, 2003).

However, a timely recognition of the need to adapt and an anticipatory adaptation are very important for a successful response to climate change by reducing vulnerabilities to its effects, exploiting opportunities and enabling reactive adaptation to happen more efficiently (Smith and Lenhart, 1996; Fankhauser *et al.,* 1999; Smith, 1997; Scheraga and Grambsch, 1998; Pielke Jr., 1998; Smit *et al*., 2000). It is imperious to prioritise and implement anticipatory adaptation responses, which are flexible due to the uncertainty (Scheraga and Grambsch, 1998) and economically justified (Smith and Lenhart, 1996; Smith 1997), with regards to:

- Avoid irreversible or catastrophic impacts, such as extinction of species (Smith, 1997)
- Long time frame decisions, *e.g.* sitting nature reserves and creating water infrastructures (Smith, 1997; Fankhauser *et al.,* 1999).
- Where continuation of current trends makes it more difficult to impose adaptive measures later, for instance continued development of costal areas (Smith, 1997; Smith and Lenhart, 1996; Fankhauser, 1999).

Some of these measures make sense whether or not effects of climate change are realised because they help to address current climate variability (Smith and Lenhart, 1996; Scheraga and Grambsch, 1998). These are no-regret strategies, for instance, enhanced responses to urban heat waves can save lives now (Scheraga and Grambsch, 1998). Moreover, improved adaptation to current climate is a step in preparation for a longer term climate change (Burton, 1997; IPCC, 2001; Yohe, 2000; Smit *et al.*, 2000).

1.1.4 The need for regional holistic impact assessments for guiding anticipatory adaptation

Adaptation has mainly been studied in the context of impact analysis (Fankhauser *et al.*, 1999). Impact assessments explore the possibilities to see what management (planned adaptation) can accomplish, and what level of climate change is unacceptable because it is impossible or too costly to adapt (Pittock and Jones, 2000). Impact assessments can guide local or regional management or policy developing adaptive responses in anticipation of future change (Scheraga and Grambsch, 1998; Smit *et al.*, 2000; Pittock and Jones, 2000). It is very important that assessments provide correct information decreasing the possibility that less effective adaptation, and in some cases maladptive strategies, which can have greater risks that the ones posed by the climate change itself, are chosen (Scheraga and Grambsch, 1998). Therefore, although climate change is a global concern, assessments of impacts and adaptabilities require consideration of their local context as a part of a wide socio-economic context including the multiple stressors (climate and non-climate related) on the affected and inter-dependent systems (Adger *et al.*, 2005; Pittock and Jones, 2000; Smit *et al.*, 2000; Burton, 1997; Scheraga and Grambsch, 1998; Parson e*t al.*, 2003), as explained as follows.

Human and natural systems are affected by current climatic conditions and non-climatic social and economic factors such as increasing resource demands and unsustainable management practices (IPCC, 2001). For instance, countries that experience low rates of growth, rapid increases in population and ecological degradation are systems already under stress, which may become increasingly vulnerable to potential changes. Climate change represents an important additional stress. It is therefore important to adapt to the existing stresses under current climate and to assess how climate change might exacerbate or ameliorate those stresses (Scheraga and Grambsch, 1998).

Moreover, adaptation to systems in response to non-climatic stimuli may unintentionally or incidentally serve as an adaptation to climate change or variability (*e.g*. wetland's preservation may also reduce vulnerability to sea-level rise (Smit *et al.*, 2000)) or, on the other hand, can exacerbate negative impacts of climate (Smit *et al.*, 2000; Smith, 1997; Pittock and Jones, 2000). Climate change will have wide-ranging effects (Scheraga and Grambsch, 1998) and successful adaptation options might impose externalities at another spatial (Yohe, 2000; Adger *et al.*, 2005; Scheraga and Grambsch, 1998) or temporal scale (Adger *et al.*, 2005). For instance, successful adaptation in the short term might not be successful in the long term and an action effective for an adapting agent might reduce another agent's adaptive capacity (*e.g*. climate change is likely to exacerbate existing stresses on fish stocks, but increasing stock through colonisation of new areas to increase productivity might impoverish the biodiversity of ecosystems (Scheraga and Grambsch, 1998)). Different adaptation options will often be associated with differing portfolios of consequent risks, even when they offer the same level of residual climate risk (Willows and Connell, 2003). The tradeoffs between opportunities to be exploited and risks to be avoided pose a serious challenge to public policy makers and resource managers (Scheraga and Grambsch, 1998).

However, current approaches are lacking some of the abovementioned requirements.

Research strategies have been reported on the impacts of climate change on specific sectors where often, explicitly or implicitly, present socio-economic conditions are assumed to continue unchanged (Holman e*t al*, 2005a).

Whilst the use of climate scenarios as inputs into vulnerability, impact or adaptation assessments is well established, there is far less experience of using socio-economic scenarios (UKCIP, 2001).

Sectoral assessments assuming that the projected future climate will take place in a world with a society and economy similar to today are common because attempting to project potentially relevant socio-economic characteristics in all their detail can become an impossibly complex and indefensibly arbitrary exercise (Parson *et al*., 2003). It has been argued that reliable prediction of such complex and uncertain processes is not possible (Parson e*t al.*, 2003, Parson e*t al.*). However, the more common sectoral approach taken to avoid this complexity problem is even less defensible (Parson e*t al.*, 2003) and such efforts are undermined (UKCIP, 2001). The paradigm shift is therefore required from sectoral concerns to integrated assessments[1] of landscapes and economies (*e.g.* Hadmer e*t al.,* 1999, Smit e*t al.,* 2001).

Progress to date, particularly with regard to integrated modelling, has focused largely on mitigation issues at the global or regional scale and only secondarily on issues of impacts, vulnerability, and adaptation (Arnell and Liu, 2001).

In order to succeed in anticipatory adaptation so crucial for the sustainability; it is essential to address impacts, vulnerability and adaptation at a regional level. Evidence is that IPCC is working towards the fourth assessment report that will give particular emphasis on to regional impacts and adaptation (HM Government, 2006). In addition, policy makers and stakeholders are also increasingly demanding impact assessments which produce policy-relevant guidance on the local impacts of global climate change (Holman *et al.*, 2005a). However, there are few studies that describe the results of integrated assessments at the regional scale as opposed to the national and global scale (Holman *et al.*, 2005a).

[1] Integrated assessments are defined by IPCC (2001) as combining results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

1.1.5 The challenges for water resources management

Complex impacts of climate change affect all sectors of society (IPCC, 2001; Gleick and Adams, 2000). This research is focused on water resources. *In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to the water systems* (Gleick and Adams, 2000). Climate change affects the hydrological cycle, through changes in precipitation, temperature and evapotranspiration. These future hydrological changes have implications for society, economy and environment (*e.g.* aquatic ecosystems) impacting both water quantity and quality. The hydrological behaviour and water resources management are also sensitive to the local socio-economic indirect consequences of global climate change, such as changes in the agricultural land cover, to non-climatic changes such as urban development, and to a combination of both such as altered consumption trends (Figure 1-1).

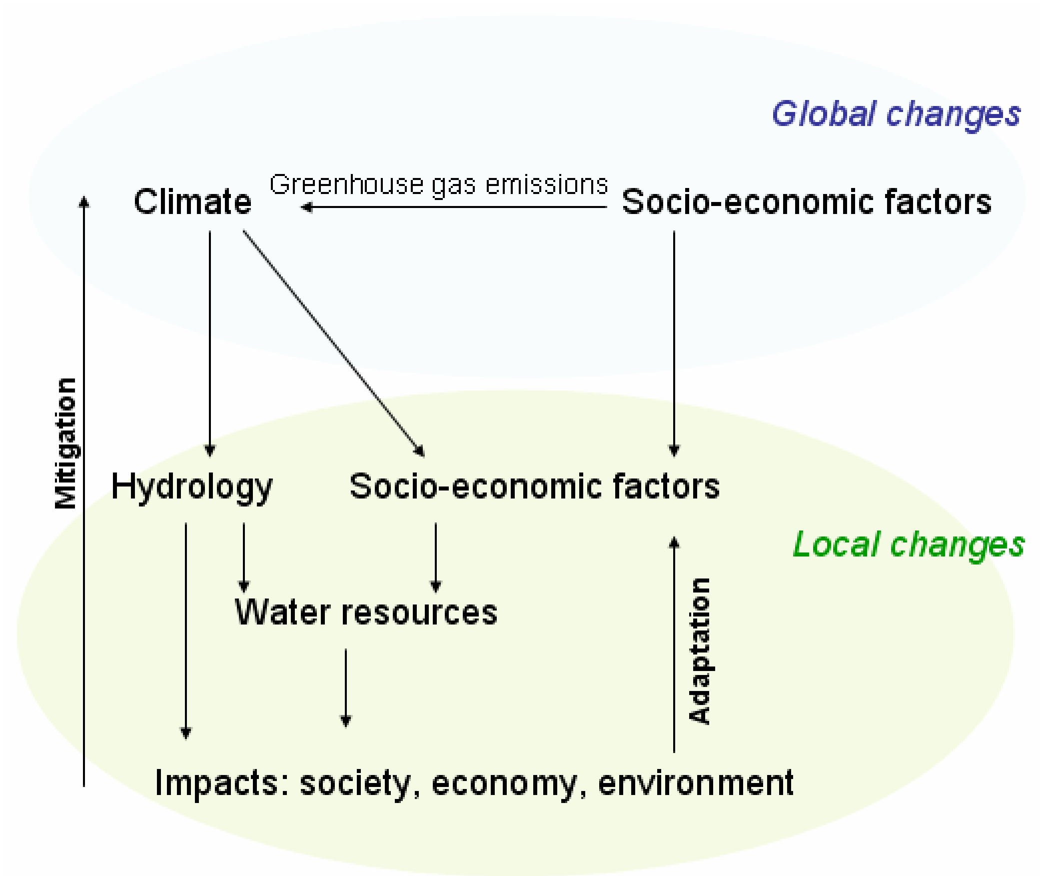


Figure 1-1: Diagrammatic representation the impacts of climate and socio-economic changes on the hydrology and water resources from the global to the local levels.

The importance of water underscores the necessity of understanding how a change in global climate could affect the availability and variability of regional water resources (Xu *et al.*, 2005) as well as the frequency of extreme events such as droughts (Varies *et al.*, 2004). The study of adaptation options is also fundamental to better inform water managers in order for them to prepare to adapt in anticipation to the future potential impacts of climate change (*e.g.* long-term water resources design (Varies *et al.*, 2004)). Therefore, a significant amount of research has been done on the connections between climate change and water resources for process research and for developing water and catchment management strategies (Jacobs *et al.*, 2000; Xu *et al.*, 2005).

Meeting the new challenges on water resources management, implies the quantification of climate change impact on basin-scale hydrology (Varies *et al.*, 2004). Certain aspects of water resources are very sensitive to both climate and to how the complex water systems are managed (Gleick and Adams, 2000); therefore, *the complexity of the impacts of climate and socio-economic changes should be addressed by looking at the combined impacts of changes on hydrology and on the human and environmental use of water* (Arnell and Liu, 2001). It is now well accepted that modelling seems to be the only resort to address this complex problems (Xu *et al.*, 2005). Therefore, the regional scale simulation of hydrological consequences of climate change has received increasing attention (Xu *et al.*, 2005), but *competent analysis of vulnerability with adaptation is difficult to perform* (Yohe, 2000).

Only a small number of studies have looked at the combined impacts of changes on hydrology and on the human and environmental use of water (Arnell and Liu, 2001). A better integration is needed of human and ecological risk assessment relative to assessments of climate change (Jacobs *et al.*, 2000). Moreover, integration of water with other sectors, such as agriculture and food production, is viewed to have a high priority for researchers (Gleick and Adams, 2000). For example, the US National Assessment prepared five separate sectoral reports on water, agriculture, human health, coastal ecosystems and forest, but *truly integrated analysis of possible impacts has not yet been done* (Gleick and Adams, 2000).

Integration of socio-economic changes including the indirect effects of climate change on hydrology and water resources has not been widely done (Gleick and Adams, 2000) and virtually all studies have assessed the implications of future climate for the current water management system (Arnell, 1998) and assuming that future managers will be working under the same rules and objectives as current managers (Arnell, 1999). However, the *impacts of climate change needs to be evaluated in a holistic assessment of the effects of our changing future, as in practice the water management system will have evolved and adapted by the time the future climate arrives* (Arnell, 1998).

Even fewer studies explicitly considered possible adaptation strategies, mostly ignoring adaptation by water managers, or asserting that water managers will be able to adapt (Arnell and Liu, 2001). More work is needed to evaluate the relative costs and benefits of non-structural management options in the context of a changing climate, such as demand management and water-use efficiency (Gleick and Adams, 2000). Impact assessments should explore the possibilities to see what management (planned adaptation) can accomplish, especially given that *characteristics of the water management system are very important buffer between hydrological effect and impact on users and the environment* (Arnell and Liu, 2001) and *non-climatic changes may have a greater impact on water resources than climate change* (Arnell and Liu, 2001).

1.2 Aim and Objectives

1.2.1 Aim

To evaluate the relative importance of climate change and socio-economic changes on water resource management in East Anglia and North West England.

1.2.2 Objectives

1. To develop a model capable of simulating the impacts of climate and socio-economic changes on water resources management.
    a. To design conceptual model linkages to integrate the water sector model with climate and socio-economic scenarios, and other sectoral models (agriculture, urban development, flooding, and biodiversity) within the second phase of the ‘Regional Climate Change Impact and Response studies in East Anglia and North West England’ project (RegIS2) integrated assessment modelling framework.
    b. To develop an empirical catchment-scale hydrological model.
    c. To develop a regional water demand model.
    d. To develop a regional model to simulate the water availability.
2. To apply the integrated assessment framework methodology.
    a. To investigate the direct and indirect impacts of climate and socio-economic changes on the hydrology and water resource management.
    b. To evaluate the potential of adaptation strategies to reduce the impacts on (and maximise opportunities to) individuals, society, and/or environment caused by changes on the hydrology and water resources.

3. To assess the use of integrated assessment at the regional-scale for evaluating the importance of climate and socio-economic changes on water resource management.

1.3 The RegIS2 project

This research study contributed to the second phase of the 'Regional Climate Change Impact and Response studies in East Anglia and North West England' project (RegIS2) funded by the Department for Environment, Food and Rural Affairs (Defra). RegIS2 (Holman and de Vries, 2005) developed and applied a methodology for stakeholder-led, climate change integrated impact assessment to evaluate regional scale impacts and adaptation options. The four major sectors driving landscape change (agriculture, coasts / floodplains, water resources and biodiversity) and scenarios of climate and socio-economic change were integrated. The project developed the use of computationally simple modelling techniques, within a user-friendly interface, to make the RegIS2 methodology available to the wider stakeholder community including policy advisors.

The model development has been conducted in the context of RegIS2, thus it is important to identify the boundaries of the PhD research regarding Objective 1. The 'Water Resources' and the 'High River Flows' models were conceptually developed and programmed in Visual Basic.NET under the scope of the PhD research. These models were integrated with other sectoral models and climate and socio-economic scenarios within the RegIS2 Integrated Assessment modelling framework that beneficiated from the 'Drivers-Pressure-State-Impact-Response' (DPSIR) approach (Holman *et al.*, *Submitted*) represented in Figure 1-2. The integration with other models involved liaising with other model developers to identify input/output model linkages and feedbacks. The integration with socio-economic scenarios was concerned with deriving pressure variables/inputs to the developed models based upon the RegIS2 storylines of the socio-economic scenarios. Finally, the developed models were integrated into the RegIS2 interface with the other existing models (Holman and de Vries, 2005) by a project partner.

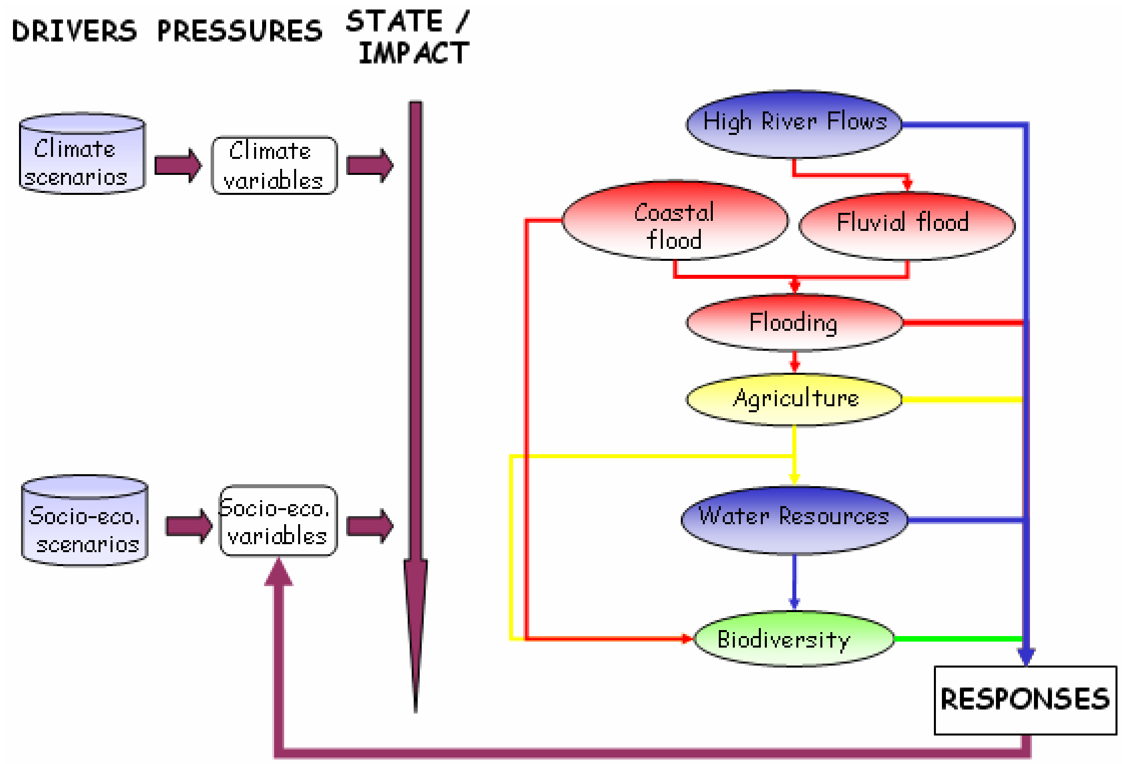


Figure 1-2: Simplified representation of RegIS2 Integrated Assessment modelling framework which benefits from the 'Drivers-Pressure-State-Impact-Response' that facilitates investigation of the interactions between the driving forces of change ('drivers-pressure'), the sensitivity of impact indicators ('state-impacts') and adaptive strategies ('responses') (adapted from Holman, 2005).

The collaboration with RegIS2 allowed a regional integrated impact assessment accounting for adaptation options and the assessment of that for evaluating the importance of climate and socio-economic changes on water resource management to be carried out in this research study. Moreover, the study of East Anglia and the North West contrasting regions, allowed the analysis of a diversity of problems, requiring the development of robust approaches to deal with the heterogeneity of conditions.

However, RegIS2 also posed constrains to this research study. In order to perform a regional integrated assessment of the impacts of climate change on water resources, the focus of this research was not to develop a new impact /catchment water balance hydrological models. Instead pre-existing modelling approaches were selected as computationally simple models were sought for allowing a rapid simulation of a large number of combinations of climate and socio-economic variables in order to identify relevant pressure variables and cross linkages and to understand the effects of uncertainty on the impacts (Section 2.4). The fast running time requirement was one of the major conclusions from RegIS project where the integrated sectoral models had unacceptably long runtimes (Holman and de Vries, 2005). Moreover, the timing of RegIS2 project and this research limited the review of potential suitable pre-existing methodologies to be used (Section 2.4).

2 Literature review

Climate change impacts the hydrological behaviour and the water resources affecting both the water quality and water quantity aspects, which threatens the sustainability of the water services. Section 2.1 summarises the water resource management planning in the UK. In the future, not just climate will change and socio-economic changes also have implications for the water resources management. The impacts of climate and socio-economic change are review in Sections 2.2.1-2.2.4. Therefore, adaptation in the water management sector to future changes is necessary, as presented in Section 2.2.5, which requires regional integrated impact assessments accounting for uncertainty (Section 2.3). In order to simulate the implications of climate change in the scope of this study, existing methods to model the hydrological compartments are review in Section 2.4.

2.1 The water resources and drought planning system in the UK

In the UK the water industry is made of private water and sewage service providers and works with governments, regulators and many stakeholder organisations through Water UK (www.water.org.uk). Aiming at ensuring security of supply in the future, the water companies prepare long-term water resource management plans in consultation with the Environment Agency. These plans are complemented by the short-term drought plans that ensure the security of the public water supply in periods of water shortage caused by exceptionally low rainfall.

The water resources plan considers costs and benefits of a range of options analysed by the water company for the supply to meet the demand. Companies set out a baseline forecast of demand for water for 25 years assuming current demand policies, including government policy and any forthcoming change in legislation about demand management and the impact of climate change on demand. This is compared against a baseline forecast of available water supply assuming current resources and future known changes. Water companies should also account for the impact of climate change on the water supply allowing for uncertainty in the assessment. (Environment Agency, 2007)

The drought plan sets out how the water company will continue to meet its duties to supply adequate quantities of water during drought periods with as little resource as possible to drought order or drought permits. Depending on the severity of the drought, the plan might include campaigns to encourage reduced consumption by the public, hosepipe bans and enhance leakage control. This plan is revised within 3.5 years from its publication (www.defra.gov.uk/environment/water/resources/drought).

2.2 The impacts of climate and socio-economic change on the hydrology and water resources

2.2.1 The impacts of climate change on the hydrology

Climate change is expected to have effects on the hydrological cycle through changes in precipitation, which is the main driver of variability in the water balance, with altered rainfall patterns and fairly general increases in rainfall intensity (Gleick and Adams, 2000; IPCC, 2001). In addition, climate change will also alter the evaporation and transpiration by plants (Gleick and Adams, 2000; IPCC, 2001) with hydrological consequences. Evapotranspiration is driven by meteorological controls such as temperature, humidity and wind speed, is mediated by the characteristics of vegetation (*e.g.* interception) and soils, and constrained by the amount of water available; and climate change has the potential to affect all of these factors (Arnell and Liu, 2001).

Considerable effort has been expended on developing improved catchment hydrological models for estimating the effects of climate change (Arnell and Liu, 2001). Some studies have specifically studied the impact of climate change on evapotranspiration (*e.g.*: Oltchev *et al.*, 2002, Panagoulia and Dimou, 1997a and 1997b, Lahmer *et al.*, 2001) and on the hydrology and land uses (*e.g.*: Kite, 1993, Sefton and Boorman, 1997, Oltchev *et al.*, 2002, Lahmer *et al.*, 2001). Arnell and Liu (2001) states that the greatest number of hydrological studies into the effects of climate change have concentrated on the potential changes of stream flow as for example mean flow (*e.g.* Sefton and Boorman, 1997) and runoff (*e.g.*: Panagoulia and Dimou, 1997a and 1997b, Lahmer *et al.*, 2001, Oltchev *et al.*, 2002, Arnell and Reynard, 1996). Variations in flow from year to year have been found to be much more strongly related to precipitation changes than to temperature changes (Arnell and Liu, 2001). For mild temperate climates, climate change tends to affect the magnitude of flows in different seasons by an amount that depends on the change in rainfall (Arnell and Liu, 2001), with monthly variability being greater than annual variability (Arnell and Liu, 2001 and Arnell and Reynard, 1996).

Although increases in rainfall intensity are likely to lead to widespread increases in flood flows, especially short duration heavy rains that cause flash floods, (Gleick and Adams, 2000; IPCC, 2001) and changes in flood risk are frequently cited as one of the potential effect of climate change, according to Arnell and Liu (2001), few studies have looked explicitly at possible changes in flood frequencies and high flows. Examples of studies that have looked at flood frequencies and floods with a short and long return period such as 2, 20 and 100 years, include the integrated assessment of Foresight Flood and Coastal Defence Project (Evans *et al.,* 2004a and 2004b) and RegIS Project Holman *et al.* (2005b); Reynard *et al.* (2001) on the impacts of climate and land use changes, and Prudhomme *et al.* (2003) that assesses uncertainty using different climate scenarios. Examples of simulation of high flows include Holman *et al.* (2005b) that estimated the flow exceeded 5% of the time and Sefton and Boorman (1997) that estimated the mean annual flood.

Smakhtin (2001) and Arnell *et al*. (2001) identify the probable greater effects of climate change on low flows than on high flows. This is opposite to Wilby *et al*. (1994) study referenced in Smakhtin, (2001) who suggests that the most affected flow indexes by climate change in the UK are Q10 (the flow with a 10 percentile exceedance probability) and Q50 (the flow with a 50 percentile exceedance probability), while the Q90 low flows are affected mostly by land use rather than by climate change. However, it is agreed that the frequency and/or severity of droughts are likely to increase (Pittock and Jones, 2000; Jacobs *et al.*, 2000). The effect of climate change on low flow magnitudes and frequency (*e.g*. sectoral studies by Sefton and Boorman (1997) and Arnell (2003, 2004b) and the integrated study by Holman *et al.* (2005b) that estimate the flow with a 95 percentile exceedance probability) can be affected by the catchment geology and soil properties (Arnell and Liu, 2001), but the frequency of low flows is affected primarily by changes in the seasonal distribution of precipitation, year-to-year variability, and the occurrence of prolonged droughts (Arnell and Liu, 2001).

Groundwater supplies are less susceptible to variations in climate than surface water; however, they may be more affected by long-term trends (Jacobs *et al.*, 2000). Although little work has been done on the impacts of climate change for groundwater basins and recharge (Gleick and Adams, 2000; Jacobs *et al.*, 2000), it is suggested that some regional groundwater storage volumes are very sensitive to changes in available recharge (Gleick and Adams, 2000). Due to decreased precipitation and increased evapotranspiration the future replenishment of aquifers is expected to decrease in the UK (Holman *et al*., 2005b; Holman, 2006) over a variety of different scenarios. As groundwater maintains the baseflow for many streams and rivers, lowering groundwater levels may reduce the seasonal flows (Jacobs *et al.*, 2000).

2.2.2 The impacts of hydrological changes on water supply

Changes in water supply conditions for economic activities and environmental uses are likely to be affected by hydrological changes, including altered frequency of extreme events, such as droughts (Varies *et al.*, 2004; Jacobs *et al.*, 2000). Of major concern is the reduction in low flows and lowered groundwater levels, which might lead to water shortages, especially during summer periods (Arnell and Liu, 2001). Under drought conditions, in the US, competition for water between the agricultural and urban users is likely to intensify (Jacobs *et al.*, 2000; Gleick and Adams, 2000). These water shortages also have implications for river ecology, for instance, reduction in the extent of both groundwater and surface water fed wetlands, reduction in habitat area with species loss, and siltation of river beds (Arnell and Liu, 2001). In addition, changes in the timing of water supply availability are likely to occur.

Reservoirs are the key components to the risk and uncertainty management of water resources system (Takeuchi, 2002). Although reservoirs have great environmental and social consequences (Takeuchi, 2002), they can be used to dampen the water supply effects (Jacobs *et al.*, 2000; Takeuchi, 2002); however, large changes in the reliability of water yields from reservoirs could result form small changes in inflows (Gleick and Adams, 2000).

2.2.3 The impacts of climate change on water quality

Water quality issues associated with potential climate change impacts are more subtle than water quantity issues (Jacobs *et al.*, 2000). Water quality impacts human health and ecosystem functioning (Jacobs *et al.*, 2000) and contamination of water sources might increase the cost of water treatment (Arnell and Liu, 2001) or even the availability of supplies. Climate change will directly affect water quality processes through an increase in water temperature (Arnell and Liu, 2001; Gleick and Adams, 2000; Arnell, 1998), which is dependent on atmospheric temperature, wind and solar radiation (Arnell and Liu, 2001) impacting aquatic ecosystems. For instance, higher water temperature is likely to eliminate some species that are already near their habitat temperature threshold like salmon and trout (Jacobs *et al.*, 2000). Increased water temperature will also result in reduced dissolved oxygen in water, which is a measure of ecosystem condition (Arnell, 1998; Mimikou *et al.*, 2000) and alter the mixing and stratification of water in lakes and reservoirs, conditions that are key to habitat value and a nutrient balance that avoids eutrophication problems (Jacobs *et al.*, 2000; Gleick and Adams, 2000). Relative sea level rise might adversely affect surface and groundwater sources of supply in coastal areas both through movement of the freshwater /saltwater interface further upstream in river basins (Jacobs *et al.*, 2000) and saltwater intrusion into aquifers (Jacobs *et al.*, 2000; Arnell and Liu, 2001; Gleick and Adams, 2000) that might already be under stress due to lowered groundwater levels (Arnell and Liu, 2001).

There are also indirect climatic causes that might deteriorate the water quality. Increase in rainfall intensity is likely to lead to increased soil erosion, turbidity and pollutant concentrations in runoff (Larcombe *et al.* 1996; Gleick and Adams, 2000) increasing the risk of nutrient loading and contamination of the water bodies (Jacobs *et al.*, 2000), to which aquatic ecosystems are very sensitive (Gleick and Adams, 2000; Arnell and Liu, 2001). Change in rainfall patterns may cause increased problems of diffuse source of pollution and agricultural by-products (Jacobs *et al.*, 2000). Increased flooding events can cause channel erosion with downstream deposition, overload storm and wastewater systems, and damage sewage treatment facilities, mine tailing impoundments or land-fills, thereby increasing the risk of contamination (Arnell and Liu, 2001; Jacobs *et al.*, 2000). Water quality is also greatly influenced by flow variability that affects the concentrations and water loads or the ability of catchments to assimilate nutrients and pollutants (Mimikou *et al.*, 2000; Arnell and Liu, 2001; Gleick and Adams, 2000; Jacobs *et al.*, 2000).

2.2.4 Impacts of climate change on the water resources under the effects of a changing future

Infrastructures have been built to minimise the risks of natural variability and to maximise the reliability of the systems providing benefits to society, albeit at a substantial economic and environmental cost (Gleick and Adams, 2000). Examples of such infrastructures are dams, reservoir, aqueducts and water treatment facilities that can, for instance, provide clean water for drinking and for industry, dispose of wastes, irrigate crops and reduce the risks of floods and droughts. Those infrastructures were designed and operated assuming that future climatic and hydrologic conditions will look like past conditions; however, this is no longer true (Gleick and Adams, 2000).

The impacts of climate change will depend on the baseline condition of the water supply system and the ability of water resource managers to respond not only to climate change but also to socio-economic changes that affect both the supply and demand (IPCC, 1998; Arnell and Liu, 2001; Varies *et al.*, 2004; Frederick, 1997). Some of these socio-economic changes might arise as a response to climate change, but others may not, such as:

- Economic, social, and legislative conditions (*e.g.* agricultural policies, urban planning/management and water demand for ecosystem protection and restoration) might change public and professional attitudes to water resources and their management (IPCC, 1998; Gleick and Adams, 2000; Arnell, 1998).

- Population increase in metropolitan areas along the coast is likely to create water distribution problems due to increased total demand, which is viewed to have a greater impact on system performance than climate change (Gleick and Adams, 2000). Increased urbanisation generally results in increased channelisation of streambeds and higher runoff rates which are likely to further contaminate water supplies and reduce opportunities for recharge of groundwater that can exacerbate saltwater intrusion in costal aquifers (Jacobs *et al.*, 2000). All these can be even further aggravated if meeting increased demand leads to groundwater overdraft.
- Changes in agricultural practices might increase chemical and nutrient loads to the water bodies exacerbating the impacts of climate change (Arnell and Liu, 2001; Jacobs *et al.*, 2000)
- Changes in domestic water demand as a result of technology (*e.g.* water efficient toilets and high water consume showers; Downing *et al.*, 2003) and lifestyles (*e.g.* increased use of hose pipes and sprinkles in gardens with designs and plants that require more water; Downing *et al.*, 2003)

Future water demand needs are a consequence of future climate and consequent socio-economic changes. The sensitivity of water demand to climate change includes altered domestic water demand where the most sensitive areas are increased personal washing and increased use of water in the garden (Environment Agency, 2001a, Herrington, 1996). According to Arnell and Liu (2001) and Downing *et al.* (2003) the agricultural demand for irrigation water is considerably more sensitive to climate change. First, a change in field-level climate, such as changes in average temperature, precipitation and soil moisture (Jacobs *et al.*, 2000), may alter the need for and timing of irrigation; secondly, increasing atmospheric dioxide carbon concentrations lower plant stomatal conductance increasing water use efficiency (an example of a beneficial effect of climate change) (Arnell and Liu, 2001; Gleick and Adams, 2000). However, the second mechanism may be offset to a large extent by increased plant growth (Arnell and Liu, 2001; Gleick and Adams, 2000). However, in the UK, the irrigation water demand is largely a response to market demand for improved food quality. Industrial use is insensitive to climate change, being conditioned by technologies and modes of use (Arnell and Liu, 2001); however Downing (2003) defends that climate change impacts on industry and commerce are likely to be higher than the impacts on domestic consumption.

2.2.5 Adaptation responses to climate change in the water management sector

In the absence of explicit efforts to address future adverse changes in water resources, the societal costs of water problems are likely to rise as competition for water grows and supply and demand conditions change (Gleick and Adams, 2000). Decisions about future water planning and management should be flexible, incorporating the risks and benefits of climate change into long-term water planning (Frederick, 1997; Gleick and Adams, 2000), and be implemented before such changes occur to maximise their effectiveness (Gleick and Adams, 2000), namely *no-regret* changes (Jacobs *et al.*, 2000). Despite its recognised importance, water managers are currently not adequately engaged in the process of evaluation of the risks of climate change (Jacobs *et al.*, 2000) and efforts so far are not moving action towards adaptation (Arnell and Delaney, 2006).

Many of the approaches for reducing risks have traditionally included supply-side options and more recently, demand-management options (Frederick, 1997; Gleick and Adams, 2000) (Table 2-1) without affecting services or quality of life (Jacobs *et al.*, 2000). This work is going on largely independently of the issue of climate change (Gleick and Adams, 2000). However, demand management is critical for balancing future demands with supplies (Frederick, 1997) and optimising water resource management under increasing constraints narrows the options available (Jacobs *et al.*, 2000).

Table 2-1: Strategies to increase water supply and decrease per-capita water demand (Arnell and Liu, 2001; Jacobs *et al.*, 2000; Frederick, 1997; IPCC, 1998)

Water supply strategies	Engineering and structural improvements to water supply: – as increased reservoir capacity – improved mechanisms for inter-basin water transfers Increased abstraction from rivers or groundwater Artificial groundwater recharge Altered system operating rules
Water demand strategies	Incentives to use less – pricing systems – legally enforceable water use standards Reduced leakage Promotion of water recycling and reuse Increased water use efficiency (*e.g.* new technologies)

In terms of public water supply, climate change is seen as only one of the many pressures and not necessarily the most important in the short term; however, the concern could be significantly influenced by the occurrence of extreme events (Arnell and Delaney, 2006). Moreover, responding to climate changes may require a broader set of information than is usually available to decision-makers (Jacobs *et al.*, 2000). However, uncertainties should not be used to delay or avoid taking certain kinds of action now, as *many uncertainties remain; indeed, we expect that uncertainties will always remain* (Gleick and Adams, 2000).

Two of the most important coping strategies must be to understand what the consequences of climate change will be for water resources and to begin planning for and adapting to those changes (Gleick and Adams, 2000). This research is focused on the former.

2.3 Impact assessment on water resources and uncertainty

2.3.1 Uncertainty in climate inputs to impact assessments

Studies of climate change effects on hydrology and water resources use climate models such as Global Circulation Models (GCM) to provide future global climate scenarios under the effect of increasing greenhouse gases (Xu *et al.*, 2005). Due to the significant mismatch between the scale at which most hydrologic and water resources studies are conducted and the large temporal and spatial scales of GCMs (Varies *et al.*, 2004; Kilsby, 1999), downscaling techniques are used (Xu *et al.*, 2005; Varies *et al.*, 2004), *e.g.* simple interpolation, statistical downscaling and high resolution dynamic modelling (detailed in Xu *et al.*, 2005). In terms of temporal scale, for instance, when considering the frequency distribution of river flow, the GCM's rainfall output of several decades is insufficient and the determination of extreme weather events is important in terms of water resources management and design (Varies *et al.*, 2004). In terms of spatial scale, GCM grid sizes tend towards one or two degrees (Varies *et al.*, 2004) whilst the quantification of climate change impacts is at the local or regional scale, *i.e.* catchment or river basin scale hydrology. The drainage basin is essential because this is the scale at which most important sources and driving forces of climate change are located, and political and technical measures to adapt takes place (IPCC, 1998; Varies *et al.*, 2004; Sivapalan *et al.*, 2003). Regional climate models, which first attracted serious attention in Alaska, have become one of the major priorities of the IPCC (Whitfield, 2003).

Large uncertainties exist due to problems with the current capacity of GCMs and downscaling techniques, although great progress has been achieved (Xu *et al.*, 2005; Jenkins and Lowe, 2003). Hulme and Carter (1999) define two different sources of uncertainties on future global climate change and management, the *incomplete* and the *unknowable* knowledge. *Incomplete* knowledge is reflected by the model designs (climate and impact models) and arises from inadequate information or understanding about the processes or a lack of resources for impact assessment. With future research this type of uncertainty can be continuously minimised. *Unknowable* knowledge results from the unpredictability of the Earth system, and the fact that science is unable to forecast future socio-economic and human behaviour in a deterministic manner.

The main uncertainties related to GCMs are issues of continuing interest in GCM development by IPCC (Varies *et al.*, 2004; IPCC, 2001c). The nature and intensity of future greenhouse gas emissions are uncertain (Jenkins and Lowe, 2003) and depend upon decisions of governments and individuals, the speed of deployment of alternative energy systems, population sizes and affluence, and many more factors (Gleick and Adams, 2000). The models that simulate the role of these gases in our atmosphere are imperfect due to uncertainties in sinks, feedbacks (Varies *et al.*, 2004; Jenkins and Lowe, 2003) and limitations in incorporating and reproducing important aspects of the hydrologic cycle such as water vapour, clouds, oceans as well as sea ice and snow (Gleick and Adams, 2000; Varies *et al.*, 2004). Moreover, Pielke Sr. (2002) defends that two important forcings on the effects of global climate are the anthropogenic land cover change and the biological effect of anthropogenically increased concentrations of carbon dioxide on the regional and global climate systems, which have been excluded in the IPCC and US National Assessment.

Different greenhouse gas emission scenarios, that incorporate the incomplete and unknowable uncertainties, cascade through any climate change impact assessment in an inter-dependent manner (Hulme and Carter, 1999). Moreover, the choice of GCM was shown to cause large uncertainties in the climate change scenarios and freshwater impacts (Wilby *et al.*, 2006a). The use of a single scenario is seen by Hulme and Carter (1999) as a dangerous practice because it leads to the suppression of crucial uncertainties and should not be used for risk and adaptation studies. Using several climate change scenarios, which is common and usually reflecting different global climate patterns (Arnell, 1999), provides the impact studies with a range of possible outcomes (New and Hulme, 2000).

2.3.2 Regional integrated impact assessments and model uncertainty

Integrated river basin management is the key strategy for sustainable water resources management (Takeuchi, 2002; Frederick, 1997). In order to better understand the impacts of climate change on water resources, assessments are required considering multidisciplinary water-related scenarios where climate change factors affect hydrological systems and water resources and socio-economic development also has an effect on water demand and supply (Varies *et al.*, 2004). Therefore, the tendency seems to be towards regional integrated and interdisciplinary hydrological and water resources assessments (Varies *et al.*, 2004; Krol *et al.*, 2001) as the following examples:

– The 'Regional climate Change Impact and Response Studies in East Anglia and North West England' (Holman *et al.*, 2005a; Holman *et al.*, 2005b) looking at integrated impacts of possible climate and socio-economic futures on coastal and inland flooding, agriculture, water resources and biodiversity at a regional scale.

– The 'global change in the water cycle' (GLOWA; www.glowa.org), whose goal is the development of integrated strategies for the sustainable and anticipated management of water and regional water resources.

– The 'Regional Assessment of Global Change Impacts Through Integrated Modelling in European River Basins' (RAGTIME; http://www.pik-potsdam.de/cp/ragtime) with the objective to investigate the impacts of climate change, land-use and land-cover change and other human activities on hydrological and ecological characteristics.

– 'Water Availability, Vulnerability of Ecosystems and Society' (WAVES; Krol *et al.*, 2001; Bronstert *et al.*, 2000; http://www.pik-potsdam.de/cp/waves/), which aims at understanding the interactions between water availability and migration from rural areas, and to contribute to the assessment of possible pathways towards a sustainable development focusing on improving the integrated dynamic understanding of the causal chain of climate- water availability-agriculture-society.

– 'The Mid-Atlantic Regional Assessment' (MARA; www.cira.psu.edu/mara), which to analyse and evaluate the potential consequences of climate variability and change for the Mid-Atlantic region's people and resources, in the context of other existing and anticipated pressures.

Water companies are also using integrated assessments that include population and household projections in the form of socio-economic scenarios (Thames PROGNOSIS model) and also recognise the policy implications of greater environmental protection by including 'sustainability losses' under different scenarios (Steven Wade from HR Wallingford, *Pers. Comm)*. Examples of integrated work assisting the UK water industry in its future water resources management include UKWIR (2007) and HR Wallingford (2005).

Although the greatest uncertainties in the effects of climate on hydrology and water resources arise from uncertainties in climate scenarios (Varies *et al.,* 2004; Xu *et al.*, 2005), there are also uncertainties in the models (*e.g.* different hydrological models can give different values of stream flow for a given input (*e.g*. Boorman and Sefton, 1997). These uncertainties result from:

- Unknown aspects of the physics, biology and/or sociology of the system being simulated (New and Hulme, 2000).
- Inadequacies in the model design (New and Hulme, 2000). For example, in integrated assessments, a good compromise is required between the clarity in the representation and the comprehensiveness regarding the main dynamic processes (Krol *et al.*, 2001), where special attention should be paid to cross linkages and feedback processes, which may be of minor importance in the present functioning of the system, but could importantly influence long-term dynamics (Krol *et al.*, 2001).
- *Unknowable* knowledge on how the system might adapt to changing climatic conditions (Arnell, 1999; New and Hulme, 2000). Water managers can have different attitudes and approaches to adaptation that also depend on their perception at the time of the need to adapt to climate change (Arnell, 1999).

Past impact studies have addressed uncertainties in a limited and often haphazard manner, through the use of scenarios, or sensitivity studies, or a combination of the two focusing on the sensitivity to different climate inputs and not generally assessing the sensitivity of outputs to uncertainties inherent to the impact model (*e.g*. uncertain parameter values in Section 2.4.1.1) (New and Hulme, 2000) and very few looked explicitly at the effect of using different hydrological models on the effects of change (Arnell, 1999). However, tools for quantitative uncertainty analysis, as presented by Yen (2002), are available for water resources planning, design. Moreover, Kandlikar *et al.* (2005) presents a simple approach to communicate uncertainty in climate change assessments distinguishing its subjective levels of understanding and UKWIR (2007) presents a practical methodology for assessing the effects of climate change on river flows and groundwater recharge.

Representing uncertainties in climate change impact studies is a growing concern amongst scientists (Hulme and Carter, 1999; Pittock and Jones, 2000; Xu *et al.*, 2005; Yen, 2002) because risk assessment and management is crucial to adaptation (Willows and Connell, 2003) and reducing vulnerability of water resources systems (Varies *et al.*, 2004). It is important for decision makers to feel confident in future projections in order to adapt (Hulme and Carter, 1999). Moreover, more accurate and reliable predictions are becoming important to civic society increasingly asked to make independent judgments about actions required to manage the natural environment and the water resources in a sustainable manner (Sivapalan *et al.*, 2003).

2.4 Hydrological modelling

2.4.1 The need of existing methods to model the hydrological compartments

The collaboration with RegIS2 project posed constrains on this research study (Section 1.3). The model to be developed was based upon pre-existing models which were chosen against the selection criterion presented in Section 2.4.1.1 and Section 2.4.1.2.

2.4.1.1 Use of catchment scale regionalised models calibrated and validated over a wide range of conditions

Within this research, the hydrological models were applied in all 200 catchments within East Anglia and the North West regions and therefore, a regionalised approach which does not require calibration and validation of the models for each catchment under baseline conditions is necessary. Regionalisation is a parameter estimation procedure assuming that similar catchment characteristics lead to similar hydrological behaviour and most common methods follow a strategy to calibrate a selected model on gauged catchments and look for possible relationships between model parameter values and land surface data (Xu *et al.*, 2005).

Hydrological models are normally designed for stationary conditions, but they are used under conditions of change in climate change studies (Xu *et al.*, 2005). The models to be selected must have been developed for a wide range of climatic and landscape conditions. The hydrological models are developed to study the future impacts of climate and socio-economic changes on catchment hydrology and therefore, the calibration and validation of the pre-existing regionalised approaches needs to have been carried over a sufficiently wide range of catchment conditions such that the approach stays within or close to the calibration range.

However, impact studies based on models calibrated and verified on observed climates have a limited ability to predict biophysical responses to greenhouse gas induced climate change or if other conditions in the catchment change (Arnell, 2002; Sivapalan *et al.*, 2003; Smith 1997; Young and Reynard) and the assumption that the hydrological model parameter values are the same today and in a different future climate, might be far from true (Xu *et al.*, 2005; Sivapalan *et al.*, 2003; Wilby, 2005). Model parameterisation techniques need to be improved and because empirical relationships do not imply causation (Arnell, 2002) there is the need for improving the understanding of hydrological processes (Xu *et al.*, 2005). This problem is being tackled by the initiative to reduce predictive uncertainty in ungauged basins launched by the International Association of Hydrological Sciences for the period 2003-2012 (Sivapalan *et al.*, 2003).

2.4.1.2 Use of adaptable models sensitive to suitable pressures that output relevant impact indicators

For an efficient implementation of the model, the pre-existing models should be easily adapted. The models to be used should incorporate a methodological approach that is easily comprehensible both in its scientific and mathematical terms to allow the model to be easily adapted in order to improve the understanding of hydrological processes. The models should also be able to incorporate the future trends in climate and socio-economic factors and to output, directly or indirectly, relevant impact indicators, which is especially important for the cross-sectoral links and feedbacks dynamics in the integrated assessment.

Regarding inputs, the hydrological models should be sensitive to physical descriptors; socio-economic and climatic pressures that are chosen in order to represent the dynamics of the system without restrain, although they might be dictated by the available datasets. According to Kilsby (1999) and Arnell and Liu (2001), information that may be required for impact assessments in water resource management and the design of water resources systems includes:

- Mean Flow and Average Annual Runoff Depth (Mean Flow per unit area) as an indicator of the water resources of a catchment;
- Low flow statistics - the most commonly used in water resource design by the UK water industry are the daily discharge with a 95 percentile exceedance probability or Q95 and the Mean Annual Minimum seven day flow MAM(7) that is also a basis for abstraction licensing (Robson and Reed, 1999).
- The naturalised Flow Duration Curve that gives the proportion of time a given flow is exceeded and is an indicator of the total manageable resource (Environment Agency, 2002) and a general hydrological descriptor (Robson and Reed, 1999).

- Mean annual flood and high flow indexes, such as Q5, the discharge with a 5 percentile exceedance probability from one day flow, and QMED, the median annual flood.
- Mean groundwater recharge and reliable yields.
- Mean seasonal variation in river flow and in groundwater recharge.
- Volumes available to reservoir in certain time periods.

2.4.2 Review of suitable hydrological models

2.4.2.1 Modelling of naturalised river flows

The ‘Low flow estimation in the United Kingdom - Report No. 108’ by Gustard *et al.* (1992) is the successor of the ‘Low Flow Studies report’ by Institute of Hydrology (1980) and contains improved procedures for the estimation of naturalised low flow measures at ungauged locations throughout the UK. It uses complex regression approaches to derive Mean Flow, Average Annual Runoff Depth, MAM(7), the Flow Duration and the Flow Frequency Curves. For estimating the Mean Flow, Gustard *et al*. (1992) provides a catchment water balance method (Section 4.1.1) and an alternative empirical regional regression equation. The former method is conceptually preferred because of its lower error and because it includes an understanding of the relationships between the processes controlling flow generation (Holmes *et al.*, 2002). The drawbacks of using this method is that it is not sensitive to land-use changes that affect evapotranspiration and runoff, neither to climate change. However, the approaches in Gustard *et al.* (1992) are adaptable and allow the estimation of relevant outputs with the simplicity of the model of having one single curve per catchment representing a wide range of impacts.

Arnell (2003) gives examples of the effect of climate change on Q95 for a small number of case study catchments for 2020s and proposes an empirical method to scale up scenarios and factors. This method is however too simplistic, estimates a single impact indicator, and no core processes describing the hydrological processes have been identified to be used by the models to be developed.

Other models reviewed include a soil based approach to rainfall-runoff modelling in ungauged catchments for England and Wales, CRASH model (Maréchal, 2004); the distributed semi-empirical model SWANCATH (Holman *et al.*, 2001); and the conceptual contiguous time SWAT model (Arnold and Fohrer, 2005). These are however complex models that are high data demanding.

2.4.2.2 Methods for estimating groundwater recharge

Actual groundwater recharge is defined by Lerner *et al.* (1990) as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. The actual amount of recharge might be smaller when, for example, low permeability drift is present or when water is stored in the soil or unsaturated zones, and therefore it is important to differentiate potential from actual groundwater recharge. According to Lerner *et al*. (1990), when modelling future conditions, it might be more appropriate to model potential recharge.

Groundwater recharge estimation is usually based on soil moisture balance techniques where the moisture content of the soil is tracked through time (Szilagyi *et al.*, 2003 and Arnell *et al.*, 1997). For example, the Agency has developed a standard soil moisture balance approach based on crop water requirements to estimate potential recharge and recharge when drift is present (Hulme *et al.* 2001), that is used in some regions (Environment Agency, 2002). However, this type of method describes all of the complex processes controlling recharge (*e.g.* precipitation, irrigation) and soil water movement (*e.g.* infiltration and saturation excess runoff, and bypass recharge) to estimate the groundwater recharge. Other types of methods are presented in Lerner *et al.* (1990) and Szilagyi *et al.* (2003); however, high data demanding or requiring potentially complex groundwater flow models.

However, the purpose of this study is to use an approach, according to the criterion presented in Section 2.4.1, that provides a broad indication of the impacts of climate and socio-economic changes on potential groundwater recharge. The only studies presenting a suitable approach for estimating groundwater recharge are Szilagyi *et al.* (2003), Arnell *et al.* (1997) and Arnell (2003).

Szilagyi *et al.* (2003) developed a method to map regional spatial patterns in natural long term mean annual potential recharge in Nebraska (with no abstractions, reservoirs nor irrigation). It does not require complex hydrogeological modelling nor detailed knowledge of soil characteristics, vegetation cover or land-uses practices, and it avoids the use of contributing drainage areas in the water balance equation which is an advantage if unknown or when contributing areas of ground and surface water differ significantly (Szilagyi *et al.,* 2003).

The methodology of Szilagyi *et al.* (2003) is summarised:

The water balance of a groundwater system is given by Equation 2-1 and Equation 2-2 adapted from Todd and Mays (2005) and Szilagyi *et al.* (2003):

$$I = P + Irr - Qs - ET \qquad \textbf{2-1}$$

Where, the infiltrated water (I) from natural and artificial sources consists of the precipitation (P) after surface runoff (Qs), evapotranspiration and evaporation of intercepted water (ET) had occurred, plus excess irrigation (Irr), mm

$$I + GW_{in} = GW_{out} + Qb + ET_g + \Delta S \qquad \textbf{2-2}$$

Where, the inputs to the groundwater system are the infiltrated water (I) plus all the groundwater inflow into the balance unit (GW_{in}) due to, for example, lateral groundwater movement, river effluent reaching the groundwater and seepage from reservoirs. The outputs from the groundwater system are the groundwater outflow from the balance unit (GW_{out}) due to, for instance, groundwater lateral movement, and groundwater discharges to springs, lakes and seas; baseflow contribution to streamflow (Qb); losses of groundwater due to evapotranspiration from the unsaturated zone (ET_g); and change in water storage (ΔS) as from groundwater abstractions; mm.

Ignoring groundwater recharge from excess irrigation and combining Equation 2-1 and Equation 2-2 gives:

$$P + Qs - ET + GW_{in} = GW_{out} + Qb + ET_g + \Delta S \qquad \textbf{2-3}$$

Assuming that:

- the long term storage change is negligible as evapotranspiration is the largest term in which estimation methods may differ by 10-20%, and there are no abstractions,
- ETg from groundwater can be neglected when compared to catchment evapotranspiration,
- at a regional scale, the groundwater inflows and outflows are insignificant.

Equation 2-3 simplifies to:

$$P - ET = Qb + Qs \qquad \textbf{2-4}$$

The Baseflow index (BFI) is the long-term average proportion of stream flow that derives from groundwater (as defined by Boorman *et al.*, 1995; Szilagyi *et al.*, 2003; Arnell *et al.*, 1997; and Arnell, 2003) and is represented by Equation 2-5 from Szilagyi *et al.* (2003).

$$BFI = \frac{Baseflow}{Total.stream.runoff} = \frac{Qb}{Qb + Qs} \qquad \textbf{2-5}$$

Therefore, inserting Equation 2-5 in Equation 2-4:

$$BFI \times (P - ET) = BFI \times (Qb + Qs) = Qb \approx \mathrm{Recharge} \qquad \textbf{2-6}$$

Where, Recharge is the groundwater recharge, mm

Groundwater recharge, ignoring human-induced effects, is therefore calculated by Szilagyi *et al.* (2003) using Equation 2-6 and the method validated well against the long term annual mean potential recharge estimated by a detailed groundwater model that includes recharge resulting from irrigation (Szilagyi *et al.,* 2003).

This is a simple and validated method to implement for regional scale studies that has been developed for Nebraska where the annual potential recharge rate can vary from 110 to 15 mm annually. However, what is the suitability of this method to perform climate change impact studies for future scenarios in the UK, where recharge is higher, at a catchment level?

Arnell *et al.* (1997) and Arnell (2003) provide a useful tool to facilitate a rapid assessment of the potential implications of climate change for groundwater recharge. It has been validated for a limited number of catchments throughout the UK, suggesting a method that does not require the use of a locally calibrated and validated catchment/aquifer model.

The method consists of a series of regional factors that are applied to a time series of natural annual mean groundwater recharge baseline data (spanning the period of 1961-1990) perturbing it to give the altered time series. These regional factors were derived using a simple aquifer recharge model run under baseline and climate scenarios conditions for eleven baseflow dominated catchments. Both Arnell *et al.* (1997) and Arnell (2003) use the same aquifer model and catchments; however, Arnell *et al.* (1997) uses climate data derived from the output of climate change experiments run by Hadley Centre in 1996 using the HadCM1 and HadCM2 climate models, and Arnell (2003) uses UKCIP02 scenarios for 2020s Low, Medium, High plus two scenarios characterising the effects of uncertainty (Section 2.3.1).

This aquifer model has two parameters that have been calibrated so that the simulated annual average runoff matched the observed and that the ratio of simulated annual recharge to simulated total annual runoff was close to the catchment BFI. Therefore, conceptually, groundwater recharge is calculated based on Equation 2-6. Therefore, it can be concluded that this method is suitable to calculate the natural potential groundwater recharge within the purposes of this research study.

2.4.2.3 Estimation of flood index

There are several methods for estimating flood frequencies, such as the Flood Estimation Handbook (FEH) that updated the Flood Studies Report (Institute of Hydrology, 1975) and presents standard methods in UK for flood frequency estimation from statistical procedures (Robson and Reed, 1999) and for estimating the flood hydrograph for a given return period using a rainfall-runoff method (Reed, 1999). However, for the purpose of this study, a single flood index is to be simulated for an average year instead of simulating the complex impacts of future extreme events on flooding as the examples of flood studies given in Section 2.2.1.

Robson and Reed (1999), estimate an index of flood, QMED, required for estimating the flood frequency. QMED is the flood that is exceeded on average *every other year* and is formally defined as the middle-ranking value in the series of annual maximum floods, where the annual maximum series comprises the largest flow observed in each year (Bayliss, 1999). QMED can be estimated from:

- past flood data, but for the purpose of this study, attending to changes in land uses and climate, past flood peak data cannot be used;
- catchment descriptors;
- by data transfer, but it is not viable to use analogue sites concerning every potential change of parameter that affect QMED;
- from channel dimensions, but bankfull channel width data could only form the basis of a second opinion and this catchment descriptor is unknown for the future and;
- from continuous simulation modelling (Robson and Reed, 1999), but this has extensive data and modelling requirements (Calver *et al.,* 1995).

Therefore, the method chosen to estimate QMED is the Catchment Descriptors, although that method is the least accurate of the five abovementioned approaches (Robson and Reed, 1999), but a compromise is required between efficiency and simplicity. QMED in ungauged catchments is estimated through statistical modelling that relates the flood quantile to catchment characteristics (Grover *et al.*, 2002) and the Catchment Descriptors method uses a generalised least squares linear regression (Equation 2-7, Section 5.1.1).

$$QMED = 1.172 AREA^{AE} \left(\frac{SAAR}{1000} \right)^{1.560} FARL^{2.642} \left(\frac{SPRHOST}{100} \right)^{1.211} 0.0198^{RESHOST}$$

$$AE = 1 - 0.015 \ln\left(\frac{AREA}{0.5} \right) \qquad \textbf{2-7}$$

$$RESHOST = BFIHOST + 1.30 \left(\frac{SPRHOST}{100} \right) - 0.987$$

Where, QMED is the flood index, m^3/s
AREA is the drainage area, km^2
SAAR is the Standard Average Annual Rainfall, mm
FARL is the index of Flood Attenuation due to Reservoirs and Lakes
SPRHOST is the Standard Percentage Runoff from the HOST soil classification
BFIHOST is the Base Flow Index from the HOST soil classification

The selected method *allows preliminary estimates of QMED to be made relatively simply* (Robson and Reed, 1999) and the estimation of this single parameter for each catchment is a computationally efficient approach to estimate a suitable flood index, as an indicator of flood flow. Moreover, the method also allows for an urbanisation adjustment, which is of relevance under future socio-economic conditions given that urbanisation typically has its strongest effects of floods of short returns period such as QMED (Robson and Reed, 1999).

2.4.2.4 Methods to estimate abstraction availability

Only a proportion of the total manageable resource for each catchment is available for abstraction. The integrity of freshwater ecosystems depends upon adequate quantity, quality, timing, and temporal variability of water flow. It is important therefore that national water management policies explicitly incorporate freshwater ecosystem needs, particularly those related to naturally variable flow regimes (Baron *et al.*, 2002). England and Wales have the most heavily protective system of abstraction control in the UK, as the Environment Agency (and its predecessor the National Rivers Authority) has statutory powers to license all abstractions (Henriques *et al.*, *Submitted*). To be reasonably consistent with current abstraction management policy in England, an approach similar to that of the Environment Agency's Resource Assessment Management (RAM) framework (Environment Agency 2002; Dunbar *et al.*, 2004) has been chosen out of the many methodologies available for calculating environmental flow allocations (*e.g.* reviews by Acreman and Dunbar, 2004; Tharme, 2003) although it is high demanding in detailed site-specific data. Moreover, it has been assumed that abstraction licensing restrictions are likely to be in operation under all socio-economic futures due to the longstanding water resources management structure in England and Wales.

The RAM framework was developed to manage water resources and to protect the riverine ecology from additional flow variation and low flows caused by abstractions and is applied to catchments, which are divided into a number of river reaches which each contain an assessment point and, where appropriate, are associated with a Groundwater Management Unit. The flow regime protecting the ecological needs of each river assessment point, defined by the ecological River Flow Objective (RFO), is derived from:

- One of the five environmental weighting bands that classify the sensitivity of each river reach (upstream of the assessment point) to the effects of abstraction impacts, on the basis of its physical characteristics, the dominant fish populations, macropyhtes and macro-invertebrates.
- The naturalised FDC, which is used as an indicator of the total long term manageable resources. The FDC provides a sound basis for comparison between catchments as it encapsulates the long term resource variation. The long term FDC may be based on a natural flow series established by gauged flow naturalisation or may be taken directly from Low Flows 2000 (Young *et al.*, *In Press*; Young *et al.*) or from other models/tools (*e.g.* Gustard *et al.*, 1992). Where the ecology might have adapted to permanently artificially supported flows, regarded as *fixtures*, such as by treated effluent returns, it is not appropriate to use the naturalised FDC as an indicator of the total manageable resource. Instead, a benchmark FDC which includes the impacts of abstractions or discharges on the top of the naturalised FDC should be used. However, in many cases, the benchmark FDC is the naturalised FDC (Environment Agency, 2002).

The licensable resource available for abstraction at any given flow is calculated as the difference between the benchmark FDC and the ecological RFO FDC, (Figure 2-1) and the reliable abstraction availability at any given flow for each assessment point given by the constrained and unconstrained limits.

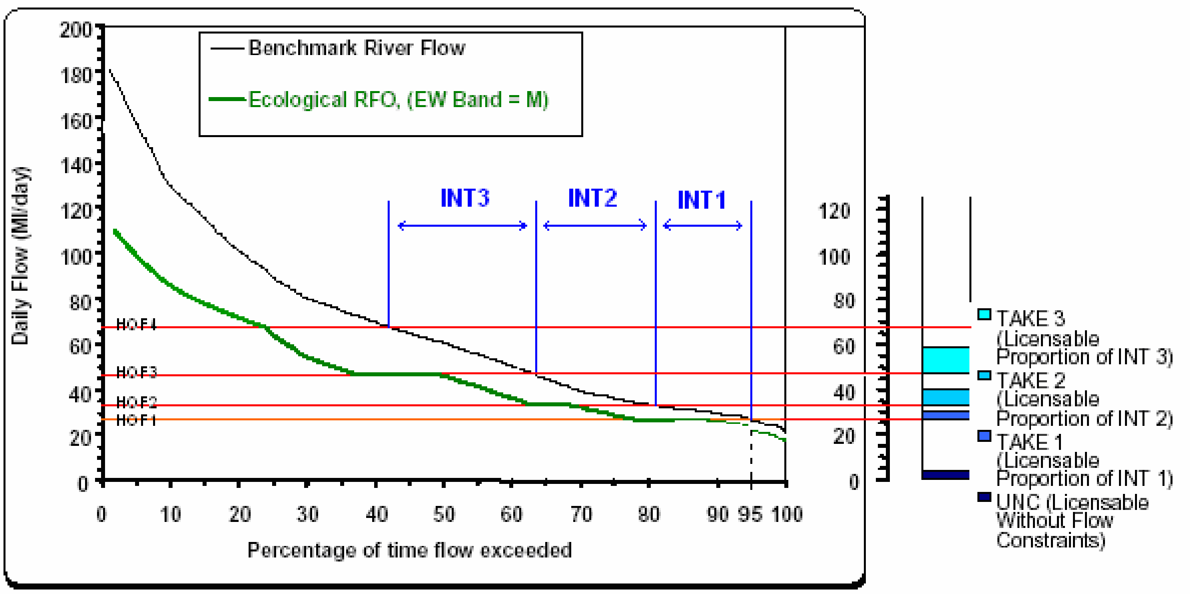


Figure 2-1: Naturalised (in black) and Ecological River Flow Objective (RFO) (in green) Flow Duration Curves, unconstrained (UNC) abstraction availability and intervals (INT1, INT2, and INT3) for estimating the constrained (TAKE1, TAKE2, TAKE3) abstraction availability (adapted from Environment Agency, 2002).

In order to protect low flows, abstractions that have unconstrained licenses, of which the vast majority are groundwater abstractions (Environment Agency, 2002) should be limited to the UNC which is the proportion of the benchmark Q95 that can be licensed for abstractions. This unconstrained water can be abstracted at any time even when river flows fall bellow Q95 which restricts abstraction for other constrained licenses. This proportion depends on the connection between ground and surface water and on the environmental weighting band *i.e.* the higher the sensitivity of the river ecology to abstractions, the less that can be abstracted and the greater the remaining part that is allocated for the environment.

In order not to extend the period of low flows and to protect the flow variability, the RAM has adopted a tiered system to allocate constrained licenses. Flows above the Q95 are divided into a number of intervals (INT) between thresholds or 'Hands off Flow' (HOF). The lowest HOF, HOF1, is set at the benchmark Q95, with INT1, HOF2, INT2, HOF3 and INT3 stacked above (Figure 2-1). Within each interval a proportion of water is allocated for the environment and a proportion for abstraction given by TAKE. The TAKE determines the degree of ecological RFO flow variability and increases as the environmental weighting band becomes less sensitive. The relevant TAKE also reflects the variation between median and low flows of the benchmark hydrograph. There are three licensable TAKES (TAKE1, 2 and 3) (Figure 2-1). Once the proportion for abstraction has been fully allocated, new licenses are allocated to the next interval up and subject to more restrictive conditions. At higher flows, above the HOF4, there are available remaining resources and additional flow proportion can be licensed. However, it is a relatively unreliable resource and less attractive to a potential license applicant as the percentage time available becomes smaller.

2.5 Summary

The nature of expected climate change will alter groundwater recharge, high, mean and low flows. Changes in climate and hydrology have implications for water supply and water quality affecting aquatic ecosystems, on which we depend, and water resources in terms of water supply for human consumption. Water resources management faces an extra difficulty of dealing with climate change because water supply and demand are impacted directly and indirectly by climate change and many other pressures across many sectors of the economy, society and environment, which might exacerbate the stresses posed by climate change. In order to moderate the future impacts on water resources, anticipatory adaptation, through supply and demand strategies, is fundamental; however, there is the need to better understand what the consequences of climate and socio-economic changes will be. The way forward to better evaluate the impacts of, and adaptation responses to, climate change and to better inform water managers are regional integrated impact assessments addressing uncertainties inherent to the global models and climate scenarios and to the complex hydrological and water resources models.

In order to develop a model that allows rapid analyses of sensitivity and uncertainty of climate and socio-economic the integrated variables, pre-existing hydrological models were used. These models were chosen against the following criterion allowing its application within the RegIS2 project: catchment scale regionalised models calibrated and validated over a wide range of conditions, easy to adapt, sensitive to relevant future climate and socio-economic variables, and that output impact indicators relevant for future water management. The models selected were Gustard *et al.* (1992) to simulate the low and high naturalised river flows, Szilagyi *et al.* (2003) to estimate the groundwater recharge, Flood Estimation Handbook – Catchment Descriptors method to simulate peak flows and the Environment Agency's Resource Assessment Management framework to estimate abstraction availability.

3 Case study regions and scenarios

This study was applied to the contrasting North West and East Anglia regions of England, which are described in Section 3.1 in terms of the key current elements that influence their modelling, *i.e.* climate, urbanisation, agriculture, water demand, water supplies and water discharges.

In order to explore the implications of possible futures in these two regions, scenarios of climate and socio-economic change consistent with the global narrative storylines of alternative paths of world development and resultant emission scenarios given by Nakićenović *et al*. (2000) (Section 3.2.1) were used. Scenarios represent plausible alternative futures, shaped by human choices and actions, which are unlike the past (DTI, 2002); are statements about some of the possible futures; are propositions of what could be and not predictions about what will happen (Morris *et al.*, 2004a). Climate scenarios developed on behalf of the UK Climate Impacts Programme (Hulme *et al*., 2002) that will be used for the quantification of regional projections of climate for the 2020s and 2050s High and Low emission scenarios are described in Section 3.2.2.

Socio-economic scenarios are necessary for factoring in non-climatic stresses and capacities to adapt and how these might change, which will alter the critical thresholds at which adaptation to climate change becomes necessary, in some cases delaying or obviating the need for planned adaptation, but in others making such adaptation far more urgent (Pittock and Jones, 2000). To quantify the regional pressure variables of socio-economic and political alternative futures reflecting different social values and systems of governance, the regionalised socio-economic storylines developed by Shackley and Deanwood (2003) as a part of RegIS specifically for East Anglia and the North West were selected and are described in Section 3.2.3.

3.1 Characterisation of the case study regions

The study has used the two contrasting regions of East Anglia and the North West England (Figure 3-1). East Anglia consists of the counties of Norfolk, which contains the Broads National Park, Suffolk and Cambridgeshire and is part of the Environment Agency's larger Anglian region (Figure 3-8). The North West consists of Cumbria, which contains the Lake District National Park, Lancashire, Merseyside, Great Manchester and Cheshire. For the purpose of this thesis, the terms *East Anglia* and the *North West* will refer to these geographic areas.

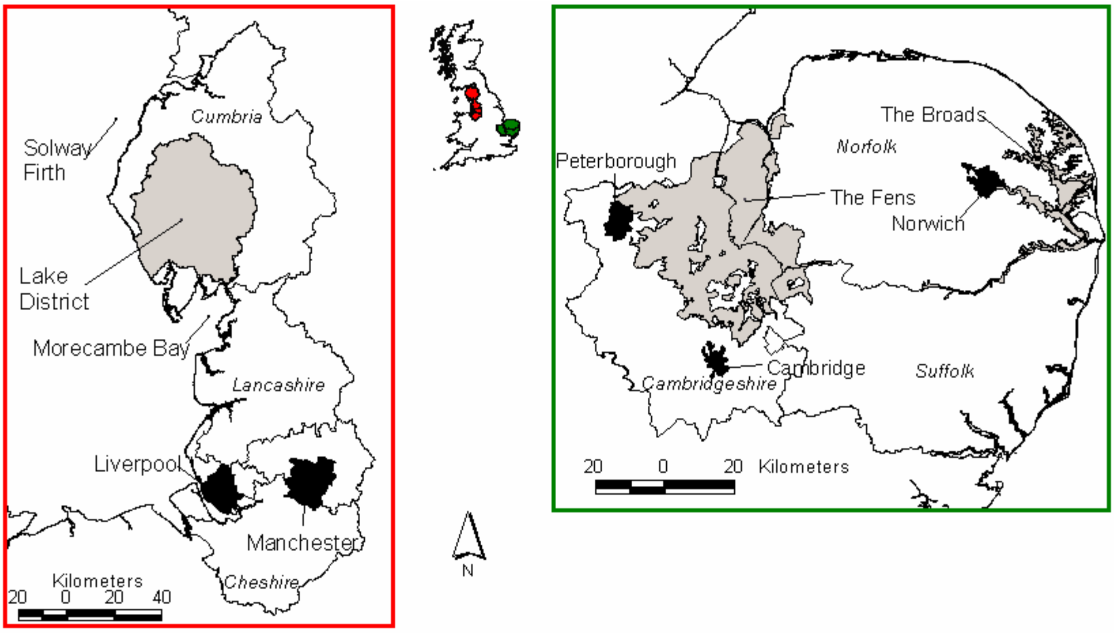


Figure 3-1: Case study regions of North West (left) and East Anglia (right) (from Holman *et al.,* 2005b).

3.1.1 The catchments

The geographical boundaries of the counties do not match the hydrological compartments. There are approximately 200 catchments in both regions represented in Figure 3-2, some of which are located outside the boundaries of the regions but flow into the regions.

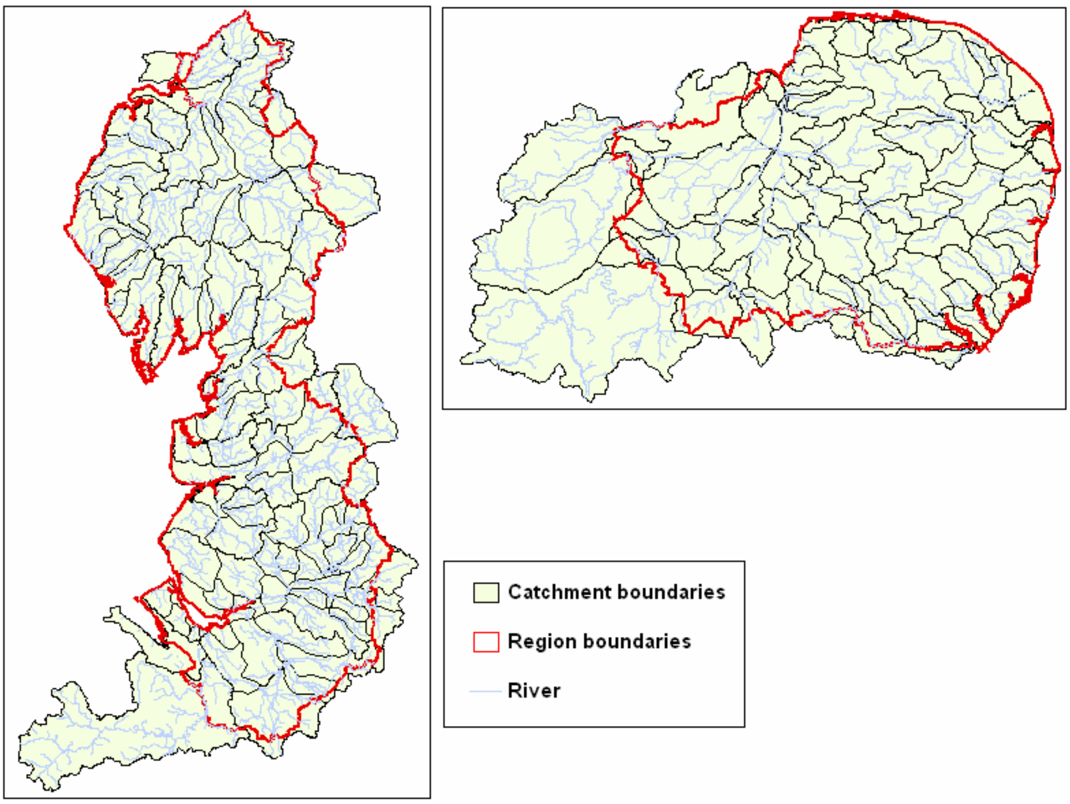


Figure 3-2: Catchments and sub-catchments in the North West (left) and East Anglia (right).

3.1.2 Current climate

In terms of climate, the low-lying East Anglia is relatively dry and warm being the region in Britain least affected by the moderating influence of the sea (Holman *et al.*, 2005b) whereas the North West, with its diversity of topography and proximity to the Atlantic Ocean, is wet and cooler (Figure 3-3). In the catchments of East Anglia, the average annual rainfall ranges from 535 to 670 mm (for the period 1961-90), equally distributed over the year, *i.e.* 50% of the precipitation occurs in each of the winter and summer half-years (from October to March and April to September, respectively). The catchments in the North West have an average annual rainfall that is more variable, due to the effects of altitude, between 720 and 2230 mm, where 56% of the precipitation occurs during the winter half-year.

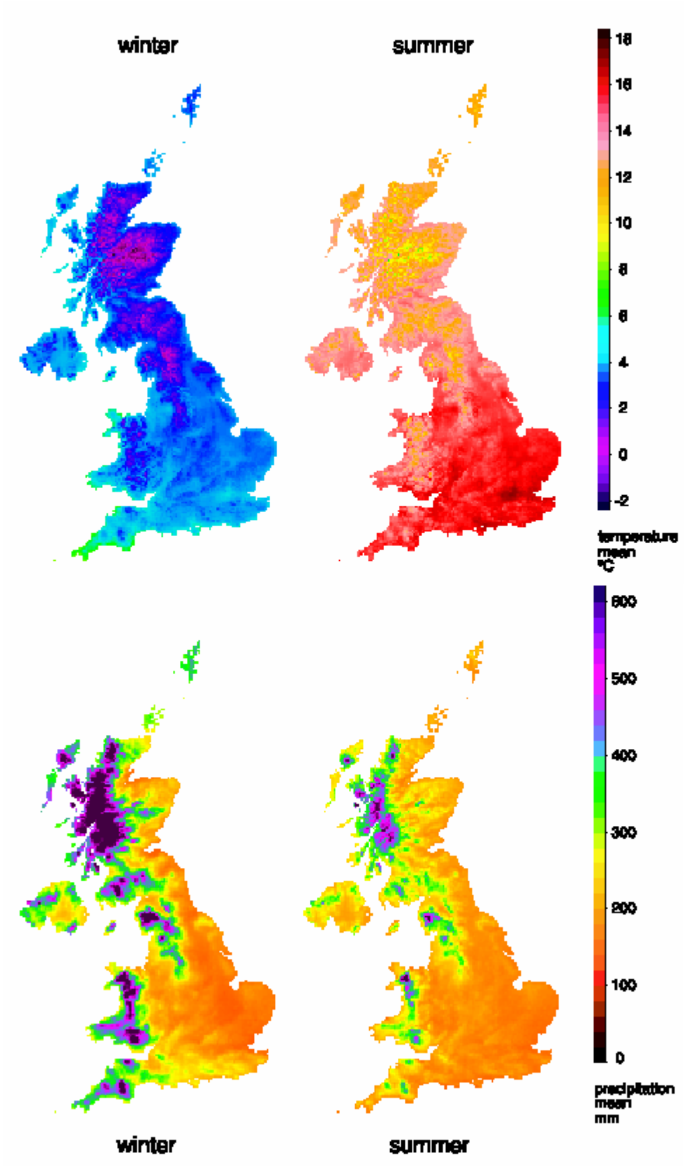


Figure 3-3: Average observed 1961-1990 winter and summer temperature (top) and precipitation (bottom) in the UK (Hulme *et al.*, 2002).

3.1.3 Urbanisation

In terms of urbanisation, East Anglia is thinly populated, with 2.2 million inhabitants, except in key urban centres such as Cambridge, Norwich and Peterborough (Figure 3-1). It has a high population growth rate. The urban development in the North West is focused in the south around the conurbations of Liverpool and Manchester (Figure 3-1) and coastal resorts such as Blackpool and the region has 6.8 million inhabitants. Figure 3-4 illustrates the urbanisation in the regions, *i.e.* the urban (contiguous residential commercial and industrial urban areas) and the suburban (suburban and rural development) land classes from the Centre for Ecology and Hydrology - Land Cover 2000 data (Fuller *et al.*, 2002).

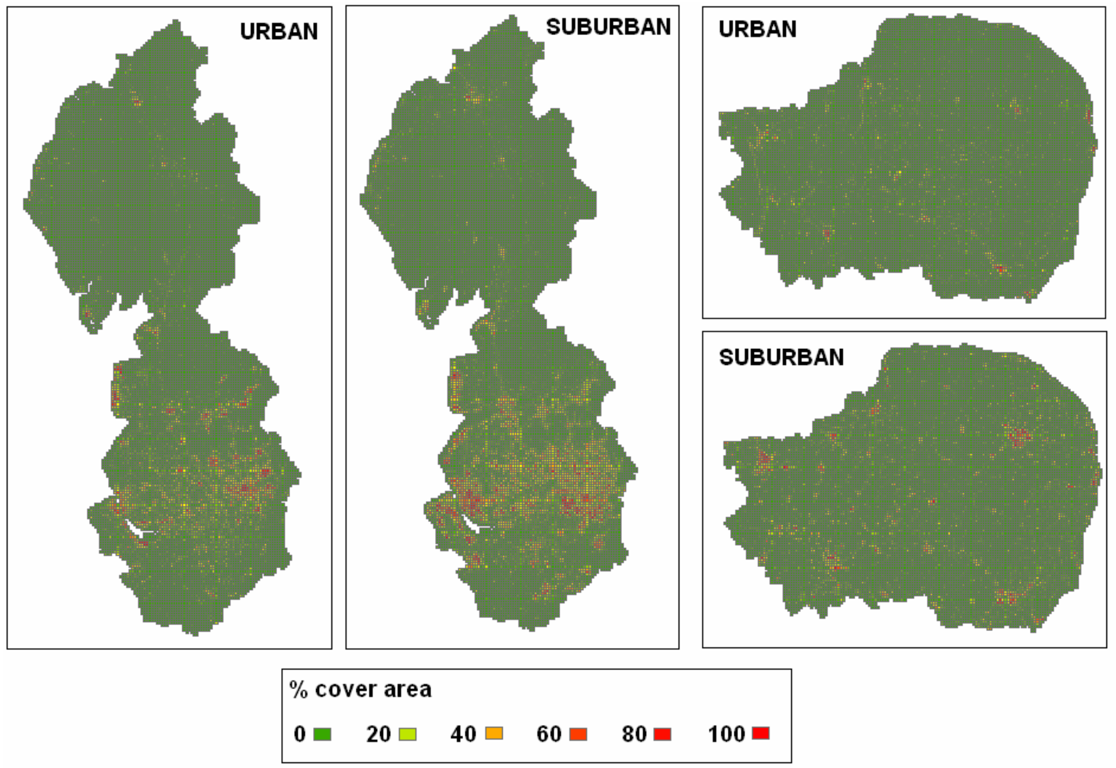


Figure 3-4: Urban and suburban land classes from the Land Cover 2000 data in the North West (left) and East Anglia (right) regions.

3.1.4 Water demand

The water demand in East Anglia (900 Ml/d) is significantly smaller than in the North West (2800 Ml/d) (Appendix 1). The distribution of the demand for the different purposes varies in the regions (Figure 3-5). The household per capita consumption of water is the same in both regions: 140-160 l.p^{-1}.d.$^{-1}$ (in 1997/98, Environment Agency, 2001 pp.25), however the domestic water demand in higher in the North West due to the greater regional population. The composition of industrial and commercial sectors in the regions is significantly different. Although approximately half of the industrial and commercial demand is from the industry sector, in the North West the majority is from the chemicals industry (22%) and in the Anglian region is from Food and Drink industry (17%) (Downing *et al*., 2003). In the Anglian region the service sector accounts for 38% and agriculture for 13% of the demand for industrial and commercial purposes (Downing *et al*., 2003). In the North West, the service sector uses 26% and agriculture only 3% of the water demand for industrial and commercial purposes (Downing *et al*., 2003). The total water demand for industrial and commercial water demand in East Anglia is 238 Ml/d and in the North West is 1160 Ml/d (in 1997/98, Environment Agency, 2001c; Appendix 1). In East Anglia, a significant proportion of water is directly abstracted for agricultural irrigation (169 Ml/d, Environment Agency, 2001c; Appendix 1). Finally, leakage accounts for 23 and 39% of the public water supply in East Anglia and the North West, respectively (Environment Agency, 2001c; Appendix 1).

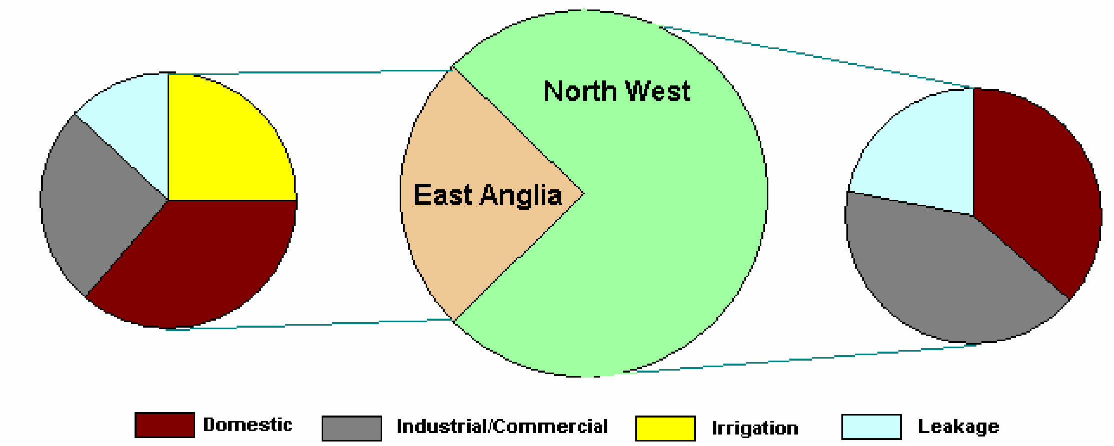


Figure 3-5: The distribution of water demand for the different purposes in East Anglia and the North West under baseline conditions.

3.1.4.1 Agriculture and irrigation demand

Agriculture in East Anglia is intensive with an emphasis on arable agriculture mainly for cereals and general cropping (Figure 3-6). Irrigation is high (Figure 3-7), mainly for potatoes and vegetables (Table 3-1). During peak periods, irrigation can account for more than 70% of the total abstraction in the intensive irrigated areas (Morris *et al.*, 2004b). In 2001, 54% of irrigated cropping area and 52% of the water abstracted for irrigation in England and Wales was used in the Anglian region (Weatherhead and Danert, 2002). In addition, an increasing proportion of irrigation water is coming from the mains (Downing *et al.*, 2003).

In the North West, agriculture is characterised by extensive grazing for sheep in the uplands (north and along the eastern boundary), permanent grassland for sheep and cattle in the lower hills and mixed arable and diary farming in low lands (south and west) (Figure 3-6; Holman *et al.*, 2005b). The demand for irrigation in this region was only 1% of the estimated actual national irrigation abstraction in 2001 (Figure 3-7; Weatherhead and Danert, 2002).

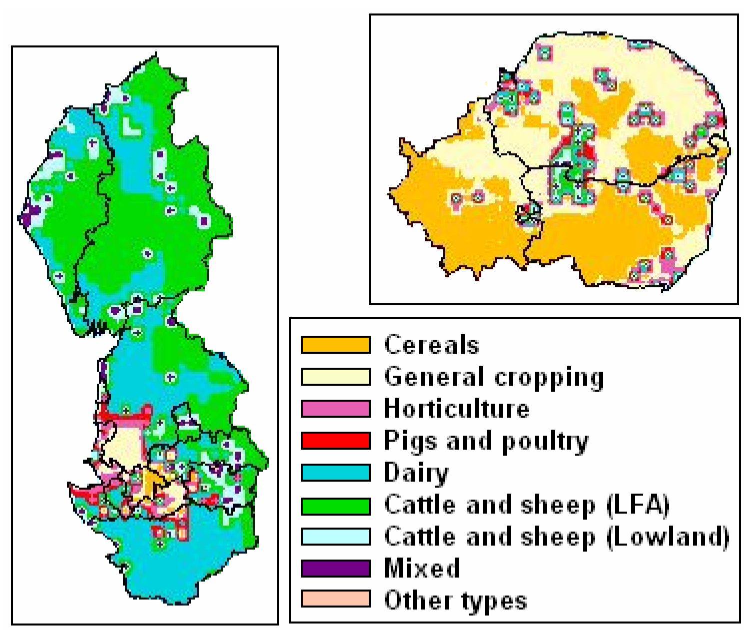


Figure 3-6: Dominant farm type by 5 km grid square on the North West (left) and East Anglia (right) from the 2003 Agricultural Census in England (http://www.defra.gov.uk/esg/work_htm/publications/cs/farmstats_web/misc_maps/Dominant_farm_types.jpg).

Table 3-1: Distribution of irrigated crop area and irrigation water use in Anglian and North West regions in 2001 (from the Survey of Irrigation of Outdoor Crops 2001 in England by Weatherhead and Danert, 2002).

Crops	Irrigated crop area (%)		Irrigation water use (%)	
	Anglian	North West	Anglian	North West
Early potato	6	14	5	9
Main crop potato	51	39	58	38
Sugar beet	6	0	2	0
Orchard fruit	1	0	1	0
Small fruit	2	0	2	0
Vegetables	25	28	25	19
Grass	2	7	1	13
Cereals	4	0	1	0
Other crops	5	12	5	22

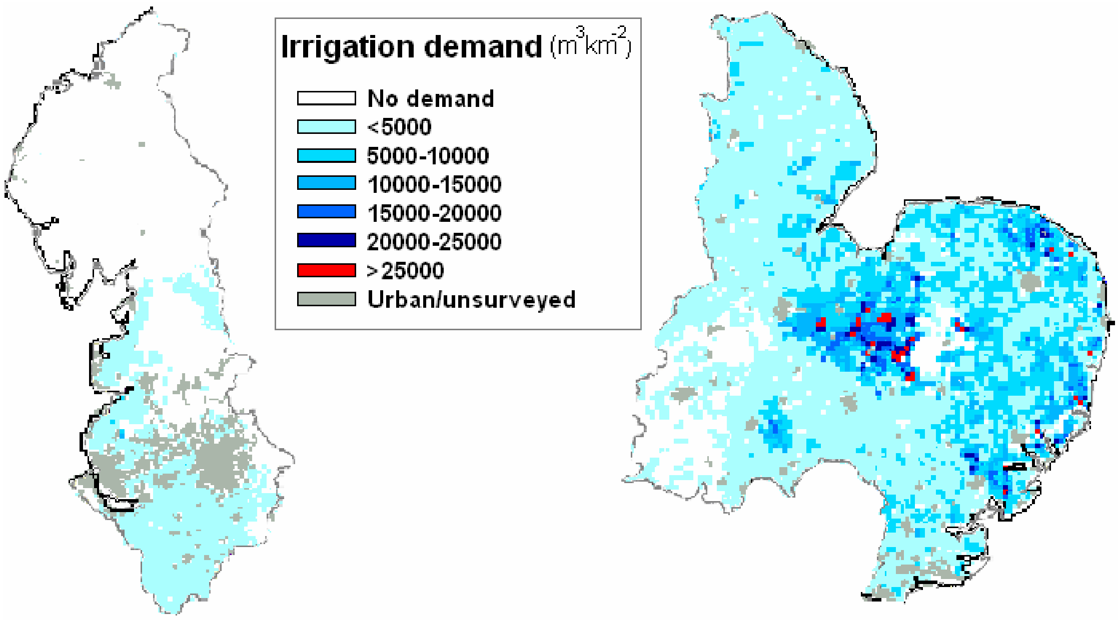


Figure 3-7: Total volumetric irrigation demand in a design dry year for all crops for the North West (left) and Anglian regions (right) (from Weatherhead *et al*., 1997).

3.1.5 Water management

The Environment Agency is responsible for managing water resources in England. One of the ways that this is done is through licensing water abstraction using Catchment Abstraction Management Strategies (CAMS). Water companies also manage the water resources. The relevant water supply companies in East Anglia are Anglian Water Services, Essex & Suffolk Water and Cambridge Water Company (Figure 3-8). The sewerage services are solely carried out by Anglian Water Services in the whole region. In the North West, the water company is the United Utilities which provides both water supply and sewerage services.

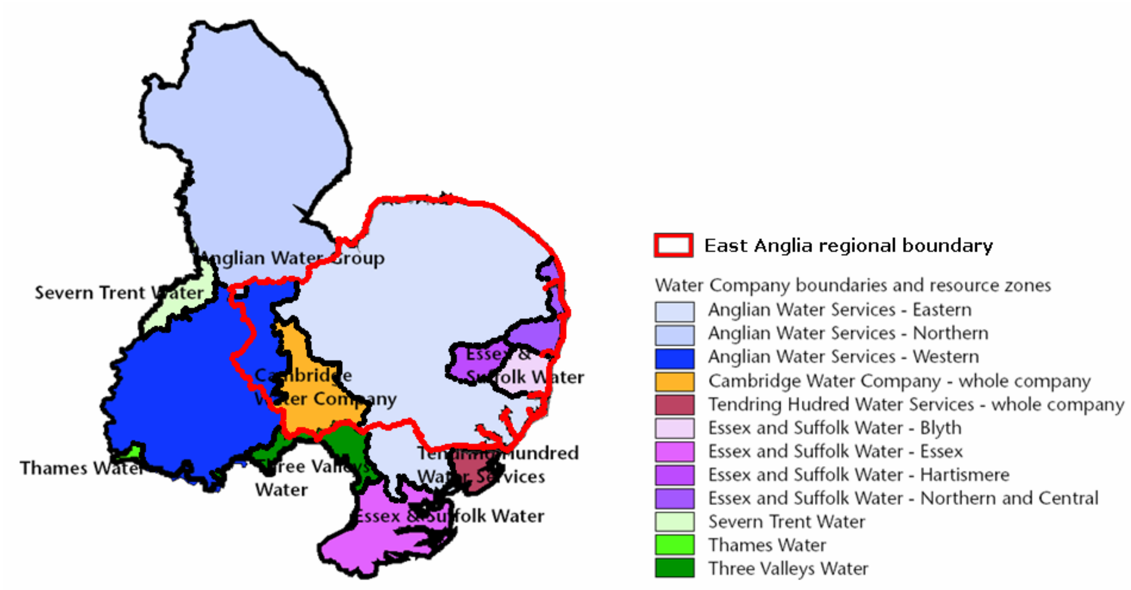


Figure 3-8: Water company boundaries and resource zones in the Anglian region (Environment Agency 2001c) and East Anglia.

3.1.5.1 Water supply in East Anglia

In terms of water supply, East Anglia depends approximately equally on surface and groundwater. For the years 1997/98, in the Anglian region 59% of water was abstracted from the surface and 41% from the ground (Table 23c and Table 23 d in Defra, 2005) and in east Suffolk, Norfolk (Norwich) and Great Ouse (Cambridge) the proportions were 46% and 54%, respectively (based on data provided by Pauline Jowett from Environment Agency, *Pers. Comm.*). In East Anglia, groundwater is found principally in Cretaceous and Quaternary unconfined aquifers in Norfolk and Suffolk (British Geological Survey, 1981; Allen *et al.*, 1997; Jones *et al.*, 2000).

In East Anglia there are two major reservoirs (Figure 3-9), the Alton Reservoir which has a reliable yield of 30 Ml/d (National Rivers Authority, 1994) and the Grafham Water reservoir. Imports to the eastern zone are 7 Ml/d from the Anglian Water Services Western zone and 11.05 Ml/d from the Ardleigh Reservoir (in 1997/98, from Anglian Water Services Ltd, 1999). There are also 1.78 Ml/d of water transfers between Essex Water Co and the eastern zone (in 1997/98, from Anglian Water Services Ltd, 1999).

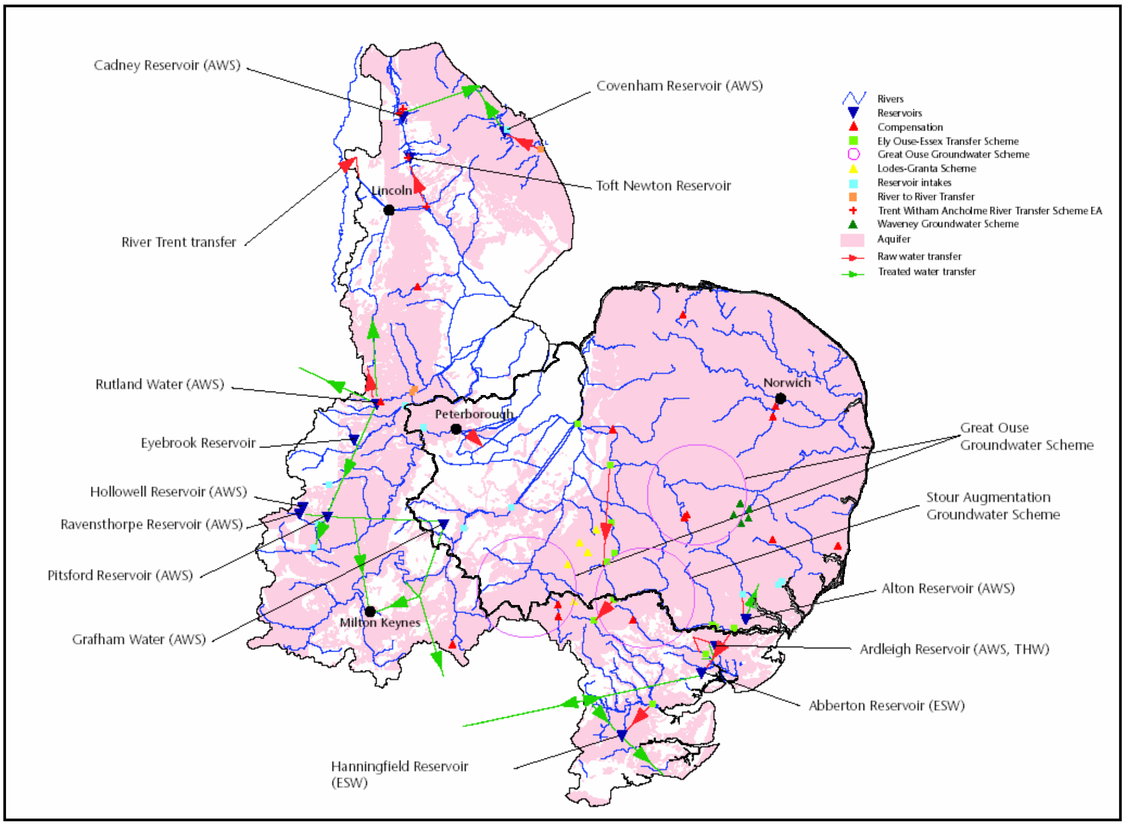


Figure 3-9: Major elements of the Anglian region water resources (Environment Agency, 2001c), where the borders of East Anglia are marked with a black line.

3.1.5.2 Water supply in the North West

In the North West, most water supplies come from surface waters, approximately 90% (for the years 1997/98 from Table 23c and Table 23 d in Defra, 2005; Mark Smith from United Utilities, *Pers. Comm.*). There are few important aquifers apart from the Traissic sandstones, and the ones that exist are confined (Mott Macdonald and Environment Agency, 1997; Allen *et al.*, 1997).

In the North West (Figure 3-10), net reservoir storage capacity is approximately 1200 Ml/d, from which 700 Ml/d are within the region (Mark Smith from United Utilities, *Pers. Comm.*), and 830 Ml/d was the average abstraction for the years 2002-2005 (Janet Bromley from United Utilities, *Pers. Comm*). In terms of water transfers, there are no water exports and the water imports are from the River Dee and Lake Vyrnwy accounting for 735 Ml/d (based on data from 1997-2003 provided by Janet Bromley form United Utilities, *Pers. Comm*).

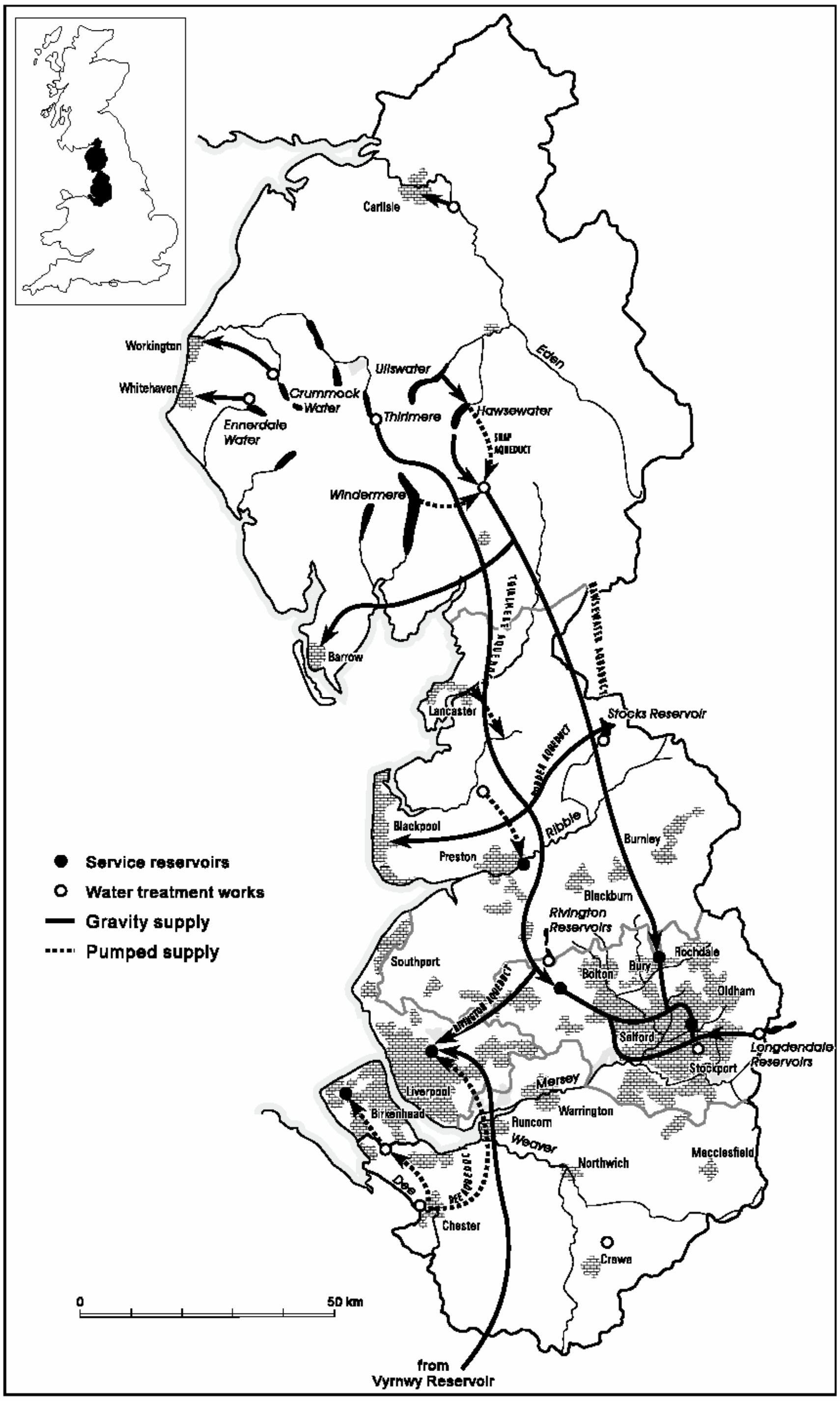


Figure 3-10: Major elements of regional water resources in the North West (Shackley *et al.* 1998)

3.1.5.3 Water discharges

The spatial distribution of Sewage Treatment Works differs between the regions (Figure 3-11). In the North West they are concentrated around key urban areas in the south, whereas in East Anglia they are homogenously distributed. Moreover, tertiary treatment of effluent is more common in East Anglia due to the higher sensitivity to eutrophication and to nitrate loads of the receiving water bodies (Figure 3-11).

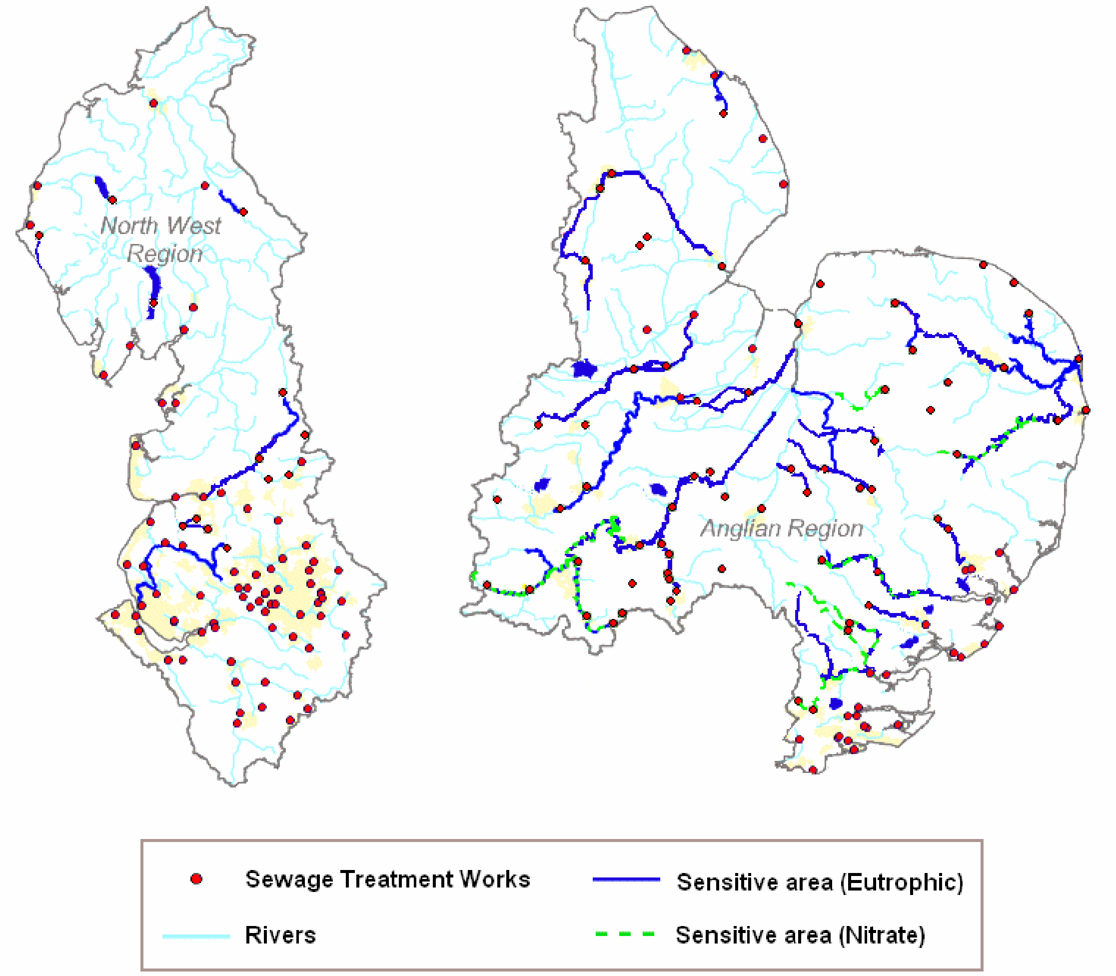


Figure 3-11: Location of Sewage Treatment Works and identification of sensitive river reaches in terms of eutrophication and nitrates in the North West (left) and Anglian (right) regions (http://www.defra.gov.uk/environment/water/quality/uwwtd/report02/images/england_wales.gif).

3.2 Description of the scenarios

3.2.1 The Special Report on Emissions Scenarios

Global socio-economic scenarios (*e.g*. Special Report on Emissions Scenarios (Nakićenović *et. al.*, 2000) and the third Global Environmental Outlook of the United Nations Environmental Programme (UNEP, 2002)) provide input drivers to climate models and a basis for impact estimates representing a diverse range of different development pathways for the world (Arnell *et al.*, 2004). In the IPCC's Special Report on Emissions Scenarios (SRES) (Nakićenović *et al*., 2000), the starting point for each projection of future global emissions of greenhouse gas and other pollutants was a narrative storyline describing the way world population, economies and political structure may evolve in the next decades. Four storylines were defined representing different world futures in two core dimensions of social change *i.e.* social values (economic and environmental) and systems of governance (global and regional) (Figure 3-12 and Table 3-2).

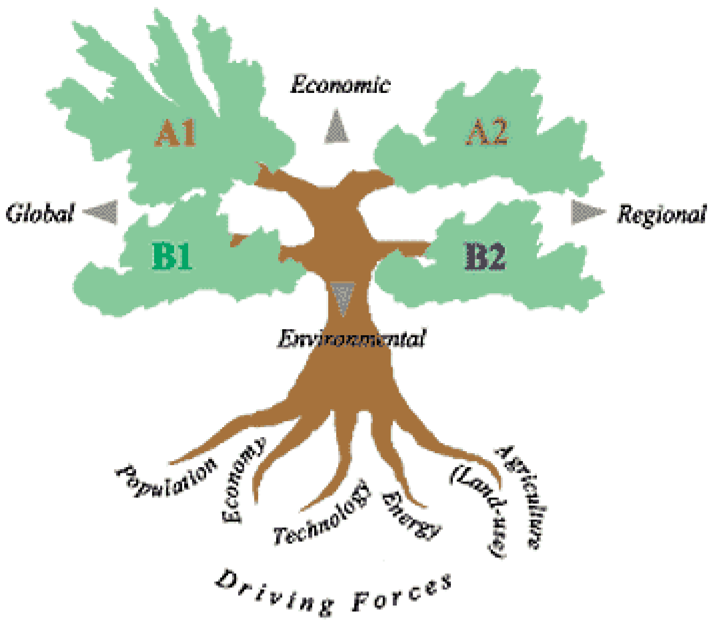


Figure 3-12: Schematic illustration of the SRES scenarios (Nakićenović *et al.*, 2000).

Table 3-2: The main characteristics of the four SRES storylines and scenario families (Nakićenović *et al.*, 2000)

	The characteristics of the SRES storylines and scenario families
A1	Describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system and are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
A2	Describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	Describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	Describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

3.2.2 Climate scenarios

The Hadley Centre for Climate Prediction and Research undertook climate change experiments driven by four different emissions scenarios that span the SRES emissions range (three for medium high (A2) and one for medium low (B2) emission scenarios) for the worldwide reference baseline of 1961-1990 (Hulme *et al.*, 2002) and for the 2080s (2071-2100). These experiments used a coupled ocean-atmospheric global climate model (HadCM3) which drove a higher resolution global atmospheric model (HadAM3H) which in turn was used to drive a high resolution regional atmospheric model for Europe (HadRM3 with a 50 km resolution) (Hulme *et al.*, 2002). The use of these models that are widely recognised provides greater regional spatial detail.

The UK Climate Impacts Programme (UKCIP) developed the UKCIP02 scenarios (Hulme *et al.*, 2002) from this work. Firstly, climate change scenarios for the 30 year periods centred in 2020s (2010-2040) and 2050s (2041-2070) and for climates which would arise if future global emissions followed higher or lower emissions pathways, were derived using the pattern-scaling procedure based on A2 regional patterns. Secondly, UKCIP used the available observed climate data at a 5 km resolution to create a set of 5 km climate scenarios by interpolating the 50 km changes in simulated climate generated by HadRM3 (compared to the simulated current data) onto the high resolution observed baseline climate data.

Although Hulme *et al.* (2002) describes and presents the four possible climate futures for the UK (Low, Medium-Low, Medium-High and High global emission scenarios) (Table 3-3) for the 2020s, 2050s and 2080s time-slices at a 5 km spatial scale, they advise not to interpret results at a scale smaller than the regional climate model resolution (50 km).

Table 3-3: Links between the SRES storylines and the UKCIP02 climate scenarios (Hulme *et al.*, 2002)

SRES Storyline	UKCIP02 Climate change scenario
B1	Low emissions
B2	Medium-low emissions
A2	Medium-high emissions
A1FI	High emissions

In this study, the UKCIP02 scenarios were used for the 2020s and 2050s time slices and for the Low and High emissions scenarios in order to capture the effects of uncertainties in future greenhouse gas emissions. Comparing the HadCM3 with other GCMs, Hulme *et al*. (2002) observed that it produces results for the UK which are about in the middle of the range for winter, but which are near the extreme of drying for summer and that the summer rainfall changes are already perhaps at the drier end of the range. The scientific uncertainty (Section 2.3.1) of using UKCIP02 scenario is analysed in Section 7.1.1 and Section 7.1.2 using the uncertainty margins recommended by Hulme *et al*. (2002). The use of these climate scenarios is likely to overestimate the impacts of climate change on the water resources.

From Figure 3-13, it can be generally observed that under the scenarios there is a greater summer warming in the southeast than the northwest and that warming is greater in summer (June-August) than in winter (December-February). Moreover, for the 2020s, the increase in mean temperature is not as significant as for the 2050s; for example, in East Anglia the increase relative to 1961-90 ranges from 0.8 to 1.0ºC for the 2020s and 1.5 to 2.3ºC for 2050s and in the North West the increase ranges from 0.7 to 0.9ºC for the 2020s and 1.3 to 2.1ºC for the 2050s.

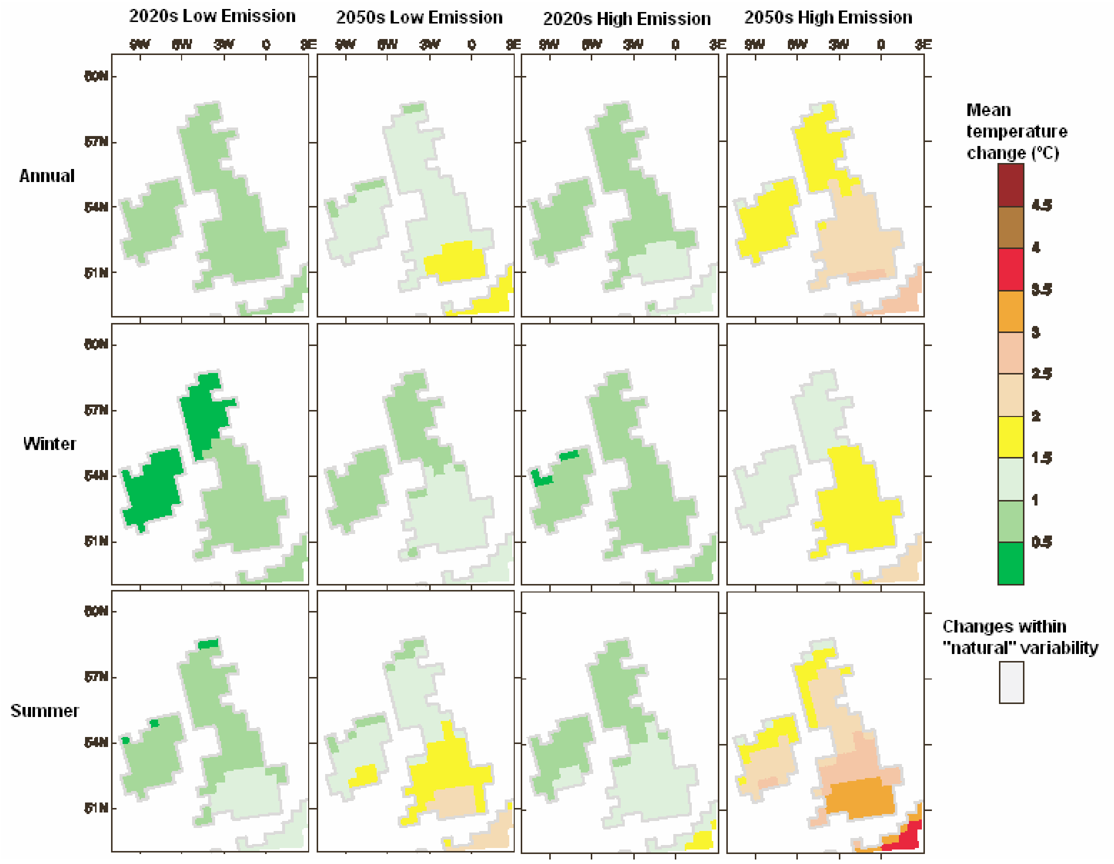


Figure 3-13: Change (ºC) in average annual, winter and summer temperature from simulated 1961-90 climate for the 2020s and 2050s Low and High emission scenarios for the UK (Hulme *et al.*, 2002).

Concerning the average annual precipitation, from Figure 3-14 it can be observed that there is generally little average annual change; relative to 1961-90, at a national level, changes range from -4 to +3% by the 2020s and -9 to +7 by the 2050s. However, there is a trend for wetter winters and drier summers. In spring and autumn, the changes in precipitation are small. For the 2020s Low and High emission scenarios both in East Anglia and the North West, winter half-year precipitation increases by 3% and summer half-year precipitation decreases by -6% and -7% for the 2020s Low and High respectively in both regions (Table 3-4). In the 2050s, changes are more significant and for the North West and East Anglia regions. In both regions winter half-year precipitation increases by +5% and +8% under the 2050s Low and High respectively and summer half-year precipitation decreases by a range of -11 to -18% (Table 3-4).

Evapotranspiration, calculated from UKCIP02 climate data using the Penman-Monteith method and provided by RegIS2, shows significant increases under the 2050s climate (Table 3-4) by 6 to 7% under the Low emission scenario and by 9 to 10% under the High emission scenario, for East Anglia and the North West respectively.

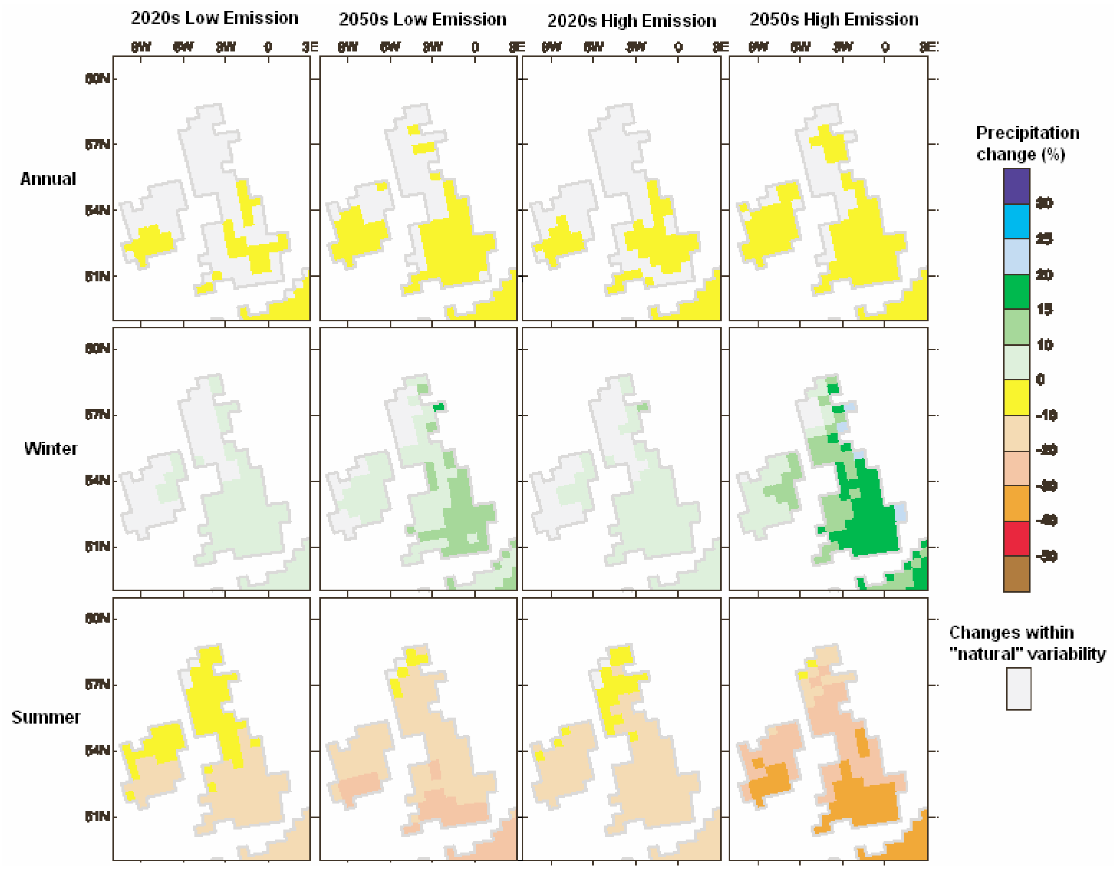


Figure 3-14: Change (%) in average annual, winter and summer precipitation from simulated 1961-90 climate for the 2020s and 2050s Low and High emission scenarios for the UK (Hulme *et al.*, 2002).

Table 3-4: Percentage change in summer and winter half-year precipitation and evapotranspiration in East Anglia and North West regions (RegIS2 dataset based on UKCIP02 data for all 5 km relevant grid cells).

	Climate scenarios	**East Anglia**		**North West**	
		Average	Standard deviation	Average	Standard deviation
Summer precipitation (mm)	2020s Low	-6.45	0.58	-6.18	0.87
	2020s High	-7.67	0.69	-7.35	1.04
	2050s Low	-11.51	1.04	-11.03	1.55
	2050s High	-18.29	1.65	-17.52	2.46
Winter precipitation (mm)	2020s Low	2.68	0.39	2.70	0.61
	2020s High	3.19	0.48	3.21	0.73
	2050s Low	4.78	0.70	4.81	1.09
	2050s High	7.59	1.12	7.64	1.74
Evapotranspiration (mm)	2020s Low	3.26	0.15	2.81	0.60
	2020s High	2.21	0.16	1.71	0.59
	2050s Low	6.95	0.37	6.44	1.00
	2050s High	10.26	0.78	9.09	1.32

Hulme *et al*. (2002) point out that wetter winters are the result of an increase in the frequency of wet days and in the number of 'intense'[2] precipitation events and those 'intense' rainfall events become less frequent in summer everywhere. In the North West 'intense' rainfall events increase more in winter and decrease more in summer than in East Anglia (Figure 3-15).

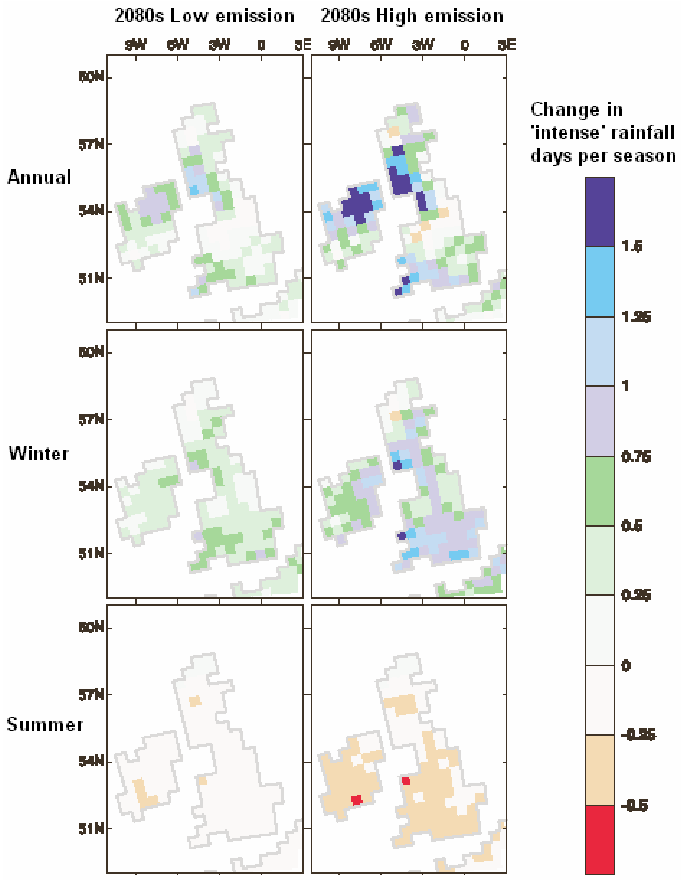


Figure 3-15: Change in the number of 'intense' rainfall days in an average season for the 2080s Low and High emission scenarios (Hulme *et al.*, 2002).

[2] An 'intense' rainfall amount is the value reached that provides the uppermost 10% (or 90th percentile) of the total seasonal precipitation (Hulme *et al.*, 2002).

3.2.3 Socio-economic scenarios

The generalised quantitative descriptors associated with the SRES storylines need to be downscaled to the spatial and temporal scales relevant to impact assessments. Arnell *et al.* (2004) describe how the SRES storylines, in terms of population and economic data, were characterised and applied at national and sub-national scales in order to assess the global scale implications of changes in climate. In the UK, a set of socio-economic scenarios consistent with the SRES storylines have been defined at the national scale (*e.g.* DTI, 2002; UKCIP, 2001) and at a regional scale (*e.g.* Shackley and Deanwood, 2003; Shackley and Wood 2001).

The UK-oriented socio-economic scenarios produced by the Foresight Programme of the UK Office of Science and Technology (DTI, 2002) describe social, political, economic, institutional and environmental circumstances in the UK during the period 2010-2030 (DTI, 2002). However, due to the need for more strategic and innovative perspectives, socio-economic scenarios for the UK based on the Foresight work were developed by the UKCIP (2001) for use in climate change impact assessment. These socio-economic scenarios have a more explicit regional and sectoral detail providing quantified values for a range of indicators, covering economic development, planning and built environment, agriculture, water, biodiversity and coastal zone management. These two sets of scenarios for the UK have been widely used as a starting point for the development of consistent and coherent specific scenarios which provide a set of standard, unifying assumptions about the basic social and economic dimension of change. Examples include Shackley and Deanwood (2003) for developing urban development patterns; Environment Agency (2001b) for forecasting water demand; Morris *et al.* (2004a) for creating agriculture and water policy scenarios. Table 3-5 shows how the different scenarios fit together.

Table 3-5: Links between the global SRES storylines and the various national/regional socio-economic scenarios (Hulme *et al.*, 2002)

SRES Storyline	**OST Foresight Scenario**	**UKCIP Socio-economic scenario**	**Environment Agency scenario**
B1	Global Sustainability	Global Sustainability	Gamma
B2	Local Stewardship	Local Stewardship	Delta
A2	Provincial Enterprise	National Enterprise	Alpha
A1FI	World Markets	World Markets	Beta

The socio-economic scenarios developed in RegIS for East Anglia and the North West (Holman *et al*., 2005a; Shackley and Deanwood, 2003; Shackley and Wood, 2001) are regionalised versions of the UKCIP socio-economic scenarios and were derived from an iterative procedure between researchers and stakeholders with interest in the sectors under consideration at national, regional and local levels. Within RegIS2, these scenarios were refined and updated. The four socio-economic scenarios are Regional Enterprise, Regional Stewardship, Global Markets and Global Sustainability (Table 3-6). They were all used in this study as multiple scenarios representing a plausible range of alternative futures are needed, to explicitly acknowledge the inherent uncertainty in such projections due to the lack of fundamental understanding of the processes determining socio-economic change (Holman *et al.* 2005a).

Table 3-6: Description of the four socio-economic scenarios (Shackley and Deanwood, 2003).

Socio-economic scenarios	
Regional Enterprise	This scenario is the most bullish of the four scenarios, suggesting vibrant, semi-autonomous regions, keen to promote and maintain their distinctive qualities in a highly competitive world. A key to their success will be the imaginative development of assets and core strengths, some economic, some social, others environmental.
Regional Stewardship	The emphasis in this scenario is on recognising and conserving regional assets, accepting that this might result in a significantly reduced level of economic growth and even a contraction of the economy in some respects. This is accepted because of the pursuit of a more all-embracing means of living, one which recognises the importance of community and the value of local natural assets.
Global Markets	This scenario is based on the pursuit of high and sustained growth within a global context. All regional assets will be brought to bear in this ambition and significant risks will be taken as to the precise composition of the development path.
Global Sustainability	In this scenario the global approaches to achieving sustainable development take precedence over regional responses. The World is seen as an interconnected whole, functionally and morally, with a concentration on the wider impacts of individual actions.

Under the Regional Enterprise (RE) scenario, there is an economic growth, higher in East Anglia than in the North West, accompanied by an increase in the regional population (Shackley and McLachlan, 2005). In East Anglia, increased urbanisation grows throughout the region, whereas in the North West development occurs particularly along transport corridors (Shackley and McLachlan, 2005). The environment is seen as a commodity which can be traded, although where direct economic gain can be demonstrated, assets will be highly valued (Shackley and Wood, 2001; UKCIP, 2001). However, generally the environment is perceived as a low priority issue with little investment and increased pressures placed on natural resources (UKCIP, 2001). In terms of water resources, surplus water from one region (such as North West) is exported to other parts that suffer water shortages (such as East Anglia) (Shackley and McLachlan, 2005).

The Regional Stewardship (RS) scenario is characterised by conservation of resources and the natural environment through strong political objectives (UKCIP, 2001). The policy succeeds as a result of changes in economic activity, social behaviour, institutional development and technology (UKCIP, 2001). Economic activity moves to small businesses and co-operatives with a stabilised Gross Value Added in both regions (Shackley and McLachlan, 2005). Working at a regional level, environmental problems are resolved through collective action (Environment Agency, 2002) using technology and ingenuity. High priority is placed on the environment; for instance: water use is highly efficient reducing the demand and environmental externalities are incorporated into economic costs at a relatively high level (Shackley and Deanwood, 2003). The capacity of different regions to achieve this balance varies greatly, and leads to diverse and sometimes perverse outcomes (UKCIP, 2001), in the North West, there would be a limited increase in production from the region (Shackley and McLachlan, 2005).

The Global Markets (GM) scenario is characterised by patchy economic growth and an increased population. In East Anglia higher development occurs in the southern part and around Cambridge and in North West the strategic places are in the south with post-industrial towns and urban cities in decline (Shackley and McLachlan, 2005). In high growth areas there is a significant exploitation of environmental resources to meet the overriding demands of global capital (Shackley and Deanwood, 2003). The awareness and concern for the environment is low and the use and management of natural resources are controlled by economic incentives, such as tradable permits (Environment Agency, 2001b). However, a greater emphasis is given to the environmental problems which immediately affect the population in the short term, such as the health-environment link, leisure and tourism (that increases in Norfolk, Suffolk and the Lake District, Shackley and McLachlan, 2005), to which explicit monetary values are ascribed (DTI, 2002; UKCIP, 2001; Shackley and Deanwood, 2003).

The Global Sustainability (GS) scenario is characterised by reconciling economic growth and sustainability (DTI, 2002) where environmental policy is based on a mix of market and regulatory instruments (UKCIP, 2001) increasingly co-ordinated at the European Union and international level (DTI, 2002). The population stabilises in the short term with some migration into rural areas (Shackley and McLachlan, 2005). There are significant increases in environmental quality (DTI, 2002), and high levels of investment in research and development result in the development of innovative clean technologies that benefit the environment (Environment Agency, 2001b). Water resources are managed at a national-level (and even an EU-level) with the aim being an equitable sharing of the resource (Shackley and McLachlan, 2005).

4 Development and validation of the Water Resources model

In this section the modelling methodology of the Water Resources model is presented and validated. The Water Resources model is divided into a number of components:

- The Mean Flow, the Flow Duration Curve and other indicators were simulated for all the sub-catchments and catchments in East Anglia and North West regions from the climatological and physical catchment descriptors (Section 4.1) making use of the integration with the climate and socio-economic scenarios and agricultural changes;
- the availability of water for abstraction was estimated for the sub-catchments and catchments (Section 4.2) from the Flow Duration Curve, allowing for the priority given to the environment according to the socio-economic scenarios;
- the regional water supply availability was derived from the water available in the catchments and balanced with the estimated water demand, accounting for supply and demand strategies within the socio-economic scenarios (Section 4.3).

Detailed information on the inputs, outputs and linkages are illustrated in Figure 4-1.

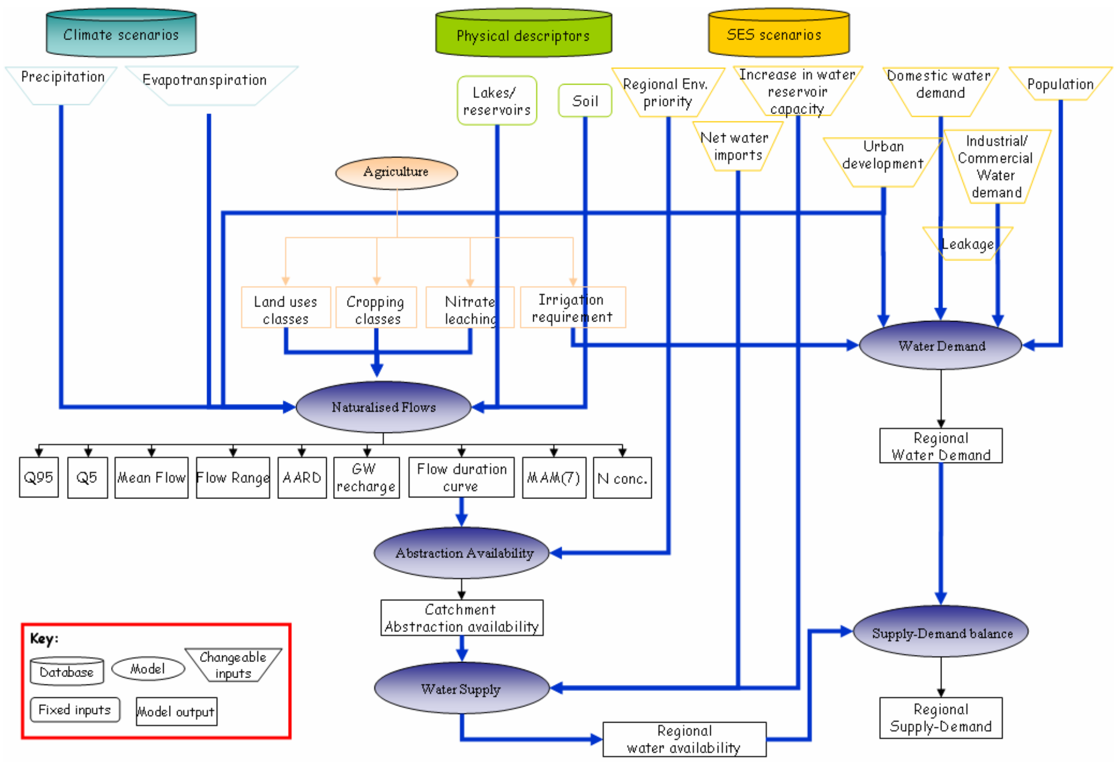


Figure 4-1. Detailed diagrammatic representation of the Water Resources model.

The non-naturalised low and high flows (as given by the 95th and 5th percentile flows, respectively) were also estimated at a catchment level from the estimated naturalised flows and the regional abstractions and effluent returns, and are presented in Section 4.4.

Finally, the operational validity (Appendix 2) of the developed model is presented in Section 4.5 through sensitivity analysis and in Section 4.6 by statistically comparing the outputs of the model with observed data for baseline.

4.1 Modelling methodology for estimating the naturalised flows

The Water Resources model uses the approach of Gustard *et al.* (1992) as the core method to simulate indicators of the impact of climate and socio-economic changes on the hydrology of the catchments (and sub-catchments, where the river flows from sub-catchment to sub-catchment according to the FEH CD-ROM, 1999) in the regions (Section 2.4.2.1).

The first indicator estimated is the Mean Flow (MF), which is calculated from physical and climatological catchment descriptors using the catchment water balance equation developed by Gustard *et al.* (1992) for unknown land-use. It uses the average annual precipitation and evapotranspiration, the latter of which was re-scaled, for the different climate scenarios (Section 4.1.1.1). For known land-use, the methodology of Gustard *et al.* (1992) was improved in order to be sensitive to cropping classes (Section 4.1.1.3) and urban development patterns (Section 4.1.1.4) allowing an integration not only with climate scenarios, but also with socio-economic scenarios and agricultural changes.

From the MF and according to the soil types from the Low Flow HOST (Hydrology Of Soil Types) groups, Q95 and MAM(7) were estimated (Section 4.1.2) and from the MF and Q95, the FDC was estimated from which Q5 and the flow range (between Q95 and Q5) were derived (Section 4.1.3), according to Gustard *et al.* (1992). Finally, to incorporate water quality and groundwater issues, the mean nitrate concentration (Section 4.1.4) and the groundwater recharge were simulated (Section 4.1.5).

4.1.1 Estimation of the Mean Flow

Gustard *et al*. (1992) estimates the MF using a catchment water balance method derived from 687 catchments in the UK (R^2 = 0.981, factorial standard error = 1.25). From Equation 4-1, MF is estimated from the catchment drainage area (AREA) and average annual runoff depth (AARD), which is estimated using Equation 4-2 and represents the difference between the Standard Average Annual Rainfall (SAAR) and the evapotranspiration losses (LOSSES).

$$MF = AARD \times AREA \times 3.17 \times 10^{-5} \quad \textbf{4-1}$$

Where, MF is the mean flow, m^3/s

AARD is the Average Annual Runoff Depth, mm

AREA is the catchment area, km^2

$3.17x10^{-5}$ is for unit conversion

$$AARD = SAAR - LOSSES \quad \textbf{4-2}$$

Where, SAAR is the Standard Average Annual Rainfall (1941 – 1970), mm

LOSSES are the catchment losses due to evapotranspiration, mm

The LOSSES parameter is estimated using Equation 4-3 from the potential evapotranspiration[3] (ETp) in mm, where evapotranspiration is limited by the soil moisture deficit, *i.e.* the adjustment factor due to catchment dryness (r) increases with increasing SAAR and hence soil water availability. The time-step is the annual average over a 30-year period.

$$\begin{gathered} LOSSES = r \times ETp \\ \text{If } SAAR < 850 \text{ mm}, r = 0.00061 \times SAAR + 0.475 \\ \text{If } SAAR \geq 850 \text{ mm}, r = 1.0 \end{gathered} \quad \textbf{4-3}$$

Data to calculate the MF was available from the following sources:

- AREA, from Environment Agency's national catchment boundary dataset
- SAAR, for the baseline: from the Meteorological Office 5 km gridded baseline climatology, and for the 2020s and 2050s Low and High emission scenarios from the average annual rainfall data (on a 5 km grid) from the UKCIP02 scenarios.
- ETp, was calculated by the Environmental Change Institute at the University of Oxford as part of the RegIS2 project using the Penman-Monteith equation from the Meteorological Office 5 km gridded dataset for baseline conditions and from the UKCIP02 scenarios using monthly averages of maximum, minimum and mean temperature, total precipitation, wind speed and sunshine hours.

[3] The potential evapotranspiration (ETp) refers to the evaporation rate from a defined extensive reference surface, which closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen *et al.,* 1998).

4.1.1.1 Calibration of the catchment water balance method

The catchment water balance method (Equations 4-1, 4-2 and 4-3) was applied to every sub-catchment and catchment in both regions under baseline conditions.

The simulated MF was compared with gauged MF data (see validation section for details on gauged data) which showed that the method does not perform well for the baseline data in East Anglia (n = 30) (Figure 4-2), where negative values of MF and a wide scatter in the relationship are obtained. A better relationship was observed for the North West (n = 48), *i.e.* simulated = 0.76 x gauged + 0.29 and the determination coefficient is 0.9757 and the concordance correlation coefficient (Appendix 2) is 0.9404.

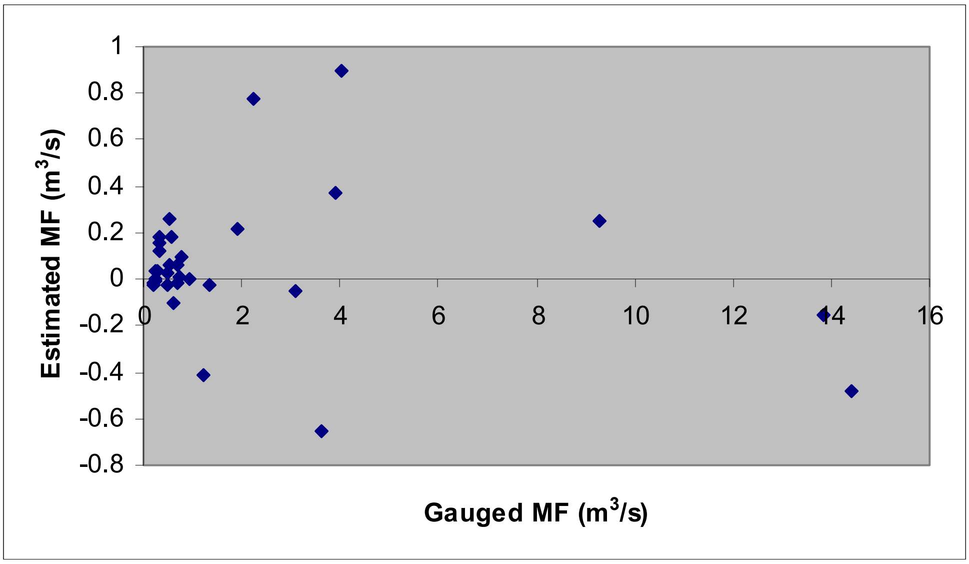


Figure 4-2. Relationship between estimated and gauged Mean Flow for East Anglia using the catchment water balance equations and the evapotranspiration dataset provided by RegIS2 project.

Although according to Holmes *et al.* (2002) Gustard's method has shown difficulties in predicting runoff in very low rainfall areas of the UK, the reason for such bad performance in East Anglia is believed to lie on the ETp dataset used. Gustard *et al.* (1992) provides details on evapotranspiration for 58 and 48 gauging stations in East Anglia and the North West, respectively, which are spread over all the hydrometric areas of the two regions. The annual average obtained is 525 mm for East Anglia and 448 mm for the North West (see Table 4-1). These values are similar to the regional evapotranspiration data derived from the agroclimatic zones contained within (Smith, 1984), which are 543 mm in East Anglia and 451 mm in the North West (see Table 4-1). Both data sources are for the period of 1941-70 and use the Penman equation to estimate ETp. However, the evapotranspiration data used in this study for the period 1961-90 is 702 mm for East Anglia and 625 mm for the North West per year (see Table 4-1). The overestimated ETp (in comparison to the ETp used by Gustard *et al.,* 1992) resulted in overestimated LOSSES for East Anglia, and the abovementioned negative MFs (where LOSSES exceeded SAAR) and underestimated MFs in the North West.

Table 4-1: Approximate average annual evapotranspiration (ETp) in East Anglia and the North West according to different methods, periods and climatological datasets.

	ETp in East Anglia (mm/year)	**ETp in the North West (mm/year)**	**Method for estimating the ETp**
Dataset used by Gustard *et al.* (1992)	≈ 525	≈ 448	A provisional version of mapped average annual ETp (1941-70) based on Penman equation was used for 687 gauging stations in the UK to derive the Low Flow Method.
The Agricultural Climate of England and Wales (Smith, 1984)	≈ 543	≈ 451	Monthly estimates of potential evapotranspiration were calculated from meteorological data (1941-70) using Penman equation (as detailed in MAFF, 1967) for a network of meteorological stations, from which isopleths of potential transpiration were drawn and average monthly PT calculated for each agroclimatic zone (Smith, 1984).
RegIS2 dataset	702	625	Penman-Monteith method to calculate the average monthly ETp from the average climate files for minimum and maximum temperature, precipitation, wind speed and solar radiation (calculated from cloudiness or sunshine hours) provided by the Meteorological Office at a 5 Km grid (1961-90).
Dataset used by Hess and Knox (*in press*)	≈ 616	≈ 526	The average monthly ETp dataset was derived at a 5 km grid scale using the FAO Penman-Monteith equation, where temperature, radiation, wind speed and humidity were extracted from the climatic dataset produced by the Meteorological Office (1961-90).
Dataset used by UKCIP 98	≈ 620	≈ 585	The average monthly ETp was calculated using the Penman formula with temperature, vapour pressure, radiation and wind speed as inputs at a 10 km grid scale (1961-90).

Other ETp datasets were used to assess if data provided by the RegIS2 project was overestimated (see Table 4-1). Hollis (2005) and Hess and Knox (*In Press*) suggest that the UKCIP02 simulated baseline data does not validate well when compared with observed climatology and therefore, only datasets with evapotranspiration estimated from observed climate data are considered. These include the dataset used by Hess and Knox (*In Press*) and UKCIP98 (Hulme and Jenkins, 1998). Both present approximate average annual values which are higher than Smith (1984) and Gustard *et al.* (1992) but lower than the ones provided by RegIS2. It is possible that the differences are due to different geographical scales, years and/or approach used to calculate ETp as shown by Oudin *et al*. (2005) for use in a daily rainfall-runoff model. Although no conclusion can be drawn as to which is the most accurate dataset, the derived evapotranspiration data of Hess and Knox (*In Press*), according to the authors, fit more closely to the weather station site data used in that study over all seasons and annually than the evapotranspiration provided by Smith (1984).

The ETp dataset provided by RegIS2 project for the World Meteorological Organisation Standard period (1961-90) was used for consistency within the project. However, it was re-scaled in order to obtain better results *i.e*. the water balance method was used with ETp within the range of the ETp used by Gustard *et al.* (1992). The ETp values for the baseline climate provided by RegIS2 at a 5 km grid were re-scaled by a conversion factor of 525/702 and 448/625 for East Anglia and the North West regions, respectively. Comparing the simulated flow derived using the re-scaled ETp data with gauged data (see Section 4.6.1), a significant improvement was achieved in the estimated MF. Regarding the ETp values for future UKCIP02 climate scenarios, the same re-scaling was undertaken because the 50 km resolution Regional Climate Model data was downscaled to 5 km using a process of simple interpolation to add the future change field onto the standard 1961-1990 5 km Met Office climatology (http://www.ukcip.org.uk/scenarios/guidance/faqs.asp#Q6).

It has been assumed that the average annual ETp for 1941-70 and 1961-90 do not differ significantly. Catchment MF calculated using the water balance method (Equations 4-1, 4-2 and 4-3) with Area, SAAR and ETp data for the period 1941-70 provided by Gustard *et al.* (1992) is very similar to the gauged MF in the National River Flow Archive (NRFA website) based on all the data available until the present date: for the 58 stations in East Anglia: simulated = 1.07 x gauged +0.14, r^2 = 0.9872 and for the 48 in the North West: simulated = 1.05 x gauged - 0.03, r^2 = 0.9763. However, recent measurements are believed not to be as close to the naturalised flows as for the period of 1941-70 (Tim Hess from Cranfield University, *Pers. Comm.*).

4.1.1.2 Land-use changes and losses from evapotranspiration

In the methods to estimate the MF presented by Gustard *et al*. (1992), the relationship between actual and potential evapotranspiration is empirical (Arnell *et al.*, 1990) and is insensitive to both land use differences between catchments (Arnell *et al.*, 1990; Gustard *et al*., 1992) and to land-use changes that might arise from future climate and socio-economic scenarios. Gustard *et al*. (1992) point out that a reason for the scattered relationship between r and SAAR is the influence of land use; *e.g.* catchments dominated by cereal crops may result in higher r value due to mean losses being lower than the mean potential rate for grass. The LOSSES parameter was therefore improved to be sensitive to land-use changes using a simple physically based approach, to allow integration of the Water Resources model with the changes in urbanisation (from the socio-economic scenarios) and cropping classes (from the Agriculture model as a consequence of climate and socio-economic changes).

For the catchments wholly inside the study area, where information on the agricultural and urbanisation land-use changes are available, the modified LOSSES parameter was estimated by the Water Resources model separately for agricultural crops (Section 4.1.1.3), urbanised areas (Section 4.1.1.4) and 'Other' land types using Equation 4-4 at a catchment level, where these components were weighted based on the catchment percentage area that they represent.

$$LOSSES = LOSSES_{Other} + LOSSES_{Crops} + LOSSES_{Urbanised} \qquad \textbf{4-4}$$

Where, $LOSSES_{Other}$, $LOSSES_{Crops}$, and $LOSSES_{Urbanised}$ are the losses due to evapotranspiration that occur in 'Other', agricultural and urbanised areas respectively, mm

In order to estimate the LOSSES from 'Other' land-uses, the Water Resources model uses Equation 4-5 with ETp re-scaled (as described in Section 4.1.1.1), with the percentage area within each 5 km grid as given by the Agriculture model converted into a percentage area within the catchment. Within those parts of catchments which extend outside the study area boundaries where information on future land uses are lacking, the LOSSES parameter has also been calculated using Equation 4-5 assuming all land-uses are 'Other'.

$$LOSSES_{Other} = ET_{p,re-scaled} \times r \times (Other)$$

$$\text{If SAAR} < 850 \text{ mm, } r = 0.00061 \times \text{SAAR} + 0.475 \qquad \textbf{4-5}$$

$$\text{If SAAR} \geq 850 \text{ mm, } r = 1.0$$

Where, Other is the proportion of a catchment with 'Other' land type

4.1.1.3 Estimation of losses due to evapotranspiration from agricultural land-uses and conceptual model validity

Losses from agricultural land uses are the actual evapotranspiration (ETa), which has been simulated from multiple runs using the daily soil water balance WaSim model (Hess *et al.*, 2000) under the different combinations of annual precipitation, ETp, crop types and soil types. In WaSim, if the soil is not ponded, the ETa from the soil is taken as the weighted average of actual crop transpiration, soil evaporation, and if the surface is ponded, ETa equals ETp (Hess *et al.*, 2000).

For each agroclimatic zone (Figure 4-3) of Smith (1984), 30 years of daily ETp and precipitation data have been obtained from an ADAS daily climate scenario dataset developed using the LARS weather generator and the UKCIP02 scenarios (as part of the Defra funded CC0378 project) for the baseline and climate scenarios. A representative 5 km grid cell was selected for each agroclimatic zone which has a central position in the zone, because the LARS weather generator simulates the weather data for each grid independently, and the data of that selected grid cell was used in WaSim.

A single soil type was chosen to be representative of each agroclimatic zone. From National Soil Map of England and Wales (Maps B10, B12 and B13), the predominant soil type of each agroclimatic zone was identified (*e.g.* clay, loam, silt, sand, clay loam and silt loam) and inputted into WaSim model.

The 16 crops modelled by the Agriculture model were amalgamated into 7 broad cropping classes (Table 4-2) according to similarities of relevance for ETa; for instance, grouping winter and spring cereals, or sunflower and maize as both are tall crops planted in summer and harvested in autumn. For each amalgamated cropping class, a representative crop has been selected (Table 4-2) to run WaSim.

Table 4-2. Used crops to derive the coefficient that relates the actual evapotranspiration of the amalgamated crop classes to the potential evapotranspiration.

Amalgamated Cropping classes	Representative crop used to run WaSim
Winter wheat and Winter barley	Winter wheat
Spring wheat and Spring barley	Spring barley
Potatoes, Irrigated potatoes 100 mm, and 200 mm	Potatoes
Sugar beet, Irrigated sugar beet 100 mm, and 200 mm	Sugar beet
Sunflower and Forage maize	Forage maize
Grass/silage and permanent grass	Grass
Spring oil seed rape and Winter oil seed rape	Spring oil seed rape

A potential soil moisture deficit map based on the ETp of short grass (1961-75) (Figure 4-3) has been derived by Knox and Holman (2004) to map the spatial variation in climate, reflecting the balance between rainfall and crop water use in summer growing season. The predominant potential soil moisture deficit zone for each agroclimatic zone (derived from Smith, 1984) was identified, from which, combined with the soil type, information for each selected representative crop on crop growth development, rooting development and transpiration factors necessary to run WaSim were obtained from Holman *et al*. (2005c).

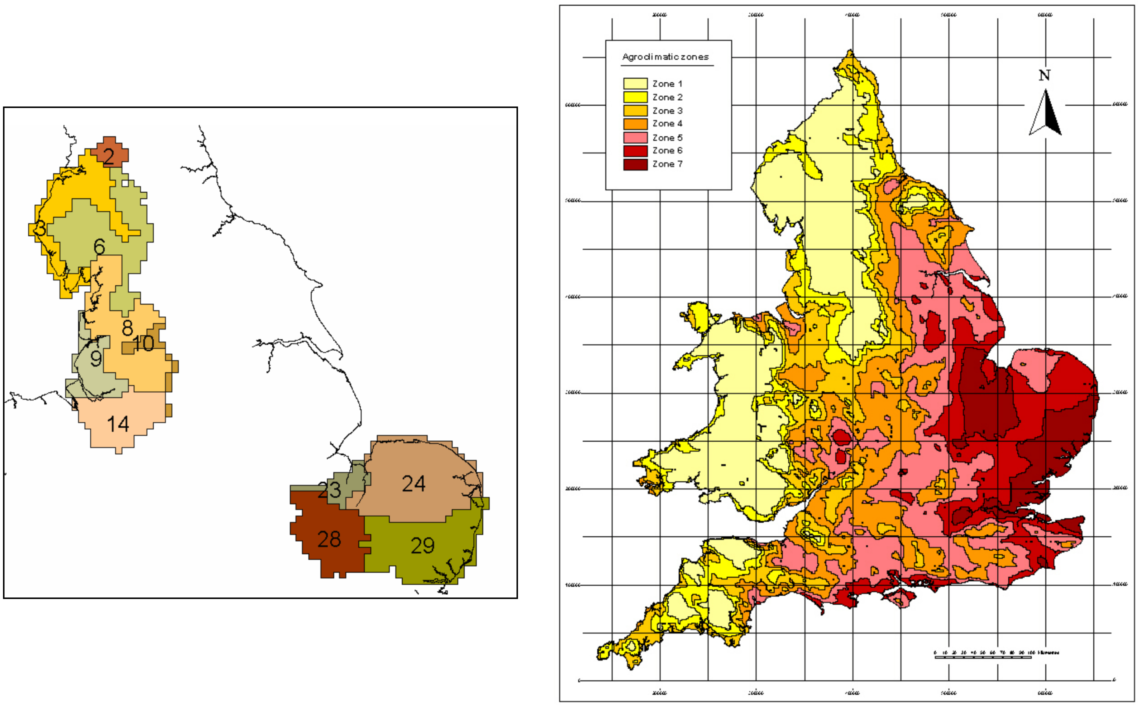


Figure 4-3. Agroclimatic zones for the 5 km grid cells in East Anglia and North West regions derived from Smith (1984) (left) and the potential soil moisture deficit zones for England and Wales (Knox and Holman, 2004) (right).

Irrigated potatoes and sugar beet were modelled without irrigation. In order to use the estimated ETa representing LOSSES to calculate AARD (Equation 4-2), it was assumed that all applied irrigation water was lost as additional evapotranspiration not contributing to recharge.

A coefficient relating the ETa of the crop estimated by WaSim to the ETp over the 30 year period, k that reflects the crop and soil water stress coefficients (Allen *et al*, 1998), was therefore derived for the different climate scenarios, agroclimatic zones, and amalgamated cropping classes (*e.g.* Figure 4-4) by dividing the average ETa by the average ETp.

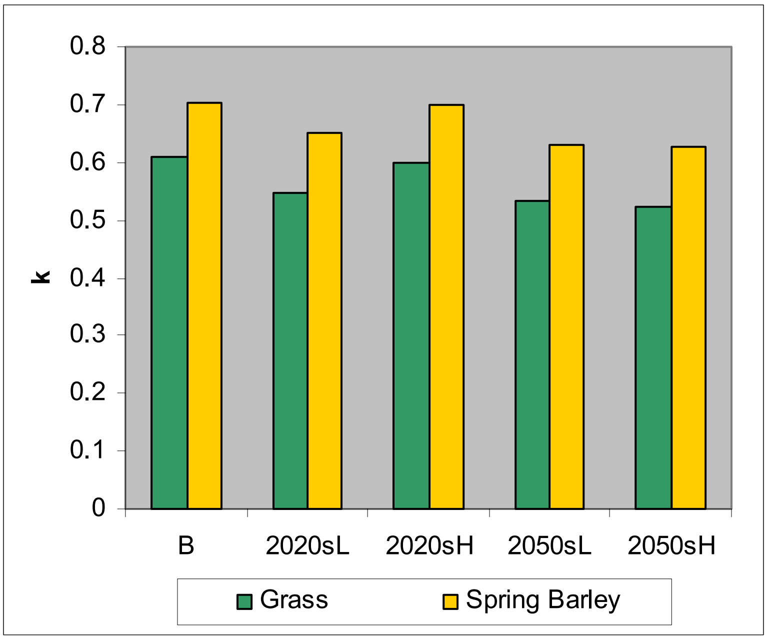


Figure 4-4. Coefficient k for the different climate scenarios (baseline, 2020s Low and High, and 2050s Low and High emission scenarios) and cropping classes (grass and spring barley), using the example of agroclimatic zone 29 in East Anglia.

For estimating LOSSES from the 16 crops whose areas are modelled by the Agriculture model at a 5 km grid, Equation 4-6 is used by the Water Resources model to derive ETa.

$$LOSSES_{Crops} = ET_{p,re-scaled} \times \sum_{i=1}^{n_{Crops}} \left(k_{i,adj.} \times Crop_i \right) \qquad \textbf{4-6}$$

Where, n_{crops} is the number of amalgamated crop classes

$K_{i,adj.}$ is a coefficient relating the actual evapotranspiration of the cropping class i to the potential evapotranspiration according to the climate scenario and agroclimatic zone of the catchment in question adjusted to the re-scaled ETp

$Crop_i$ is the proportion of a catchment with the cropping class i

k was derived from the daily ETp data and not from the re-scaled ETp (smaller than ETp) in order to reflect the ETp provided by RegIS. If k would have been derived from the re-scaled ETp:

– In wet areas, where k upper limit had been reached as defined by WaSim, k derived from the re-scaled ETp would have approximately the same value as if it had been derived from ETp. For the same rainfall and decreased ETa, the soil was saturated and the difference would only be on increased drainage and runoff.
– In dry areas, k derived from re-scaled ETp would be greater than k derived from ETp.

However, k was adjusted to be applied to the re-scaled ETp (Equation 4-6), in order to increase in both dry and wet areas, multiplying k derived from ETp by the reverse proportion that ETp was re-scaled.

4.1.1.4 Estimation of losses due to evapotranspiration from urbanised land-uses and conceptual model validity

The percentage of Urbanised areas, as given by the Urban and Suburban land classes, in each catchment are given by the Land Cover Map 2000 for the baseline (1 km gridded spatial data), and from the 5 km gridded spatial urbanisation patterns within the socio-economic scenarios for future time slices. For the latter, the relative proportions of Urban and Suburban areas within the overall urbanisation patterns depend on the descriptive storylines of the socio-economic scenarios, where some scenarios show a more rapid increase in suburban dwellings (*e.g.* RE and GM socio-economic scenarios). Urban areas are assumed to consist of 100% of hard surfaces and Suburban of 50% of hard surface, with the other 50% being grass from which ETa occurs (Section 4.1.1.3).

Van de Ven *et al*. (1992) has shown that < 0.5 mm of rainfall is needed to 'wet' a road surface before runoff occurs, whilst Hollis *et al.* (2004) assumed that the amount of rainfall needed to wet a dry road surface is 0.4 mm, not allowing for depressional storage in the hard surface.

The variable 'wetdays', defined as the number of days where precipitation is greater than 0.4 mm, was derived from the ADAS daily climate scenario dataset for the baseline and different climate scenarios, for the above mentioned representative grids of each agroclimatic zone (Figure 4-5). If daily precipitation is smaller than 0.4 mm, then resulting evaporation is neglected and if is greater then that value, 0.4 mm is left to be lost through evaporation assuming a single daily rainfall event. Therefore, LOSSES estimated by Equation 4-7 might be underestimated.

$$LOSSES_{Urbanised} = \frac{Suburban}{2} \times ET_{p,re-scaled} \times k_{grass,adj.} + \left(Urban + \frac{Suburban}{2} \right) \times 0.4 \times Wetdays \quad \textbf{4-7}$$

Where, Suburban is the proportion of a catchment with Suburban land class

Urban is the proportion of a catchment with Urban land class

$K_{grass,adj.}$ is a coefficient relating the actual evapotranspiration of grass to the potential evapotranspiration adjusted to the re-scaled ETp

Wetdays is the number of days when rainfall is greater than 0.4 mm in a year, days

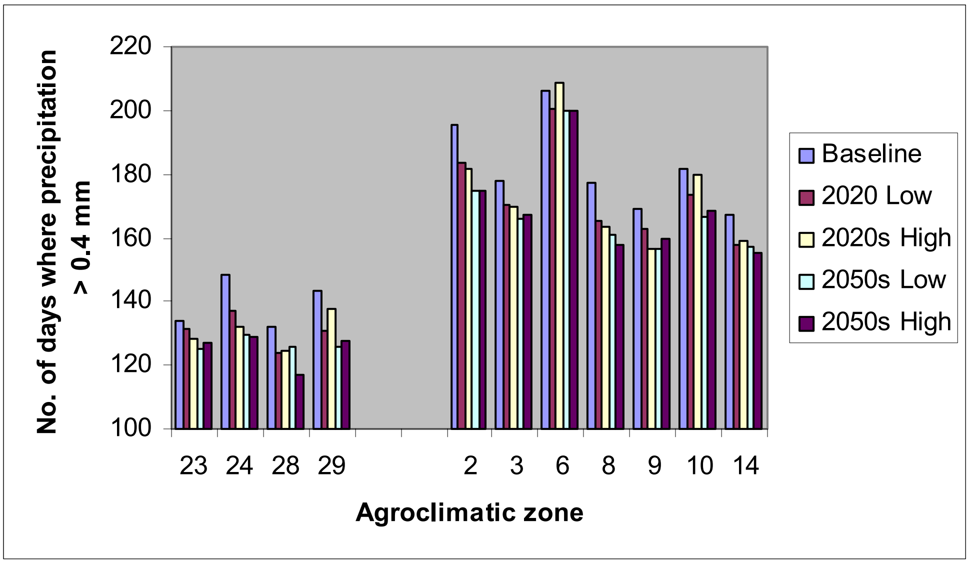


Figure 4-5: Number of 'wetdays' for the agroclimatic zones within East Anglia and North West regions for the baseline and different climate scenarios.

The number of days where precipitation is greater than 0.2 and 1 mm, for each agroclimatic zone, from the ADAS daily climate dataset was validated against maps with the same information from the Meteorological Office (http://www.metoffice.gov.uk/climate/uk/averages/19611990/mapped.html) for baseline conditions due to the lack of information on the number of days where precipitation is greater than 0.4 mm from the Meteorological Office. The results are presented in Figure 4-6 and are considered acceptable.

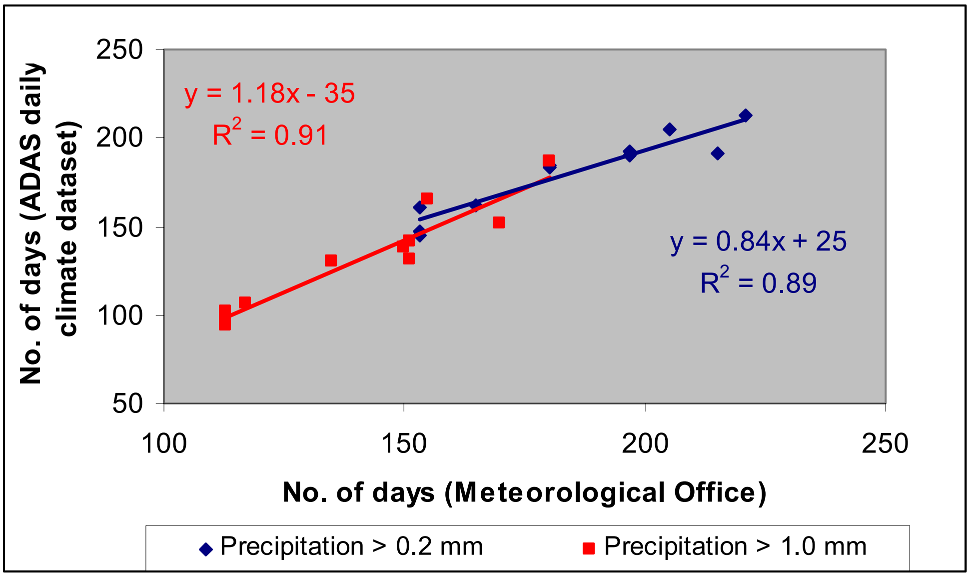


Figure 4-6. Validation of the number of days where precipitation is greater than 0.2 mm and 1.0 mm comparing the results obtained from mapped days of rain from the Meteorological Office and derived from the ADAS daily climate dataset.

4.1.2 Estimation of the low flow indexes Q95 and MAM(7)

The Water Resources model estimates the Q95 and MAM(7) using the method presented in Gustard *et al.* (1992) where these parameters are expressed as a percentage of MF for each of the 10 low flow HOST groups plus lake and urban fractions.

The urban fractions (URBAN) in a catchment are assumed to be the sum of Urban and Suburban parameters described above, and the catchment weighted area averages of lakes and HOST classes have been calculated from the 5 km gridded version of the National Soil Map of England and Wales, and the latter grouped into the 10 low flow HOST groups. The method presented in Gustard *et al*. (1992) was developed using a provisional HOST classification system and data set; however, the final HOST classes as presented by Boorman (1995) were used for the grouping. Finally, weighted average value of Q95 and MAM(7) for each catchment have been calculated based on the MF and the fraction of the catchment in each of the 12 low flow HOST groups.

4.1.3 Estimation of the Flow Duration Curve

The naturalised FDC is derived by the Water Resources model. The method of Gustard *et al.* (1992) is used, which consists of a set of 20 type curves (Figure 4-7) that are defined for different values of Q95 as a percentage of the MF. Using these curves, flows as a percentage of the MF can be derived for other probabilities. Multiplying these values by the MF, the naturalised FDC is obtained.

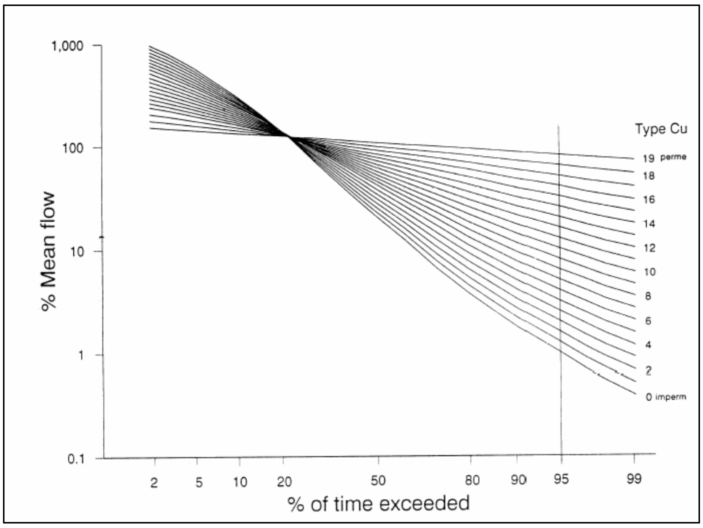


Figure 4-7. Type curves and frequency relationship for estimating the FDC. (Gustard *et al*., 1992)

The flow range, that provides an indication of the difference between the low and high end shape of the curve, was estimated from the FDC, as the difference between Q5 and Q95.

4.1.4 Estimation of the mean nitrate concentration

The agriculture model outputs the nitrate leaching (on the 5 km grid) that has been used to derive a simple indicator of mean nitrate concentration by dividing by the MF of the correspondent catchment. This concentration is presented at a 5 km grid and not at a catchment scale due to the lack of information on nitrate leaching from the grids of catchments that are partially or totally outside the boundaries of the regions. Therefore, the purpose is mainly to analyse spatial trends in changes from the baseline to the scenario in dilution due to MF and nitrate leaching, and not its absolute value at a 5 km grid.

4.1.5 Estimation of the potential natural groundwater recharge and analysis of model suitability

The natural potential groundwater recharge has been estimated by the Water Resources model using the water balance and baseflow index method presented in Section 2.4.2.2 using Equation 4-8.

$$GW_{Recharge} = AARD \times BFIHOST \tag{4-8}$$

Where, $GW_{Recharge}$ is the groundwater recharge, mm/annum

BFIHOST is the catchment weighted average of base flow index obtained from the HOST soil classification (Boorman et al., 1995)

The AARD is used, and as it was estimated using the improved LOSSES parameter, the impacts of land-use changes, such as cropping classes and urban areas, as a result of climate and socio-economic changes are reflected in the estimated potential natural groundwater recharge.

Moreover, this is an improvement to the methods of Szilagyi *et al.* (2003), Arnell *et al.* (1997) and Arnell (2003) which used ETp. As ETa is used (although in a simpler form than Hulme *et al.*, 2001) the method to estimate the potential groundwater recharge has a physical understanding of the water available in the catchment after evaporation and evapotranspiration losses, which is the definition of potential groundwater recharge given by Environment Agency (2002).

Equation 4-8 has been derived by simplifying the water balance of a catchment. The assumptions mentioned in Section 2.4.2.2 are now analysed concerning its validity for East Anglia and the North West regions:

– Steady state is assumed

The average annual groundwater storage change is expected to be null over 30 year time-slices.

– groundwater evapotranspiration is negligible

In East Anglia and the North West regions, the depth to the water table is generally greater than a meter and groundwater evapotranspiration from the unsaturated zone is assumed negligible. Losses from groundwater fed wetlands occur due to evaporation and are neglected as wetlands are assumed not to be significant in terms of their area in the regions.

– groundwater flux across basin boundaries can be neglected

At a regional level the groundwater flux across the basin can be neglected according to Szilagyi *et al.* (2003) and that method avoids the use of contributing drainage areas in the water balance equation. However, this study is applied at a catchment scale as does Arnell *et al.* (1997) and Arnell (2003).

4.2 Modelling methodology for estimating the abstraction availability

The availability of water for abstraction at a catchment scale from surface and groundwater was estimated using a socio-economic indicator of the regional concern for river ecological status termed the Regional Environmental Priority described in Section 4.2.1, using an approach similar to that of the Environment Agency's Resource Assessment Management (RAM) framework (presented in Section 2.4.2.4) as described in Section 4.2.2..

Details on the inputs, outputs and linkages of the model to estimate the abstraction availability are illustrated in Figure 4-1.

4.2.1 The Regional Environmental Priority

Within the RAM methodology (Environment Agency, 2002), the five environmental weighting bands define the flow regime, based on the ecological sensitivity of the reach upstream of the assessment point to abstraction impacts (Acreman and Dunbar, 2004; Dunbar *et al*., 2004). In the absence of such data regionally, this parameter has been changed within the Water Resources model to a subjective 5-point Regional Environmental Priority (REP) scale, which represents the willingness of society within a socio-economic scenario to allocate water to aquatic ecosystems to prevent abstraction-related hydrological stress by protecting the low flows and flow variability of the catchments. This pressure variable is applied to all the catchments within a region equally and sets the river flow objectives, regardless of the sensitivity of the ecological status of each catchment, which is assumed to be reasonable for regional estimates. The REP values chosen range from 1 (very high priority) or 2 (high) for environmentally-focussed futures (Regional Stewardship and Global Sustainability, respectively) to 4 (low) or 5 (very low) for market-driven futures (Regional Enterprise and Global Markets, respectively), with the Baseline being given as 3 (medium).

A very strong commitment to water resource sustainability is associated with RS (Morris *et al*., 2004a). Policy on water resources takes on a strongly regional focus, valuing and conserving what is found within the region as water resources will be seen as priorities for enhancements to build back the stock of environmental capital (UKCIP, 2001). However, the capacity of East Anglia and the North West regions to achieve this varies significantly. In East Anglia, due to the limited available resources, a ‘high’ REP was chosen whereas ‘very high’ was selected for the contrasting North West. Under GS scenario, the adoption of a ‘high’ REP demonstrates a commitment to sustainability and is associated with a moderation of market processes in favour of resource and environmental conservation.

GM, characterised by market led resource allocation and highly developed trading systems, would be ultimately associated with unrestricted abstraction and use of water driven by economic imperatives (Morris *et al*., 2004a), therefore, a ‘very low’ REP was chosen. Under RE, market values also dominate; however, decisions reflect regional priorities and environment is perceived to have economic value allowing regional autonomy. Therefore a ‘low’ REP was chosen.

4.2.2 Estimation of abstraction availability at a catchment scale

From the REP and the naturalised FDC based on an average over a 30-year period the unconstrained abstraction and the constrained abstraction availability at any given flow are estimated as in RAM (Section 2.4.2.4). The intervals were chosen assuming that potential abstractors are not prepared to accept relatively unreliable resources from the high flow end of the FDC (above HOF4, see Section 2.4.2.4).

The average daily abstraction availability is calculated adding the unconstrained to the constrained abstraction availability. The latter was converted to an average daily value based on the percentage of time the naturalised flow is within each of the intervals for which the constrained abstraction availability was estimated.

Although the *RAM framework assessment for river reaches incorporates the impacts of groundwater abstractions* (Environment Agency, 2002), it has limitations that affects estimates mostly in East Anglia where approximately half of total abstraction comes from groundwater; however, the catchments with important aquifers (Chalk and Crag) have a good connection between ground and surface water and therefore abstracting baseflow is similar to abstracting groundwater. In the North West, approximately 90% of water is abstracted from surface waters and there are few important aquifers that tend to be confined.

Another limitation arises form the fact that the FDC was assumed to reflect the total manageable resource due to the lack of information on the abstractions and discharges, which assumes that the benchmark FDC is the naturalised FDC and therefore that abstractions equal discharges in all the catchments (Section 2.4.2.4).

4.3 Modelling methodology for estimating the regional water demand and supply

Because of regional supply networks, abstraction of water does not necessarily occur close to the point of use, or indeed in the same catchment. Water is currently transferred over large distances, and the future extent of such transfers or the network that supports them cannot be predicted for the various socio-economic futures. As a result, water supply is estimated at the regional scale.

The regional water demand was calculated as the sum of the agricultural water demand (from the Agriculture model developed within RegIS2) and domestic, industrial and commercial demand based upon the socio-economic scenarios (Section 4.3.1). The regional water supply was derived from the water available to be abstracted in the catchments allowing for water imports/exports and reservoir storage capacity from the socio-economic scenarios (Section 4.3.2). Finally, the relative balance of the supply and the demand for the regions is estimated (Section 4.3.3).

See Figure 4-1 with detailed model inputs, outputs and linkages for the regional water supply, demand and supply-demand balance sub-models.

4.3.1 Estimation of the regional water demand

The regional water demand was given by the sum of the following average regional water usages:

- Agricultural irrigation – estimated by the linked Agriculture model, which is sensitive to climate and socio-economic scenarios;
- Domestic water demand – from the socio-economic scenarios, depending on the regional population and per capita water consumption;
- Industrial/commercial water demand – from the socio-economic scenarios;
- Leakage – that depends on the volume of public water supply and a socio-economic scenario-specific leakage coefficient.

These pressure variables representing an annual average over a given 30-year period were quantified for the different socio-economic scenarios and time-slices according to the storylines presented in Table 4-3, which is presented in Appendix 1.

Table 4-3: Water demand management under the different socio-economic scenarios (UKCIP, 2001and Environment Agency, 2001b).

	Drivers of water demand	**Domestic water demand**	**Industrial/ Commercial water demand**	**Leakage**
Global Markets	Water demand increases significantly due to economic growth and minimal environmental concern	Metering is adopted and high water prices promote the adoption of low-cost efficiency measures	Implementation of low cost water use minimisation measures	High water prices encourage reduction in water leakage
Regional Enterprise	Low demand side management and low capital investment in water efficiency. Price mechanisms limit the increase of water demand.	Metering systems	Lack of investment Tradable abstraction permits	Leakage levels are high due to passive leakage control policies
Global Sustainability	Water demand falls due to strong demand side management and adoption of clean technology	Uptake of water efficient appliances to balance the increased demand due to improved standard of living	Resource intensive systems of production subject to strict environmental regulation	‘best practice’ leakage policies and innovative technical solutions
Regional Stewardship	Low growth and effective demand management measures lead to reduced water demand	Reduced demand from water conservation technologies and low water use behaviour	Eco-efficiency, but expensive measures inhibited by the lack of capital for investment. High water-using activities in East Anglia might relocate.	Major investments to reduce leakage

The domestic and industrial/commercial water demand were assumed to be invariant to climate change. The impact of the rise in temperature due to climate change on domestic water demand is mainly due to increased personal showering, lawn sprinkling and other garden use (Herrington, 1996; Environment Agency, 2001). According to Downing *et a*l. (2003), the impact of climate change on domestic water demand is a modest increase above the changes caused by the socio-economic scenarios and does not appreciably differ across the regions. For instance, under economically-focused futures (Global Markets and Regional Enterprise), where climate change has a greater impact on the domestic water demand, it increases in Anglian region by 1.45% under 2020s Low and 3.04% under 2050s Medium-High. Therefore, it was assumed that socio-economics are the dominant driver of domestic water demand in terms of per capita consumption and population growth.

Downing *et al*. (2003) defends that climate change impacts on industry and commerce are likely to be higher than the impacts on domestic consumption and notably different across the socio-economic scenarios. For instance, in Anglian region, where the impacts of climate change on industrial and commercial water demand are more significant, under 2020s Low GS it increases by 2.4% and under 2050s Medium-High GM by 5.7% above the socio-economic scenarios (Downing *et al*., 2003). However, it has been assumed that industrial use is insensitive to climate change as it is mainly conditioned by technologies and modes of use (Arnell *et al*., 2001, pp. 221).

4.3.2 Estimation of the regional water supply

To derive the regional abstraction availability, the constrained and unconstrained abstraction availability in each catchment were summed. Where regional boundaries do not match river basin boundaries, the catchment water availability is reduced by the proportion outside the regional boundary. An alternative approach would be to consider that such upstream parts of the catchments provide some water to be abstracted if it is in excess of the demand in the area outside the region, but this was rejected because of the complexity of additional water supplies (reservoirs and water transfers) in these areas.

The provision of water supply is given by the regional abstraction availability to which the reservoir storage capacity and net regional water imports are added. The regional reservoir storage capacity only accounts for 'big' reservoirs from where water is supplied to the region located within the region and which are assumed to be fully filled yearly at times of high flows. Smaller reservoirs, such as winter storage reservoirs for agricultural purposes, are accounted to maximise the uptake of constrained abstraction licenses. The net regional water import is the regional net balance of the water transfers in and out of the region.

The increased reservoir storage capacity due to new, extended or raised reservoirs, and the net regional water imports, reflecting an average annual over a given 30-year period, were derived from the socio-economic scenarios according to the storylines presented in Table 4-4. In Section 3.1.5 these pressure variables are presented for baseline conditions and the future strategies are discussed in Section 7.1 in the context of adaptation.

Table 4-4: Water supply management under the different socio-economic scenarios (UKCIP, 2001).

	Drivers of water supply	**Reservoir storage capacity**	**Net regional water imports**
Global Markets	High water prices and increased water demand encourage the development of *new* sources of supply	There is little resistance to the development of new reservoirs except where significant recreational opportunities are threatened	
Regional Enterprise	Increased demand is met by *extending* traditional water sources	New and enlarged reservoirs	Development of inter-regional transfers
Global Sustainability	Little need to develop new sources of water supply		
Regional Stewardship	Few new supply side investments are needed	Where supply difficulties arise, storage capacity is increased	Exchange of water resources between regions in the UK becomes more difficult

4.3.3 The regional water supply-demand balance

A measure of the robustness of the supply-demand system to the pressures exerted in the scenario is the relative balance of the available supply and the demand from the Water Resources model.

Because the constrained abstraction availability is not as reliable as the unconstrained abstraction availability and may not be totally abstracted, two supply-demand balances are calculated. The first is calculated as the difference between the estimated regional water supply and water demand. The second is the difference between the regional water availability, with the components of unconstrained abstraction availability, reservoir storage capacity and net water imports, and the regional water demand.

4.4 Modelling methodology for estimating the non-naturalised low and high flows and conceptual model validity

Socio-economic factors alter the estimated catchment naturalised flows due to abstractions and discharges. In order to estimate the non-naturalised Q95 and Q5 at a catchment scale, a simple new methodology was derived which is illustrated in Figure 4-8 and presented and validated in conceptual terms in this section. This methodology was based on the regional abstraction availability and water demand, due to the lack of information on the future spatial distribution of abstractions, supply networks, sewage treatment work and direct industrial discharges. The modelling methodology of the effects of regional abstractions on decreasing, and returns on increasing, the naturalised catchment flows are presented in Section 4.4.1 and Section 4.4.2 respectively, and the derivation of the non-naturalised flows in Section 4.4.3..

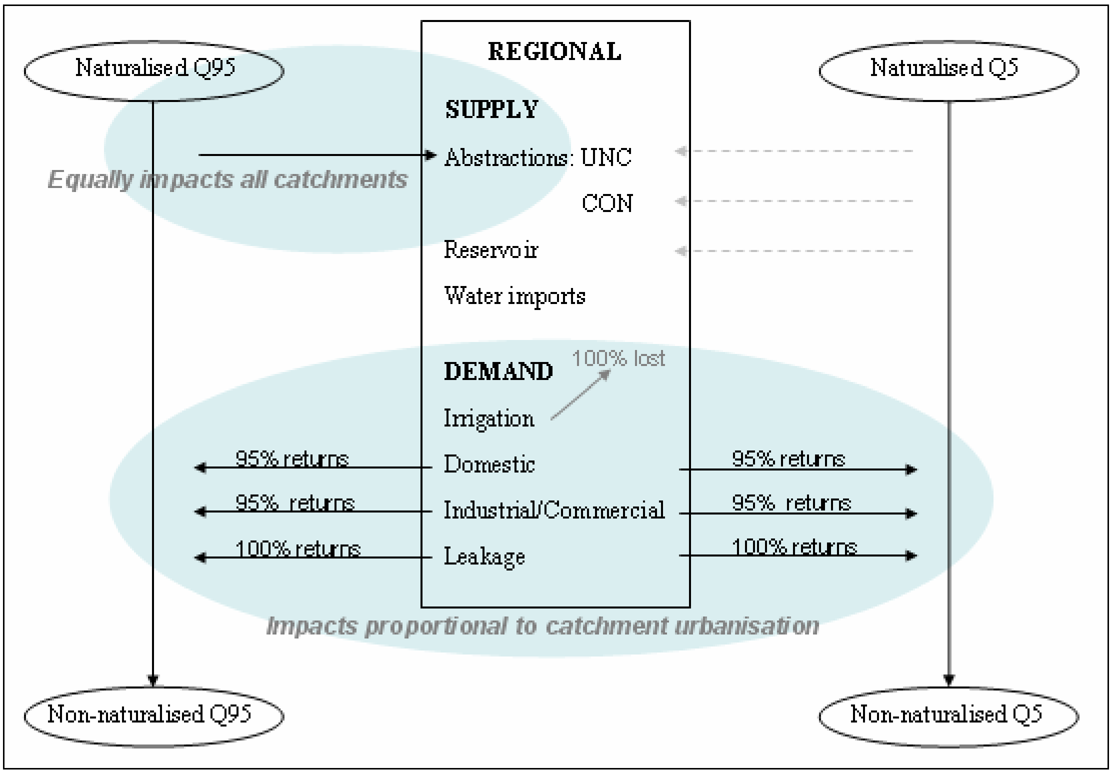


Figure 4-8: Diagrammatic representation of the method to derive the non-naturalised catchment flows from the naturalised ones and the regional unconstrained (UNC) and constrained (CON) abstraction availability to meet the regional demand.

4.4.1 The effects of abstractions on the low flows

Water can be provided by different sources such as catchment abstractions (constrained and unconstrained), reservoir storage, and water imports. It is assumed that to meet the regional demand, the first water sources to be used are the net regional water imports and reservoir storage due to existing infrastructure; and only when these sources are not sufficient, other sources are used (Equation 4-9 a). In that case, the necessary unconstrained surface and groundwater is abstracted (Equation 4-9 b) and only if the unconstrained abstractions in all the catchments throughout a region plus reservoir storage and net water imports are insufficient, are the less reliable constrained sources used. In this situation, all unconstrained abstractions are taken (Equation 4-9 c), regardless of the demand for water in the catchments where it is abstracted, assuming that the surplus water abstracted is transferred within the region.

The impacts of the constrained and constrained abstractions and reservoirs, which are assumed to be filled at times of high flows, on the naturalised flows of a catchment are assumed to be negligible for Q5. The naturalised Q95 is assumed to be only impacted by the unconstrained abstraction (Section 2.4.2.4) as the constrained abstractions do not take place at the times that the river flow is lower than Q95.

As the unconstrained abstraction is, by definition, the limited water that can be abstracted in order not to reduce Q95 by more than a given percentage that depends on the environmental flow requirements of the river, the low flows in all catchments are equally impacted in ecological terms by the abstractions needed to meet the regional demand because, although different amounts may be abstracted from catchment to catchment, the REP that sets the percentage of Q95 to be abstracted is the same for all the catchments and given by the socio-economic scenario.

The impact of abstractions on reducing the naturalised Q95 is therefore given by Equation 4-9,

a) If $Demand_{region} \leq Reservoir_{region} + Net\ water\ imports_{region}$:

$A = 0$

b) If $Demand_{region} \leq Reservoir_{region} + Net\ water\ imports_{region} + UNC_{region}$:

$$A = UNC \times \frac{Demand_{region} - Reservoir_{region} - Net.water.imports_{region}}{UNC_{region}} \qquad \textbf{4-9}$$

c) If $Demand_{region} \geq Reservoir_{region} + Net\ water\ imports_{region} + UNC_{region}$:

$A = UNC$

Where, A - impact of abstraction on Q95 of a catchment in m^3/s
UNC - Unconstrained available water for a given catchment in m^3/s
UNC_{region} - Unconstrained available water in all the catchments of the region in m^3/s
$Demand_{region}$ - Regional water demand in m^3/s
$Reservoir_{region}$ - Regional reservoir storage capacity in m^3/s
Net water $imports_{region}$ – Regional net water imports in m^3/s

4.4.2 The effects of returns on high and low flows

All sources of water, such as abstractions and reservoirs that remove water from the environment within the regions and water imports, satisfy the regional agricultural water demand (simulated by the linked Agricultural model), domestic, industrial/commercial demand, calculated from the socio-economic scenarios, and leakage from that proportion of the water demand supplied by the mains. Not all of the water supplied is consumed and it is assumed that 95% of the water used for domestic and industrial/commercial purposes and 100% of leakage from the mains network is returned to the environment and that water used for irrigation is 100% lost due to evapotranspiration. The latter assumption is more adequate under future drier conditions with more efficient irrigation water use.

It is further assumed that if demand cannot be satisfied, water is allocated proportionally to the different purposes independently from the socio-economic scenarios. The average annual returns of water to the environment, at a regional level, are therefore calculated using Equation 4-10:

a) $\mathrm{Re}\,turns_{region} = Leakage + (IC + Dom) \times 0.95$, if Demand < Supply

b) $\mathrm{Re}\,turns_{region} = \dfrac{Supply}{Demand} \times \left(Leakage + (IC + Dom) \times 0.95\right)$, if Demand > Supply **4-10**

Where, Returns $_{\text{region}}$ - Water returns to the environment in the region in m^3/s

Leakage - Leakage from the mains in the region in m^3/s

IC - Industrial and Commercial water demand in the region in m^3/s

Dom - Domestic water demand in the region in m^3/s

Supply - Regional water supply in m^3/s

Demand - Regional water demand in m^3/s

In order to distribute the returns spatially within the region, the water returns are assumed to take place where the demand exists, which is assumed to relate to urbanisation patterns given by the socio-economic scenarios, due to the higher domestic and industrial/commercial water demand and greater leakage due to higher network pipe density in urban areas. Equal weighting is given to the Urban and Suburban areas in terms of impacts on the returns. The contribution of returns to the naturalised river flows of a catchment is therefore given by Equation 4-11.

$$\mathrm{Re}\,turns_{catchment} = \frac{\mathrm{Re}\,turns_{region}}{(Urban + Suburban)_{region}} \times (Urban + Suburban)_{catchment} \qquad \textbf{4-11}$$

Where, Returns $_{\text{catchment}}$ - impact of returns on the naturalised flows of a catchment in m^3/s

Urban and Suburban - Urban and Suburban land-classes in the catchment/region (%)

4.4.3 Derivation of the non-naturalised Q95 and Q5 flows

Finally, the non-naturalised Q95 and Q5 for the catchments are derived using equations 4-12 and 4-13.

$$Q95 = \mathrm{Q95}_{\text{naturalised}} - A + \mathrm{Re}\,turns_{catchment} \qquad \textbf{4-12}$$

$$Q5 = Q5_{naturalised} + \mathrm{Re}\,turns_{catchment} \qquad \textbf{4-13}$$

In essence, the model adds the discharges to the naturalised flows and removes the abstractions. It assumes that the water abstracted and the sum of the components of discharges, for which annual daily averages are used, are constant throughout the year.

4.5 Sensitivity analysis

In this section, a sensitivity analysis of agricultural and urbanisation land-use changes on ETa (according to the method presented in Sections 4.1.1.1, 4.1.1.2 and 4.1.1.3) is carried out.

The parameter k for seven cropping classes and for the baseline and four climate scenarios was derived for each agroclimatic zone in both regions. The driest agroclimatic region in East Anglia (agroclimatic zone 28) (Figure 4-9) and the wettest in the North West (agroclimatic zone 6) (Figure 4-10) are analysed in terms of the sensitivity of k to changes in agricultural land-uses and climate change.

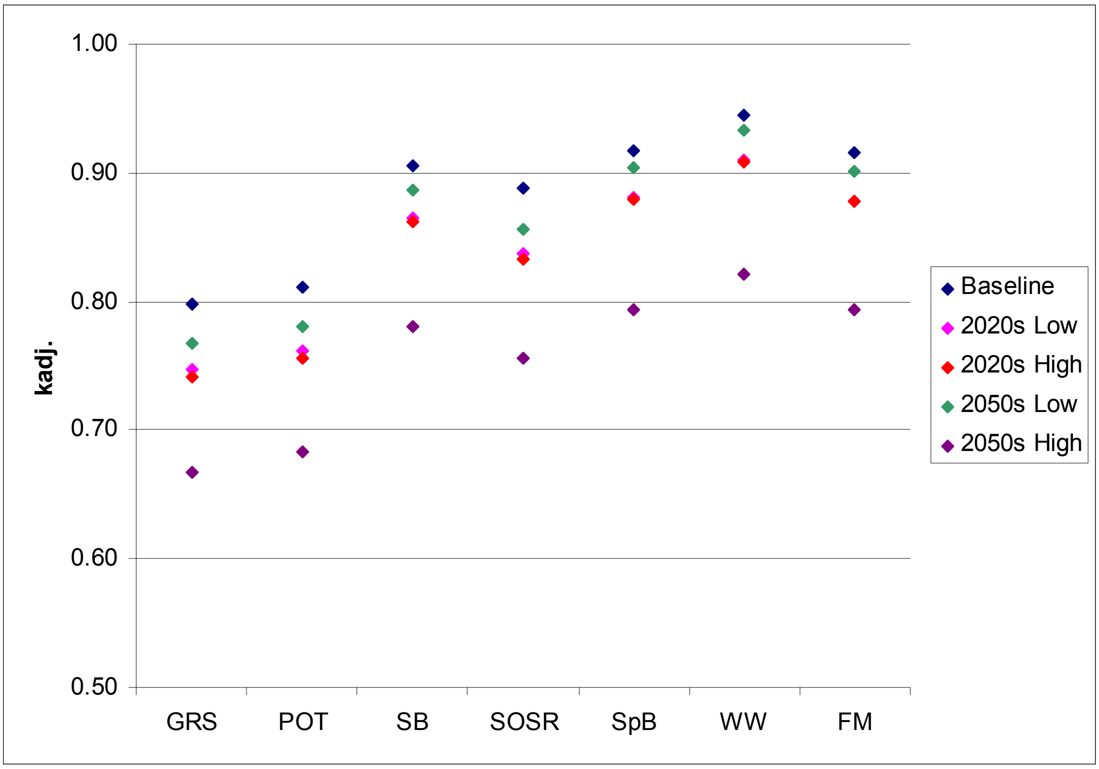


Figure 4-9: k adjusted for the seven modelled cropping classes in East Anglia (agroclimatic zone 28) under baseline conditions and the four climate scenarios. Where: grass – GRS, potatoes – POT, Sugar Beet – SB, Spring Oil Seed Rape – SOSR, Spring Barley – SpB, Winter Wheat – WW, and Forage Maize – FM.

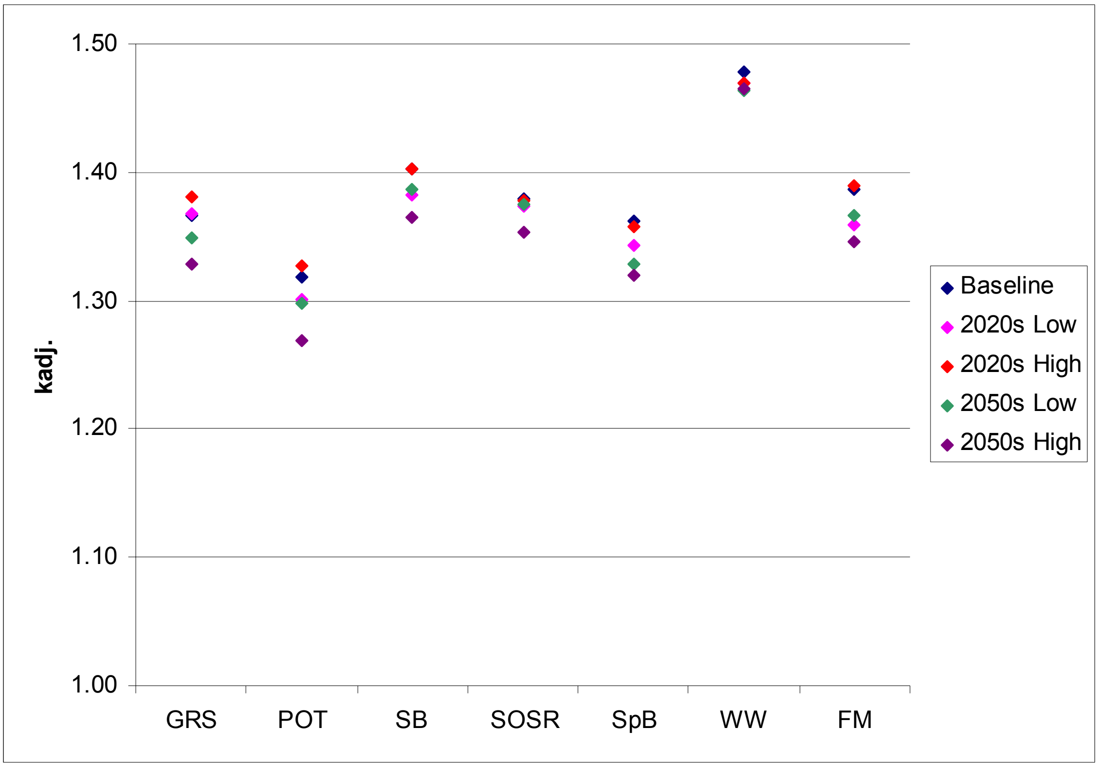


Figure 4-10: k adjusted for the seven modelled cropping classes in the North West region (agroclimatic zone 6) under baseline conditions and the four climate scenarios. Where: grass – GRS, potatoes – POT, Sugar Beet – SB, Spring Oil Seed Rape – SOSR, Spring Barley – SpB, Winter Wheat – WW, and Forage Maize – FM.

From Figure 4-9 and Figure 4-10 it can be observed that k as a function of climate does not show the same trend in the different agroclimatic zones. For instance, in agroclimatic zone 28, k is higher for the baseline followed by 2050s Low and in agroclimatic zone 6 is higher under 2020s High followed by baseline. This trend depends on a combination of daily ETp and rainfall and soil types, and in some cases, as illustrated in Figure 4-10, also on the crop itself. It is not possible either to assess the crops whose k value is more sensitive to climate change or which crops have higher or lower k values because, once again, it depends on a combination of factors.

Comparing the chosen contrasting zones, it can however be noticed that in the drier agroclimatic zone 28:

- the soil water stress is higher and k values are lower; and
- kadj. is more sensitive to climate change; for example, $kadj._{Grass}$ in East Anglia is 0.80 for baseline and 0.67 under 2050s High (a reduction of 0.13) and in North West agroclimatic zone is 1.38 for 2020s High and 1.33 for 2050s High (a reduction of 0.05).

Due to the high sensitivity of k to climate change in this zone in East Anglia, although ETp increases with climate change, ETa decreases which is the opposite to that in the North West zone (see Figure 4-11 for 0% of paved area that corresponds to 100% grass).

A sensitivity analysis of the % of paved area was carried out for these agroclimatic zones. From Figure 4-11 it can be observed that with the decrease of grass area and increase of paved area, losses due to evapotranspiration significantly decrease. In urban areas (100% of paved area), where evaporation occurs, the differences between the climate scenarios in each zone are smaller and solely due to changes in the wetdays variable. Impacts of climate change are less pronounced in urban areas in terms of losses due to evapotranspiration.

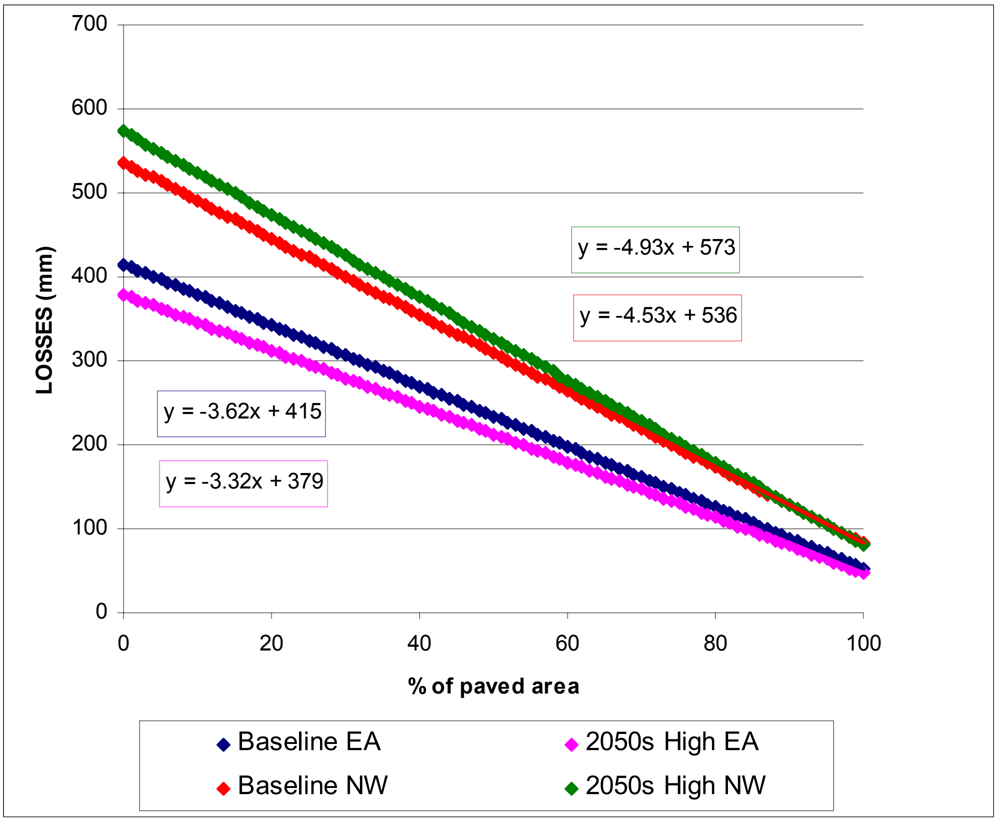


Figure 4-11: Effect of paved area on the LOSSES occurring in East Anglia (agroclimatic zone 28) and North West (agroclimatic zone 6) for the baseline and 2050s High climate scenario. Where, 0% of paved area corresponds to grassland, 50% of paved area to a Suburban area and 100% of paved area to an Urban area.

4.6 Statistical validation of the Water Resources model

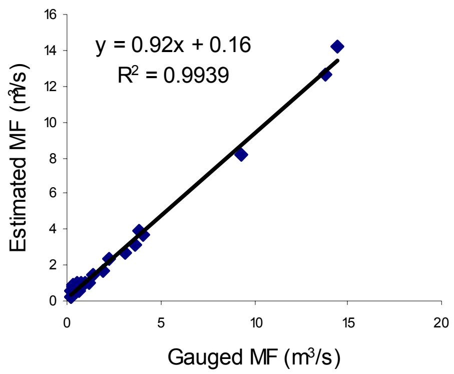
The estimated and measured MF, Q95, and Q10, using data available from the Centre for Ecology and Hydrology National River Flow Archive (NRFA website), have been compared for 31 gauging stations in East Anglia and 48 in the North West (see Appendix 3). The selected gauging stations are located at the outlet position of the catchments within the national Environment Agency catchment boundary dataset used for the modelling.

The statistical validation is based upon the geometric mean regression and concordance correlation coefficient explained in Appendix 2.

4.6.1 Validation of the calibrated Mean Flow

The catchment water balance method was calibrated in Section 4.1.1.1 by re-scaling the evapotranspiration dataset in order to be within the same range as the values used by Gustard *et al.* (1992) to develop the equations for estimating the MF.

A significantly better relationship was obtained between the simulated MF using the re-scaled ETp and the water balance equation as presented by Gustard *et al.* (1992) and gauged MF. The functional regression lines are: simulated = 0.92 x gauged + 0.15 for East Anglia (n = 30) and simulated = 0.99 x gauged + 0.18 for the North West (n = 48) using the geometric mean regression, and the concordance correlation coefficient 0.9936 and 0.9903 respectively (see ordinary predictive regression line in Figure 4-12).



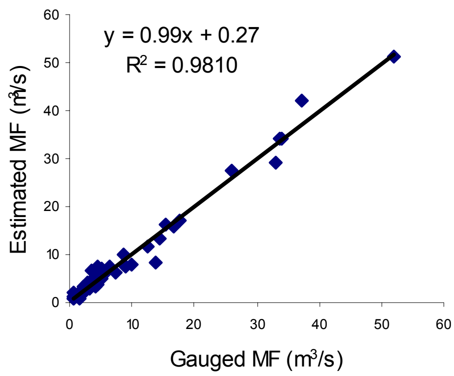


Figure 4-12: Comparison between the Mean Flow (MF) simulated using the water balance equations from Gustard *et al.* (1992) and the re-scaled evapotranspiration dataset provided by RegIS2 project and the gauged MF for East Anglia (on the left) and North West (on the right), using the ordinary predictive regression line.

4.6.2 Validation of the naturalised Mean Flow, Q95 and Q10 flows for baseline conditions

A regional validation of outputs for the baseline conditions using the modified LOSSES parameter (Sections 4.1.1.2, 4.1.1.3 and 4.1.1.4) was carried out for the MF and high and low flow ends of the FDC.

The functional regression lines between the estimated and the gauged MF are: simulated = 0.91 x gauged - 0.10 for East Anglia (n = 30) and simulated = 0.97 x gauged + 0.23 for the North West (n = 48) using the geometric mean regression, and the concordance correlation coefficient 0.9851 and 0.9815 respectively (see ordinary predictive regression line in Figure 4-13).

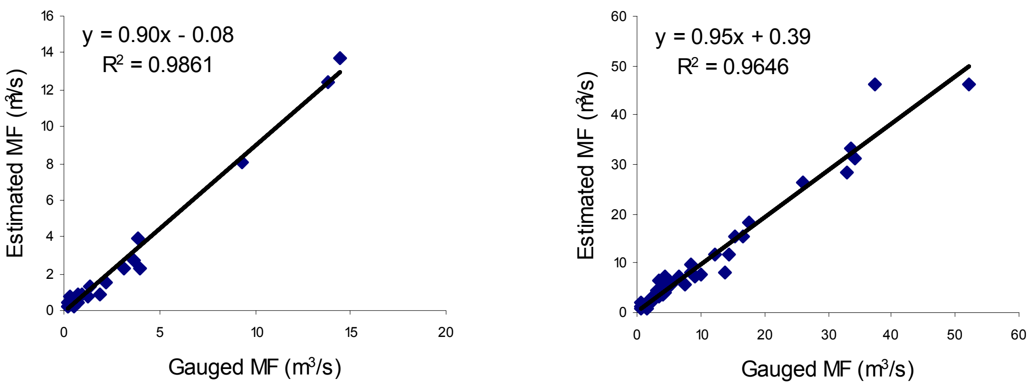


Figure 4-13: Comparison between the Mean Flow (MF) simulated using the improved LOSSES parameter and the gauged MF for East Anglia (on the left) and North West (on the right), using the ordinary predictive regression line.

The method of Gustard *et al.* (1992) using re-scaled evapotranspiration data better fits the gauged data (as the concordance correlation coefficients in Section 4.6.1 show better agreement *i.e.* closer to the unit). However, the estimates of MF obtained with the derived improved methodology (in this section) are considered acceptable. Using the MF, Q95 and Q10 were estimated, and are now validated.

The functional regression lines between the estimated and the gauged Q95 are: simulated = 0.95 x gauged + 0.01 for East Anglia (n = 30) and simulated = 1.08 x gauged + 0.03 for the North West (n = 48) using the geometric mean regression, and the concordance correlation coefficient 0.9433 and 0.9675 respectively (see ordinary predictive regression line in Figure 4-14).

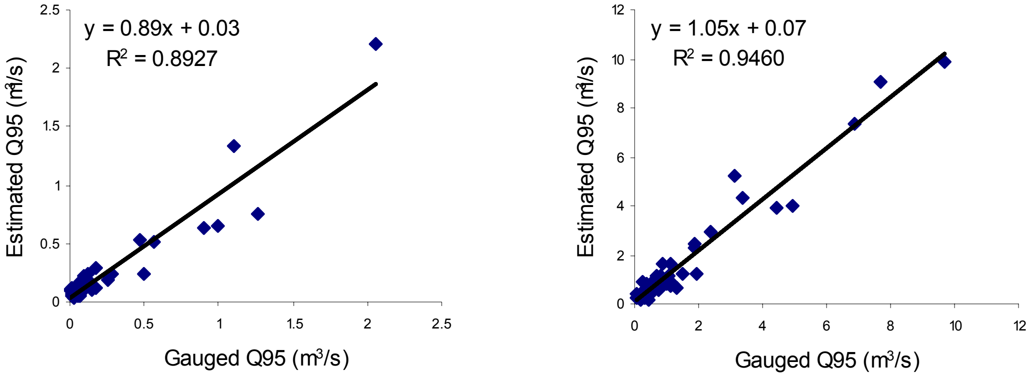


Figure 4-14: Comparison between Q95 simulated using the improved LOSSES parameter and the gauged MF for East Anglia (on the left) and North West (on the right), using the ordinary predictive regression line.

The functional regression lines between the estimated and the gauged Q10 are: simulated = 0.85 x gauged + 0.01 for East Anglia (n = 30) and simulated = 0.97 x gauged + 0.98 for the North West (n = 48) using the geometric mean regression, and the concordance correlation coefficient 0.9779 and 0.9791 respectively (see ordinary predictive regression line in Figure 4-15).

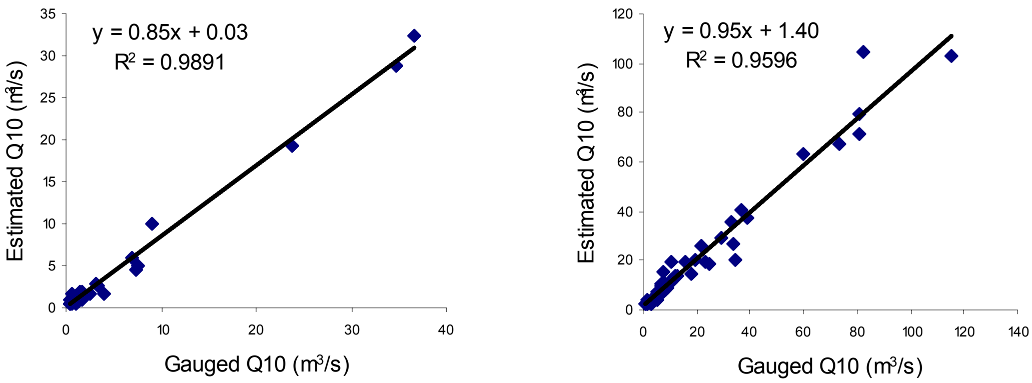


Figure 4-15: Comparison between Q10 simulated using the improved LOSSES parameter and the gauged MF for East Anglia (on the left) and North West (on the right), using the ordinary predictive regression line.

The results of the validation are considered acceptable. Human influences (*i.e.* abstractions, effluent returns and reservoirs) on the naturalised flows are more evident for the low flows where the concordance correlation coefficient is lower and the estimates of MF seem to be the more robust.

For this validation, data on all the gauging stations in the North West was used. However, in East Anglia, for validating the MF and Q10 Waveney at Ellingham Mill gauging station 34013 was excluded and for validating Q95, data for the Ouse at Bedford Ouse gauging station 33001 was rejected. This is because they do not follow the same trend as all the other stations. At the first gauging station, totalising flows accurately was a continuing difficulty which led to station closure (http://www.nwl.ac.uk/ih/nrfa/station_summaries/034/013.html). Regarding the second station, estimated Q95 was significantly overestimated possibly due to abstraction for public water supply, industrial and agricultural purposes (http://www.nwl.ac.uk/ih/nrfa/station_summaries/033/001.html) that might not be moderated by the exiting effluent returns.

4.6.3 Validation of the non-naturalised flows for baseline conditions

Measured Q95 data available from NRFA website for the selected gauging stations were used to validate the estimated non-naturalised Q95 daily flows for the baseline conditions, which is more sensitive than Q5 as it is affected by abstractions and returns and has a lower absolute value more susceptible to changes. The functional regression lines are: simulated = 0.87 x gauged + 0.06 for East Anglia (n = 30) and simulated = 0.93 x gauged + 0.36 for the North West (n = 48) using the geometric mean regression, and the concordance correlation coefficient 0.9303 and 0.9585 respectively (see ordinary predictive regression line in Figure 4-16).

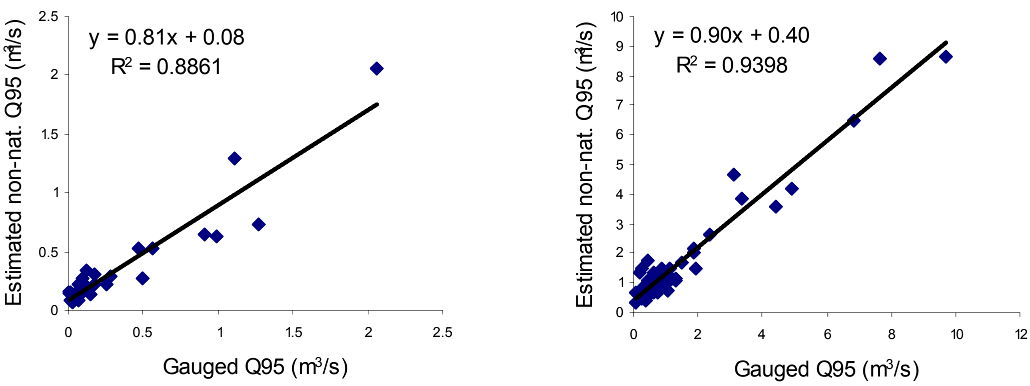


Figure 4-16: Comparison between the simulated non-naturalised Q95 and the gauged one for East Anglia (on the left) and North West (on the right), using the ordinary predictive regression line.

It was noticed that the non-naturalised simulated flows are underestimated compared to the naturalised ones because for the catchments used for the validation, abstractions have a greater impact than returns. However, analysing all the catchments, on average, non-naturalised flows are higher than naturalised because returns are greater than abstractions, which is as expected because despite not all the water abstracted is returned to the system, water is not only provided by surface and groundwater, but also from water imports and reservoirs. Therefore, the simulated non-naturalised flows are generally slightly higher in value than the naturalised ones and the catchments used for validation are not representative. Still, the developed method is considered an acceptable attempt to account for the impacts of abstractions and returns given the simple assumptions used to reflect their spatial distribution.

The impacts of returns are greater than the ones caused by abstractions, and in a larger extent in the North West. The estimated increase in catchment flows due to returns in the North West is up to 1.8 m^3/s which seems reasonable as it is less than the discharge of 4.1 m^3/s from the biggest United Utilities' Sewage Treatment Works *i.e.* Davyhulme at Manchester and comparable to that from the Carlisle and Fleetwood Sewage Treatment Works (http://www.unitedutilities.com/?OBH=261). Moreover, given that the average returns for this region is 31 m^3/s and that the average daily flow of sewage per capita for UK is 300 litres per day (Gray, 1992), the average returns to the region correspond to 8.9 million population equivalent. That seems a realistic figure because there is 6.8 million inhabitants in the region and some direct industrial discharges also occur.

The estimated non-naturalised high Q5 was not validated because there is very little difference between that and the naturalised one, which was semi-validated by the high flow Q10 (Section 4.6.2). The concordance correlation coefficient between the naturalised and non-naturalised simulated Q5 is 0.9999 for East Anglia and 0.9998 for the North West. Therefore, Q5 is not sensitive to returns, which validate the assumption that non-naturalised Q5 is not sensitive to abstractions because these are smaller than the discharges.

4.6.4 Validation of the abstraction availability for baseline conditions

In order to validate the abstraction availability the annual internal renewable resources were compared with the estimated total manageable resource. The annual internal renewable resources data were obtained from Environment Agency (2001c, pp. 26) for the regions in question and is defined as the average annual flow of rivers and recharge of groundwater generated from endogenous precipitation (http://earthtrends.wri.org/searchable_db/variablenotes.php?varid=6&theme=2). The annual internal renewable water resources are 1.49 km^3 in East Anglia[4] and 10.97 km^3 in the North West. The total manageable resource derived using the Water Resources model, *i.e.* the area of the naturalised FDC, is 1.23 km^3/yr for East Anglia and 9.60 km^3/yr for the North West. The values are approximate and considered acceptable.

4.7 Summary

The Water Resources model simulates the impacts of climate and socio-economic changes on the hydrology and water resources of East Anglia and the North West regions. Firstly, impact indicators on the hydrology of the catchments and sub-catchments (*e.g.* flow indexes and groundwater recharge) were estimated from catchment descriptors. The method developed by Gustard *et al.* (1992) was used for estimating the impact indicators and improved to derive runoff which is sensitive not only to soil types (which are assumed to be constant over time), but also to changes in urban areas (from the socio-economic scenarios), and vegetation cover (from the Agriculture model) that significantly affect evapotranspiration losses. The actual evapotranspiration was estimated from the potential evapotranspiration (re-scaled and from the climate scenarios) and derived crop and water stress coefficients for the amalgamated crop classes, and respective agroclimatic zones, which was successfully validated.

[4] Assuming that East Anglia's water resource is 36% of the resource in Anglian region.

Secondly, the impact of climate and socio-economic changes on the water resources was simulated. The regional water availability was estimated from the reservoir storage capacity and net water transfers pressure variables derived from the socio-economic scenarios, to which abstraction from surface and groundwater sources was added. The latter was estimated using a simplification of the RAM framework from the estimated naturalised river flows and societal and political willingness to protect ecological river objectives (as given by a pressure variable derived from the socio-economic scenarios). The regional water demand from domestic, industrial/commercial purposes accounting for leakage as a part of the public water supply were derived from the socio-economic scenarios and added to the estimated agricultural irrigation needs (from the Agriculture model) to simulate the regional water demand. Then, the regional water supply was balanced with the regional water demand.

Finally, the impacts of catchment's abstractions and returns (assumed to be related to the urbanisation level) on the hydrology (low and high flows), were simulated from the naturalised flows and the regional abstractions and returns and successfully validated.

5 Development and validation of the High River Flow model

Flooding is associated with a deterioration of the water quality. Flooding in urban areas can potentially result in sewage treatment works overflow, especially if stormwater is not appropriately managed, which leads to increased nutrient loads into and faecal contamination of the receiving water bodies. In urban areas, if the soil is compacted due to inappropriate soil management or if the soils are impermeable such as clay soils, runoff and even overland flow might occur resulting in sediment and nutrient (namely nitrates and phosphates from fertilisers) loads into the nearby rivers. In order to better assess the impacts of future climate and socio-economic changes on water resource management, it became important to analyse the change in flooding events integrating water quantity (Section 4) with water quality aspects.

The development and validation of the High River Flow model that estimates the flood index QMED is described in this chapter. Firstly, the modelling methodology and its conceptual validity (Appendix 2) are presented in Section 5.1. Then, a sensitivity analysis is carried out in Section 5.2 and the model is validated using statistical analyses in Section 5.3.

5.1 High River Flow modelling methodology

The derivation of the QMED, for all the sub-catchments and catchments in the East Anglia and the North West regions depicted on the Environment Agency's national catchment boundary dataset, involves a number of steps, based upon the Catchments Descriptor method of Robson and Reed (1999) (Section 2.4.2.3). Firstly, QMED was calculated from physical and climatological descriptors, which are described in Section 5.1.1, assuming that the catchments are entirely rural in nature. Concerning the climatological descriptors, the method was revised in section 5.1.2 in order to improve the simulation of the impacts of future precipitation changes. Finally, in Section 5.1.3, the estimated 'rural' QMED was adjusted for urban development from the socio-economic scenarios. See Figure 5-1 with a representation of the High River Flow model inputs and outputs.

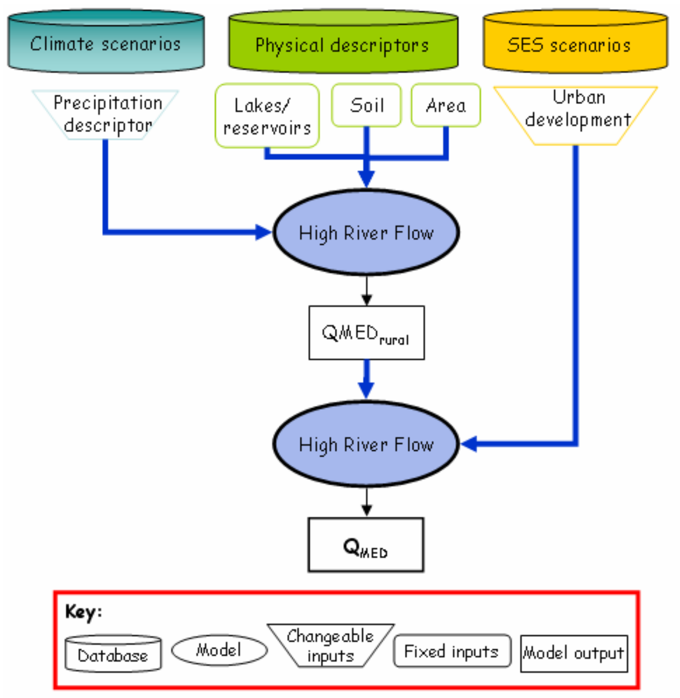


Figure 5-1. Detailed diagrammatic representation of the High River Flow model.

5.1.1 Estimation of the flood index QMED

In order to estimate QMED, firstly $QMED_{rural}$ was simulated from five catchment descriptors defined by Bayliss (1999), assuming that all the catchments are rural, using Equation 5-1 (from Robson and Reed, 1999) which is applicable to all sub-catchment drainage areas in the two regions because they are greater than 0.5 km^2.

$$QMED_{rural} = a \times \left(\frac{PREC}{1000}\right)^{1.560}$$

$$a = 1.172 \times AREA^{1-0.015\times\ln\left(\frac{AREA}{0.5}\right)} \times FARL^{2.642} \times \left(\frac{SPRHOST}{100}\right)^{1.211} \times 0.0198^{BFIHOST+1.30\times\left(\frac{SPRHOST}{100}\right)-0.987} \qquad \textbf{5-1}$$

These catchment descriptors are sub-divided into two categories:

- The physical descriptors that are assumed to be invariant for each catchment, which are represented by the constant a in Equation 5-1:
  - Drainage area in km^2 (AREA), obtained from catchment boundaries.
  - Soil drainage type, represented by estimates of standard percentage runoff (SPRHOST) and base flow index (BFIHOST) obtained from the HOST soil classification (Boorman *et al.*, 1995). The catchment weighted area averages of SPRHOST and BFIHOST were calculated from the soil types depicted on a 5 km gridded version of the National Soil Map of England and Wales (Maps B10, B12 and B13).

  - Index of flood attenuation due to reservoirs and lakes (FARL) obtained from the FEH CD-ROM (1999).
- The adapted climatological precipitation descriptor represented by PREC (described further below) from the baseline climatology or climate scenarios.

5.1.2 Modified climatological descriptor and conceptual model validity

In the original Equation 5-1 derived by Robson and Reed (1999), PREC is defined for the standard period 1961-90 in mm (*i.e.* Standard Average Annual Rainfall, SAAR). In the High River Flow model, for the baseline climatology, PREC was therefore given by SAAR obtained from the Meteorological Office 5 km gridded baseline climatology.

However, for climate impact studies, a significant limitation of the Catchment Descriptors method of Robson and Reed (1999) arose, as it is only sensitive to the average annual rainfall. Under current climatology, the seasonal rainfall distribution is relatively uniform as shown in Figure 5-2. For all the catchments in the North West, 44% of SAAR occurs in the summer half-year (April to September) (r^2 = 0.93) and 56% in the winter half-year (October to March) (r^2 = 0.98); while for East Anglia 50% occurs in each half-year (r^2 = 0.75 and r^2 = 0.88 for the summer and winter half-years respectively). However, climate change is expected to lead to changes in seasonal precipitation variability (Hulme *et al.*, 2002), with all of the UKCIP02 climate scenarios showing summer half-year precipitation decreases and winter half-year precipitation increases, by lower extent, producing an overall regional reduction in Average Annual Rainfall (example in Figure 5-2 for 2050s High scenario). If the original Catchment Descriptors method of Robson and Reed (1999) with SAAR was used with the climate change scenarios, it would suggest a future reduction in QMED, which is contrary to most studies (*e.g.* Evans *et al.*, 2004a, Holman *et al.*, 2005b, Arnell and Reynard, 1996, Reynard *et al.*, 2001; Prudhomme *et al.*, 2003) that simulate an increase in high flows and flood quantiles due to changes in the annual distribution and intensity of rainfall events (see Section 3.2.2).

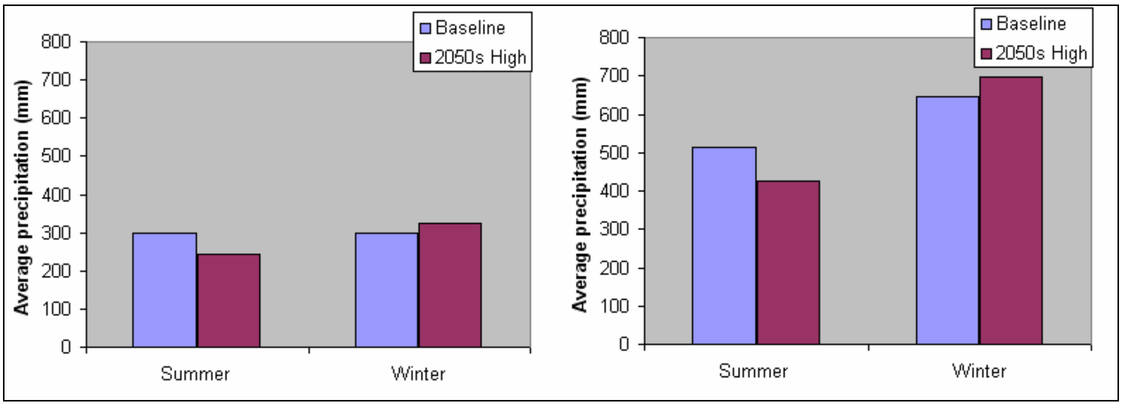


Figure 5-2. Average summer and winter half-year precipitation for baseline conditions and for 2050s High scenario estimated for East Anglia (left) and the North West (right) regions.

Therefore, a modification of the Catchment Descriptor method was derived to overcome the abovementioned limitation and the rational is explained as follows.

On average, winter is the dominant season of flooding in the UK, with January having the greatest number of flood events (Bayliss *et al.*, 1993). Hess *et al.* (1988) also show that 80% of floods occurred during the period November to March for catchments of more than 500 ha, based on an examination of gauging station records by Severn Trent Water Authority. Spatial variations in the season of flooding are observed in Figure 5-3 where floods tend to occur during autumn in the North West, while in East Anglia, where soils return to field capacity later (Bayliss *et al.*, 1993), winter is the dominant season of flooding.

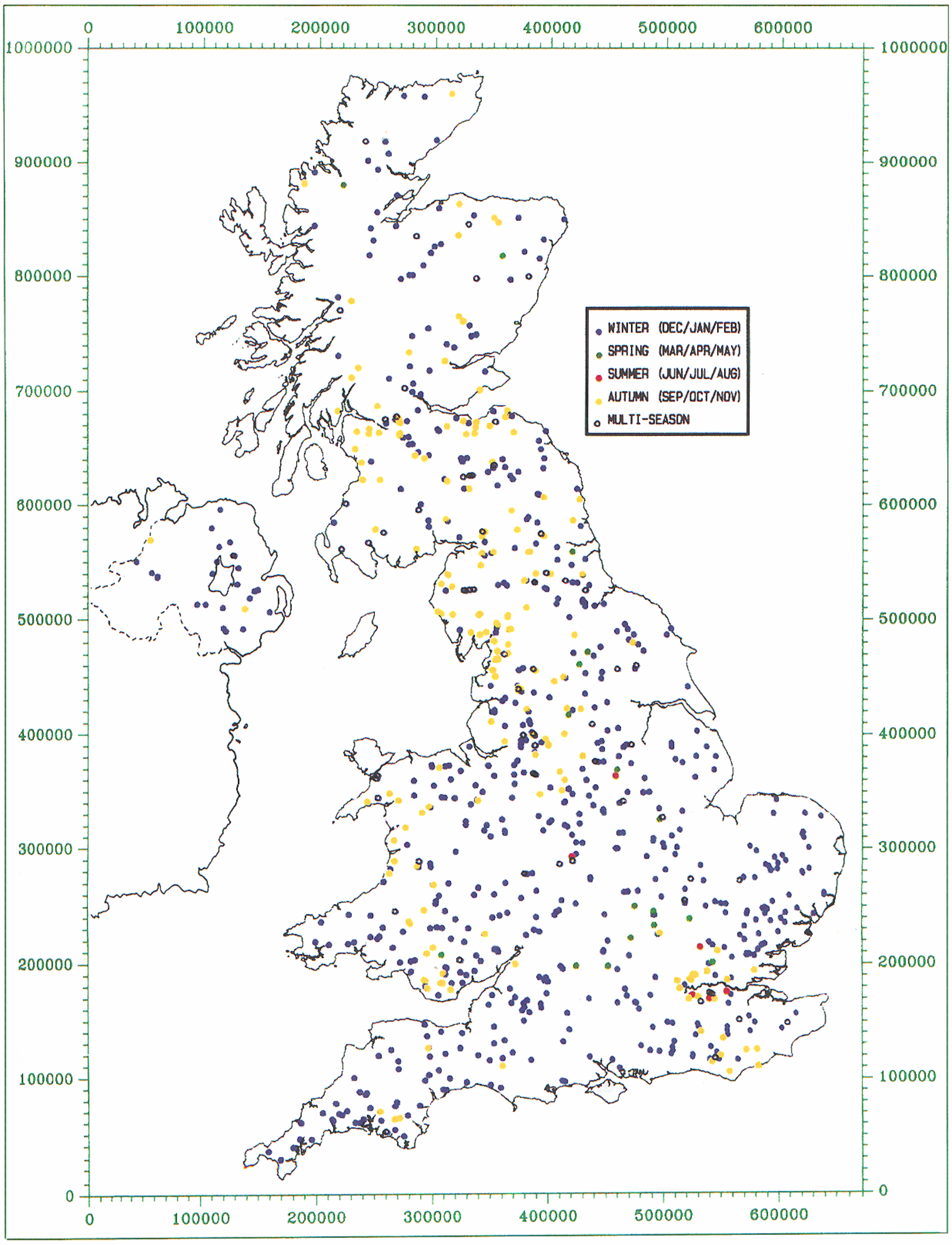


Figure 5-3: Month which has the greatest number of floods grouped by season for the UK (Bayliss *et al.*, 1993).

To assess the regional significance of winter half-year flooding, an analysis of the seasonality of flood events using Annual Maxima data from the High Flows UK website for all the gauging stations in both regions and for all available water-years was carried out. This showed that 82% (n = 91) and 75% (n = 95) of floods occur in the winter half-year in the North West and East Anglia regions, respectively. Therefore, it can be confirmed that the winter half-year is the dominant flooding period in both regions.

There is a very pronounced spatial difference in the linkage between rainfall and flood regimes. For the catchments in Great Britain selected by Cunderlik *et al.* (2002) (Figure 5-4), the difference between the timing of rainfall and floods is on average 77 days. In the North West, the difference is very short, generally less than 45 days (Figure 5-4). The mean day of occurrence of rainfall, calculated from over-threshold extremes, is from October to December, and the mean day of occurrence of flooding is in November and December (Cunderlik *et al.* (2002)). Therefore, a close linkage between rain and flood regimes, both occurring during winter half-year period, was observed in this region.

In East Anglia, the difference between rainfall and flood events is higher, mainly between 90 and 135 days (Figure 5-4). The mean day of rainfall events are in August and September, which justifies the fact that only 75% of floods occur during the winter half-year (in January and February according to Cunderlik *et al.* (2002)), as opposed to the 82% for the North West. Although for baseline conditions there is not a close linkage between these events, it is highly correlated with catchment characteristics that vary with climate change. Cunderlik *et al.* (2002) identified the number of rain days, soil moisture deficit, average annual rainfall, and extreme 1 and 2 days of precipitation as the more significant. According to Hulme *et al.* (2002), summer precipitation decreases, winter precipitation increases and 'intense' rainfall days increase in winter and decrease in summer, leading to a closer link between rainfall and flood events. With caveats, winter half-year floods were assumed to be related to winter half-year rainfall under future scenarios in this region.

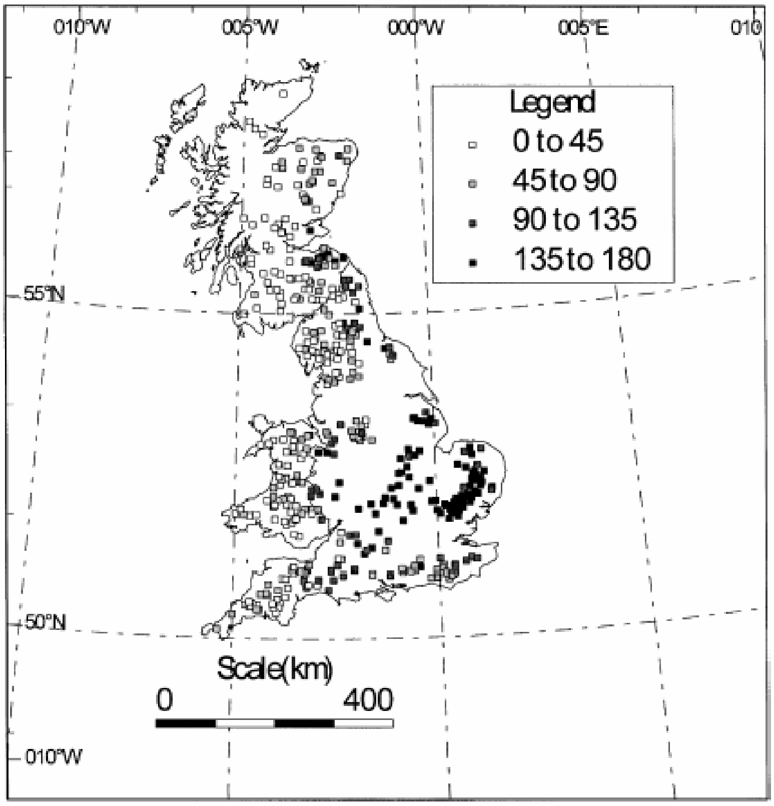


Figure 5-4: Spatial representation of the difference between rainfall and floods, in mean days of over-threshold extreme occurrences (Cunderlik, *et al.*, 2002).

Considering the seasonality of flood events and the difference in days between rain and flood events for both regions, under future scenarios, the floods were generally assumed to be sensitive to the winter half-year precipitation.

This assumption should however be qualified especially in the context of currently heavily urbanised catchments and urban growth in the future socio-economic scenarios. Urbanised catchments respond quickly to rainfall and, as Hess *et al.* (1988) indicates, can have a fairly even seasonal probability of flooding. For example, a small number of predominantly urban catchments in the Birmingham, Nottingham and London areas (Figure 5-3) show larger flood events tending to occur during summer months (June-August) when intense rainfall is often experienced (Cunderlik *et al.*, 2002 and Bayliss *et al.*, 1993). However, future days with ‘intense’ rainfall are expected to decrease in the summer (Hulme *et al.*, 2002) and Bayliss (1993) shows that generally in the UK, urbanised catchments still have the flooding season mainly in autumn. Moreover, according to Bayliss (1993), the proportion of heavily urbanised areas decreases as catchment size increases, and the majority of summer floods occur in catchments of less than 150 km^2 which is not the case for the majority of the catchments that the High River Flow model is applied to. Hence, for the abovementioned reasons, estimates of QMED were assumed to be sensitive to the change in winter half-year precipitation for future scenarios.

Based on the above, it was therefore assumed that the SAAR, given by PREC in Equation 5-1, in the Catchment Descriptors method is actually a surrogate for the average winter half-year rainfall. To estimate QMED for future scenarios, the method was adapted with a simple correction applied to SAAR to derive the PREC climatological descriptor (Equation 5-2).

$$PREC = SAAR \times Change\ in\ winter\ precipitation \qquad \textbf{5-2}$$

5.1.3 Urbanisation adjustment

Urbanisation typically has its strongest effect on floods of short return period, such as the QMED (Robson and Reed, 1999). Therefore, for catchments with urban development (given by more than 2.5% of sealed surface area according to Robson and Reed (1999)), an urban adjustment was applied to the estimated $QMED_{rural}$ as recommended by Bayliss (1999) and Robson and Reed (1999), using Equation 5-3 from Robson and Reed (1999). This adjustment accounts for the resulting change in catchment infiltration characteristics from rural to urbanised land-cover and has the greatest effects in naturally permeable catchments.

$If\ URBEXT \leq 0.025$:

$$QMED = QMED_{rural}$$

$If\ URBEXT > 0.025$:

$$QMED = QMED_{rural} \times (1 + 0.615 \times URBEXT \times b) \times (1 + URBEXT)^{0.83} \qquad \textbf{5-3}$$

Where,

$$b = \left(\frac{70}{SPRHOST} - 1 \right)$$

$$URBEXT = URBAN + 0.5 \times SUBURBAN$$

This adjustment accounts for the soil types in the constant b and the urban extent in the URBEXT parameter. In order to calculate the URBEXT parameter, the proportion of land with Urban and Suburban land-classes for each sub-catchment and catchment was derived from the 1 km gridded Land Cover Map 2000 for the baseline and from the RegIS2 1 km gridded spatial urbanisation patterns within the socio-economic scenarios for the 2020s and 2050s time slices. For the latter, the proportion of Urban and Suburban areas depends on the regional descriptive storylines of the socio-economic scenarios, where some scenarios show a more rapid increase in suburban dwellings (*e.g.* Regional Enterprise and Global Markets socio-economic scenarios).

The urban adjustment describes the net effect of urbanisation if a typical degree of flood alleviation has taken place (Robson and Reed., 1999) and information on local variations in the degree and type of flood amelioration is not available for incorporation within an urban adjustment model (Bayliss, 1999). Modern urban developments include flood mitigation works designed to offset the effects of urbanisation, although older developments might instead contain flood alleviation or flood defence structures that have been added at a later date (Robson and Reed, 1999). The High River Flow model assumes that the flood amelioration in the future is the same as in the past.

5.2 Sensitivity analysis

In this section, a sensitivity analysis of the modified climatological descriptor on estimated QMED (according to the method presented in Section 5.1.2) is carried out. The sensitivity of QMED to the change in winter half-year precipitation (PREC) is given by Equation 5-4 derived from Equation 5-1 used for estimating QMED and illustrated in Figure 5-5.

$$\%QMED = 100 \times \left[\left(1 + \frac{\%PREC}{100} \right)^{1.560} - 1 \right] \qquad \textbf{5-4}$$

Where, %QMED is the % change of QMED from baseline, %

%PREC is the % change of winter half-year precipitation from baseline, %

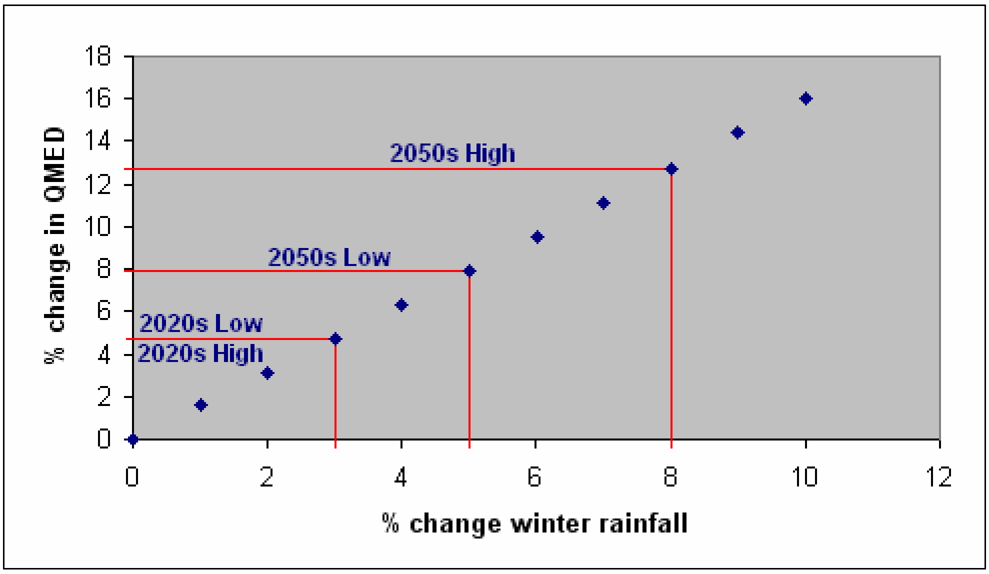


Figure 5-5: Change of QMED as a function of the change of winter half-year precipitation (expressed as a percentage of change from the baseline). Red lines refer to the change for 2020s Low and High and 2050s Low and High emission scenarios as an average for the catchments of both regions.

The change in QMED from baseline is a power function of the change in winter half-year rainfall. The regional average change of winter precipitation, that is the same for East Anglia and the North West regions, increases from baseline over the scenarios by 3% under the 2020s Low and High and by 8% under the 2050s High emission scenario, which is reflected in an increased flood index by 5 to 13% respectively (Figure 5-5).

5.3 Statistical validation of the High River Flow model

In this section, a mathematical statistic analysis is carried out for the operational validity (Appendix 2) of the High River Flow model. Although the Catchment Descriptors method is a recognised and nationally validated approach, in Section 5.3.1 additional regional validation of the simulated QMED by the High River Flow model was carried out for baseline conditions comparing it with the real system. For the future climate change scenarios the revised methodology using PREC (Section 5.1.2) was validated in Section 5.3.2 by checking for consistency of the estimated flood index with that derived from other models and studies.

5.3.1 Validation of QMED for baseline conditions

The validation for baseline conditions was based on a comparison of the simulated QMED with observed data. The 'measured QMED' that reproduces the observed data was obtained from measured peak-over-threshold and Annual Maxima data series available from the High Flows UK website. Of the gauging stations with data available in the two regions, 15 gauging stations were selected in East Anglia and 39 in the North West (Appendix 3), all of which are located at the depicted outlet position of the catchments within the national Environment Agency catchment boundary dataset used for the modelling.

The 'measured QMED' was estimated from Annual Maxima data for all of the stations with more than 14 years of observed data by taking the median of the series (Robson and Reed, 1999). All complete water-years with recorded data were used in order to have representative long term records and to avoid selecting flood-rich/flood poor periods. For two catchments in the North West with less than 14 years of data, peak-over-threshold series from the 6 years of complete water-year data (1996-2002) were used to estimate QMED according to the method presented by Robson and Reed (1999). Where QMED is estimated from a record with less than 14 years of data, an adjustment for climatic variation is suggested by Robson and Reed (1999), but the estimated QMED for these catchments are consistent with that for the other catchments in this region.

The results of the geometric mean regression (Appendix 2) are presented in Figure 5-6 and Figure 5-7 and the concordance correlation coefficient (Appendix 2) between the measured and estimated QMED is 0.6403 for East Anglia (n = 15) and 0.9487 for North West (n = 39).

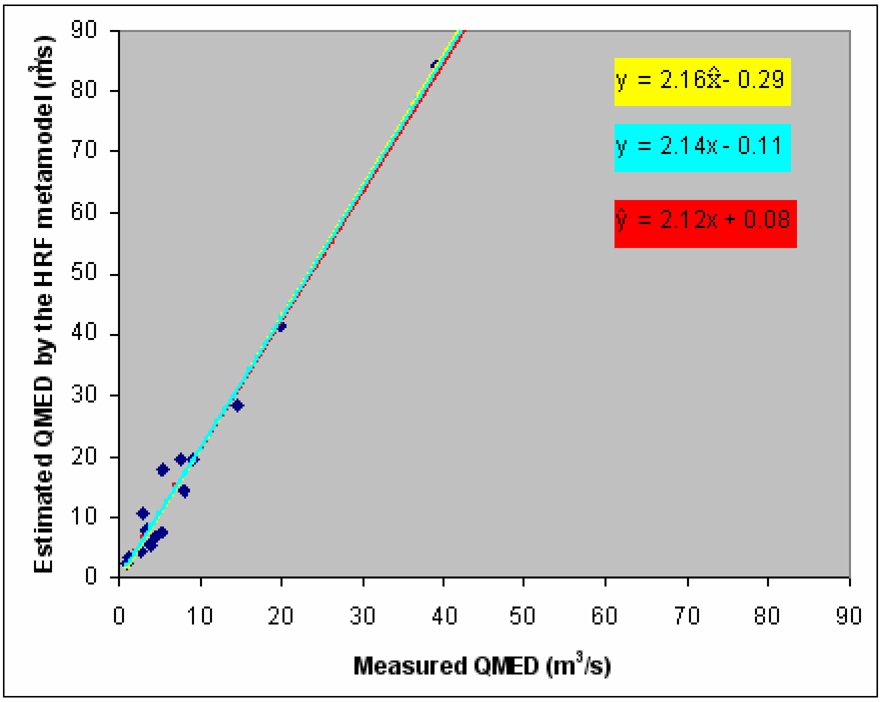


Figure 5-6: Validation of the simulated QMED for East Anglia using the geometric mean regression that calculates the functional regression line in blue from the two predictive regression lines that are presented in yellow (x̂ on y) and in red (ŷ on x plotted on a graph of the usual sort).

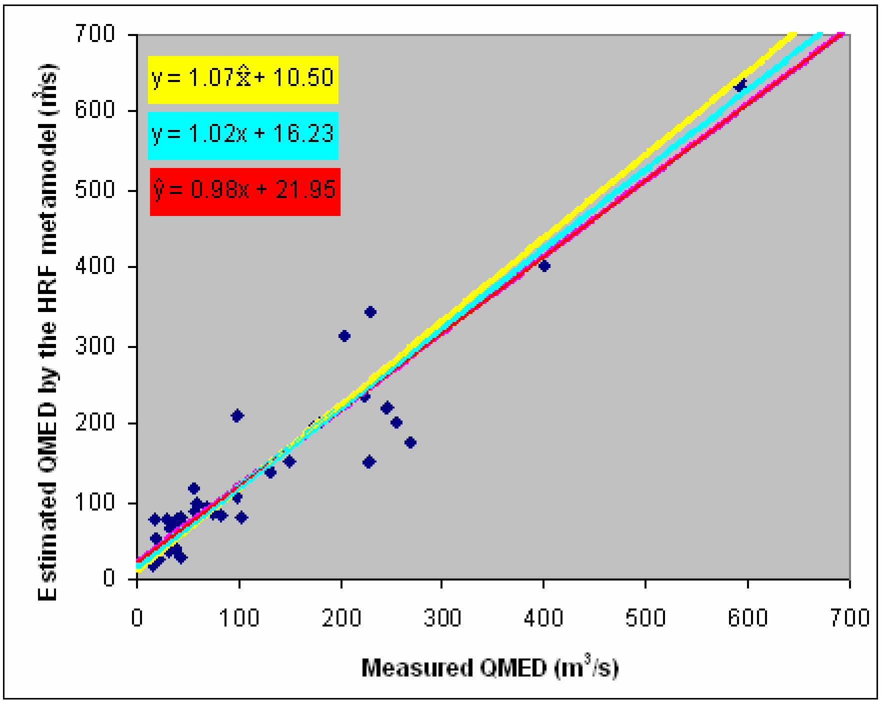


Figure 5-7: Validation of the simulated QMED for the North West using the geometric mean regression that calculates the functional regression line in blue from the two predictive regression lines that are presented in yellow (x̂ on y) and in red (ŷ on x plotted on a graph of the usual sort).

The differences in slopes of the predictive regression lines in Figure 5-6 and Figure 5-7 are small, especially for East Anglia, which shows that the data points lie close to the regression lines (good correlation between the variables). For East Anglia (Figure 5-6), the two slopes are 2.12 and 2.16 (all >1) such that the hypothesis of slope = 1 does not seem to be valid. The two intercept values are -0.29 (<0) and 0.08 (>0) and the intercept of the geometric mean functional relationship is -0.11 which suggests that the hypothesis of intercept = 0 is reasonable. For the North West (Figure 5-7) it is observed that the method performs better as the data are scattered around the symmetry line which agrees with the slope ≈ 1 but the high intercept value suggests that the intercept = 0 does not seem valid. For baseline conditions, especially in East Anglia where QMED is overestimated and the concordance correlation coefficient is very low, it is apparent that the High River Flow model does not validate well for the selected catchments.

Because the High River Flow model for baseline conditions is using the Catchment Descriptors method as presented in the FEH that has already been validated by its developers but does not seem to validate well for the selected catchments, it was decided that additional regional validation should check the input data validity.

Much of the input data to the High River Flow model (PREC, URBEXT, BFIHOST and SPRHOST) was derived independently of the FEH CD-ROM (1999). Therefore, a comparison of estimated QMED by the High River Flow model against the QMED calculated using data directly from the FEH CD-ROM (1999) for all the catchments, using approximate catchment boundaries and area, was performed for both regions. Both gave similar QMED values with the slope and intercept of 1.03 and 0.19 for East Anglia, and 1.01 and -1.51 for North West, and a correlation coefficient equal to 0.99 in both cases. This indicates that the variable performance of the High River Flow model against measured QMED data was due to a limitation of the Catchment Descriptors method itself.

It was checked whether the model performs as expected for the selected catchments used for validation purposes that are representative of the regions, given that the conditions that the Catchment Descriptors method has been calibrated against are being met.

The Catchment Descriptors rural method (Equation 5-1) is based upon the analysis of historical data series from 728 rural UK catchments with r^2 (on ln QMED) = 0.916, and factorial standard error (f.s.e.) = 1.549. The urban development adjustment (Equation 5-3) was based on model calibration results from 115 urbanised catchments and has r^2 (on ln QMED) = 0.862, and f.s.e. = 1.66. The f.s.e. was used by Robson and Reed (1999) to construct approximate confidence intervals that account for both model and sample errors, although the latter is much smaller than the former (Robson and Reed, 1999). The 'measured QMED' have been plotted against the estimated QMED by the High River Flow model, which 95% confidence interval, represented in the y-bar, was weighted according to the urban and rural fractions of each catchment (see Figure 5-8 and Figure 5-9).

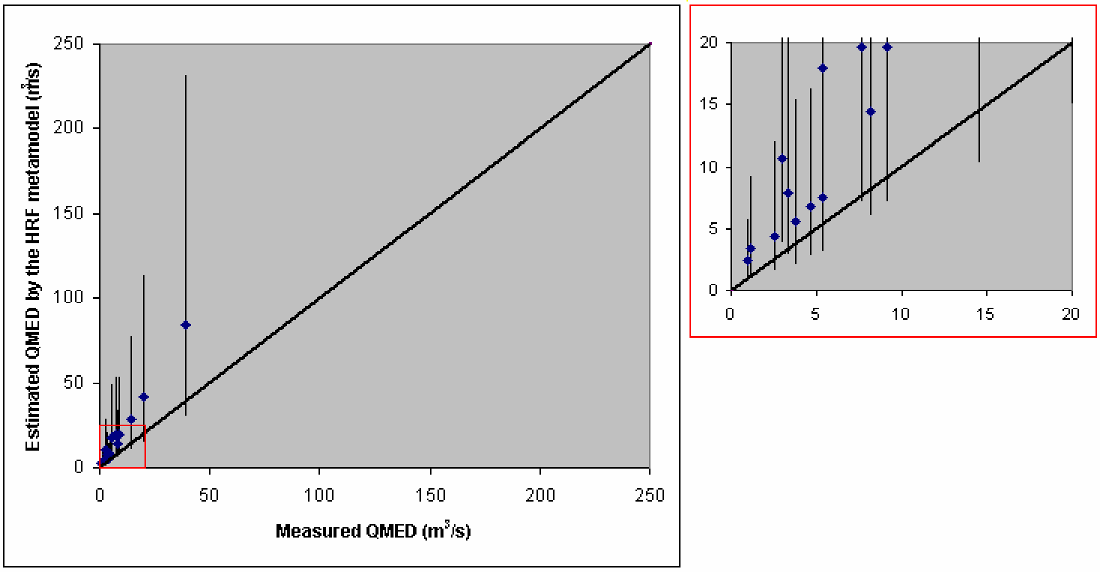


Figure 5-8: Estimated QMED by the High River Flow model (with y-bars representing the 95% confidence interval) vs. 'measured QMED' for East Anglia for baseline conditions.

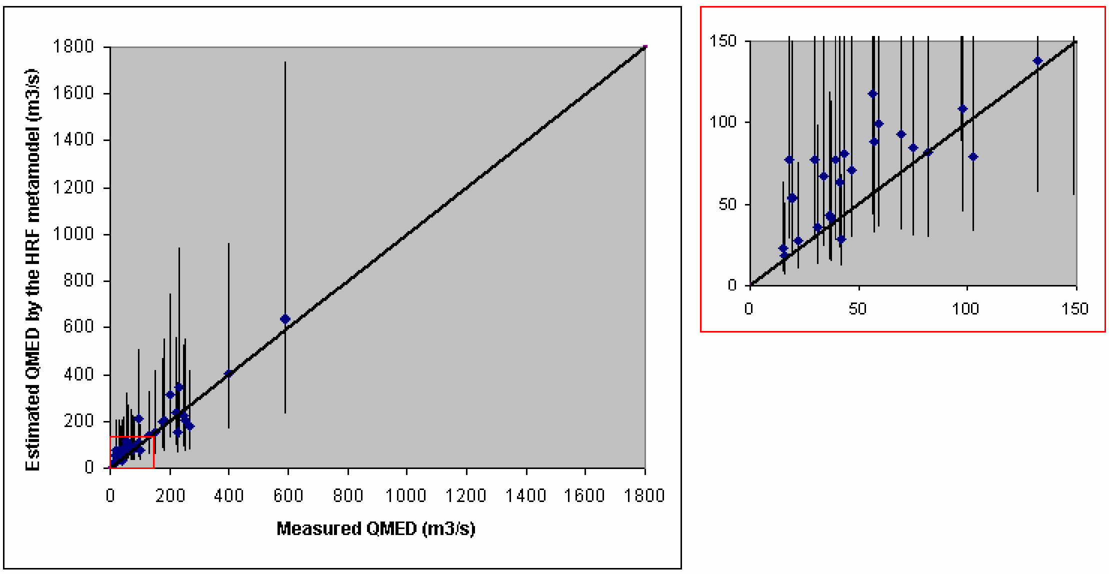


Figure 5-9: Estimated QMED by the High River Flow model (with y-bars representing the 95% confidence interval) vs. 'measured QMED' for the North West for baseline conditions.

The y-bars intercept the symmetry 1:1 line in most cases which suggests that the Catchment Descriptors method for the selected catchments the regions is giving results within the 95% confidence interval. The exceptions might fall within the remaining 5 % or might be due to the abscissa being the calculated ‘measured QMED’ and not the actual measured QMED. However, this latter possibility is assumed not to be very significant because the method used to calculate ‘measured QMED’ has a lower error associated. For example, the ‘measured QMED’ based on annual maximum data with record lengths of 15 years or more has a 95% confidence limit for QMED = (0.813 QMED, 1.23 QMED) whereas estimated QMED from Equation 5-1 has a 95% confidence limit for QMED = (0.42 QMED, 2.40 QMED) (Robson and Reed, 1999). It can also be observed that the application of this method to East Anglia presents limitations as the regional estimated QMED is close to the lower limit of the national 95% confidence interval given by the developer (Figure 5-8).

The Catchment Descriptors method used by the High River Flow model for baseline conditions is a highly generalised model and as Robson and Reed (1999) admit, the confidence intervals for QMED are seen to be very wide. In order to minimise errors in QMED estimates, the analysis of the impacts of future climate and socio-economic changes on QMED are presented as relative changes from baseline. However, the method is suitable for an integrated regional application as it is simple and describes broad variations in QMED (Robson and Reed, 1999).

5.3.2 Validation of QMED for future scenarios

The QMED estimated by the High River Flow model, that is the flood exceeded on average *every other year* (Robson and Reed, 1999), for future scenarios were compared with those from the literature to establish whether the simulated changes are consistent and credible. There are a limited number of published studies focused on the impacts of climate change and, to a lesser extent, socio-economic scenarios on the flood quantiles for a given return period (Prudhomme *et al.*, 2003 and Reynard *et al.*, 2001) usually greater than 2 years and on the high flows exceeded 5% of the time (Q5) (Holman *et al.*, 2005b; Arnell and Reynard, 1996).

The flood quantiles for a return period greater than 2 years are expected to show greater increases under future scenarios than QMED. This is because floods with a shorter return period, such as QMED, are less affected by the changes in climate (Reynard *et al*., 2001 and Prudhomme *et al*., 2003). But is QMED expected to increase under climate scenarios given that it has a short return period? Although QMED and Q5 cannot be directly compared, Arnell and Reynard (1996) show that Q5 varies under the 2050s from a -8% to 6% according to the evapotranspiration scenarios; whilst Holman *et al*. (2005b) for the same time slice, estimates an increase by 5 and 10% depending on the emission and socio-economic scenario. For similar scenarios the High River Flow model estimates an average increase of QMED by 10 and 15%. This suggests that QMED, that has a shorter return period than that of estimated flood magnitudes and higher return period than Q5, is expected to increase under climate change and that the use of the winter half year change to give increase flood flows in the High River Flow model is supported.

In order to analyse if the changes in QMED are credible and realistic, an evaluation of QMED estimated by the High River Flow model was performed against the 1 in 2-year flood event estimates in Prudhomme *et al.* (2003) that is the only study available on the impacts of climate change on QMED. Prudhomme *et al.* (2003) used outputs from 8 GCMs and a hourly time step rainfall-runoff model in five catchments (Figure 5-10 and Table 5-1) in Scotland, the North East, Midlands, Southeast, and Wales. The median of the results, *i.e.* the percentage change in the magnitude of QMED from the baseline, for the 2020s and 2050s for the large number of runs have been grouped by GCMs by Prudhomme *et al.* (2003).

As none of the catchments are in East Anglia or the North West, Equation 5-4 used by the High River Flow model for estimating QMED, was used to calculate the changes in QMED from the changes in winter-half year precipitation for these five catchments. This gave the percentage change in QMED solely due to climate change to allow comparison with Prudhomme *et al.* (2003) who did not consider future changes in urbanisation.

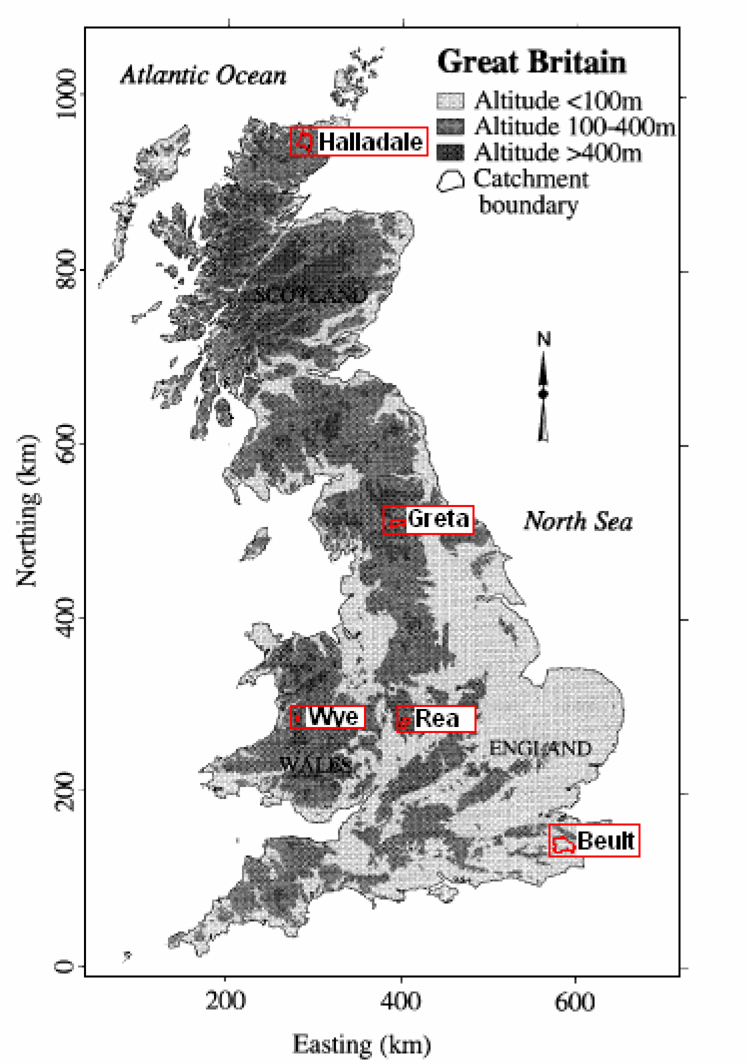


Figure 5-10: Case study catchments of Prudhomme *et al.* (2003): Scotland (Halladale), Northern England (Greta), Midlands (Rea), Southeast England (Beult), and Wales (Wye).

Table 5-1: Details of the selected case study catchments of Prudhomme *et al.* (2003): location (from Prudhomme *et al.*, 2003), drainage area (from FEH CD-ROM, 1999 and Prudhomme *et al.*, 2003) and winter half-year precipitation for the baseline and percentage change from the baseline for UKCIP02 2050s Low and High emission scenarios (UKCIP02 source).

Catchment	**Area, km^2**	**Winter half-year precipitation**		
		Baseline, mm	**Change 2050s Low, %**	**Change 2050s High, %**
25006 – Greta at Rutherford Bridge (North East)	86.1	603.17	4.4	7.1
28039 – Rea at Calthorpe Park (EA Midlands)	74.0	414.89	4.4	7.0
40005 – Beult at Stile Bridge (Southeast England)	277.1	388.98	4.0	6.3
55008 – Wye at Cefn Brwyn (Wales)	10.6	1370.8	3.7	5.8
96001 – Halladale at Halladale (Scotland)	204.6	627.48	5.1	8.0

The estimates of the changes in QMED by the High River Flow model and Prudhomme *et al.* (2003) for the five case study catchments for the 2050s are summarised in the dot diagram in Figure 5-11. The estimates are for different climate scenarios and therefore the student's independent two-sample equal variance t-test was used for the validation. The probability (or p-value[5]), with a two-tailed distribution was calculated using Statistica7 software to analyse if the means in the two groups are statistically different.

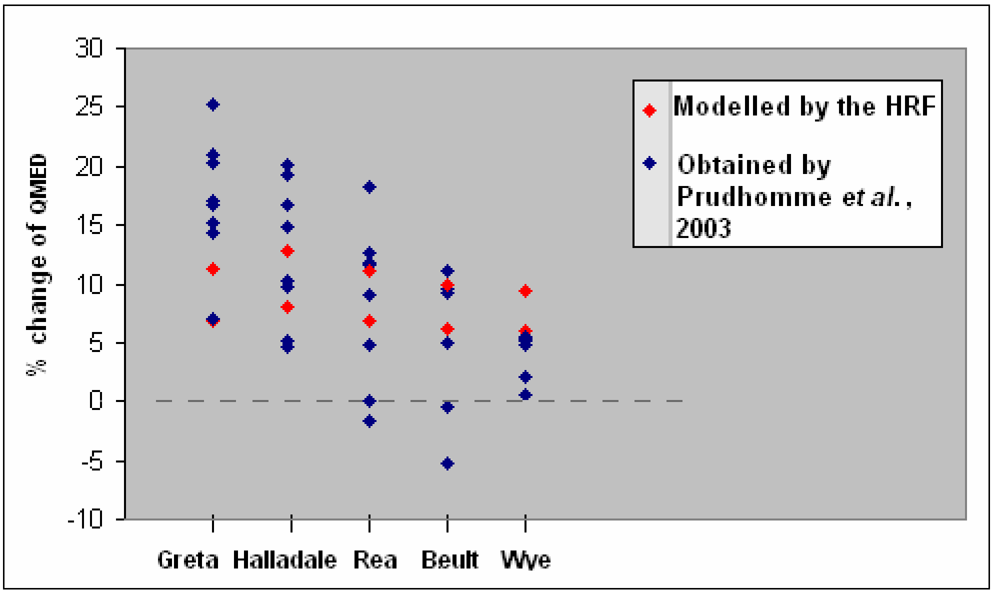


Figure 5-11: Dot diagram showing the percentage of change in the magnitude of QMED in the 2050s estimated by the High River Flow model for Low and High scenarios (in red) and the median percentage of change in the magnitude of QMED in the 2050s grouped by GCMs by Prudhomme *et al.* (2003) (in blue) for five catchments in the UK.

The conventional significance level of $p = 0.05$ was used, that is customarily treated as a *border-line acceptable* error level in many areas of research (Statistica7, Help File). The difference between means in the two groups was significant (at the 95% level of confidence) for the Wye catchment ($p = 0.05$), and that for the Greta, Halladale, Rea and Beult catchments, the null hypothesis failed to be rejected (p = 0.09, 0.65, 0.90, and 0.56 respectively).

It can be observed that the estimates of QMED by the High River Flow model are within the range of uncertainty of estimates using other climate scenarios and another conceptual hydrological model, with the exception of the small 10 km^2 Wye catchment. As discussed earlier, small catchments can have more summer events than bigger catchments so that the Wye catchment may not be so responsive to the winter half-year rainfall that is very high for this catchment (Table 5-1).

5 The smallest level of significance that would lead to rejection of the null hypothesis (that the mean of the populations of the two groups are equal).

Catchments with greater increases in winter-half year precipitation, Halladale, Greta and Rea, (Table 5-1) have a greater increase in the magnitude of QMED (Figure 5-11). That principle within the High River Flow model illustrated in Equation 5-4 is consistent with the results of Prudhomme *et al.* (2003) although the difference in the changes in QMED between the different catchments given by the High River Flow model are not as large as those given by Prudhomme *et al.* (2003). Additionally, Prudhomme *et al.* (2003) observed a regional pattern showing upward trends over time of the median of changes of flood magnitude, which is also consistent with the High River Flow model.

These comparisons suggest that the pattern of behaviour of estimated QMED from the High River Flow model is consistent with Prudhomme *et al.* (2003) study and that the model can be used for regional impact studies for future conditions. Nevertheless, it is a simplistic approach which has limitations that should be considered in analysing the QMED output at the catchment scale.

5.4 Summary

The High River Flow model, which is based on the Catchment Descriptors method of the Flood Estimation Handbook, allows preliminary estimates of QMED to be rapidly made in all sub-catchments and catchments in East Anglia and North West England. Firstly, QMED was estimated for rural catchments using physical and climatological properties according to the original method for baseline conditions. For future climate scenarios the method was adjusted assuming that, because of the relatively uniform current seasonal distribution of rainfall in the UK, the Standard Average Annual Rainfall is actually a surrogate for the average winter half-year precipitation shown to be related with flooding events. The estimated QMED for rural catchments is finally adjusted for the change in infiltration characteristics associated with changes from rural to urbanised conditions to allow the model to be sensitive to urbanisation patterns for the future socio-economic scenarios.

For baseline conditions the simulated and ‘measured’ QMED were compared and the High River Flow model results are generally within the 95% confidence intervals presented for the method, although the QMED tends to be overestimated in East Anglia. For the future climate change scenarios the revised methodology was validated and the estimates of QMED by the High River Flow model are within the range of uncertainty of estimates using other climate scenarios and conceptual hydrological model from Prudhomme *et al.* (2003). Furthermore, a sensitivity analysis has shown that the relationships within the model are the same as those expected in the real system. It can be concluded that the High River Flow model can be used for integrated regional impact studies for describing broad variations in QMED for the baseline and future scenarios.

6 The impacts of potential future changes on the hydrology and water resources in East Anglia and North West

In this section the impacts of future conditions on East Anglia and the North West are explored. Firstly, the developed models were used independently to quantify the effects of climate change on the hydrology and water resources in East Anglia and North West. However, in the future not only climate will change but future human and aquatic environment water needs are unlikely to be static or constant. Therefore, internally consistent socio-economic scenarios (Section 3.2.3) were used to analyse the combined impacts of climate change and human policies and choices. Four climate and four socio-economic scenarios were used in order to acknowledge the uncertainty in the projection of greenhouse gas emissions and the processes determining socio-economic change. All combinations of climate and socio-economic scenarios were considered given that the regional socio-economic factors may not follow the paths of world development. Table 6-1 presents the consistency between the regionalised socio-economic scenarios and the climate scenarios which reflect scenario emissions arising from global socio-economic scenarios (Section 3.2.2).

Table 6-1: Consistency between the regionalised socio-economic scenarios and the climate scenarios (from Shackley and McLachlan, 2005).

	Climate change scenario	
	Low	**High**
Global Sustainability	More consistent	Less consistent, unless fossil fuel energy is not a key issue for sustainable development
Global Markets	Less consistent	More consistent
Regional Stewardship	More consistent, assuming all regions respond in a similar way and that fossil fuel consumption is a key issue for sustainable development	Less consistent, unless most other regions respond differently
Regional Enterprise	Less consistent, unless most other regions respond differently	More consistent, assuming all regions respond in a similar way

In order to investigate the impacts of climate and socio-economic changes in East Anglia and North West England and their relative importance to the hydrology and water resource management:

– the significance of the autonomous responses of the rural environment to climate change were assessed. The linked agriculture model incorporates spontaneous responses which are reflected in the variables to which the hydrological models are sensitive, such as rural land-use changes and irrigation demand;

– the significance of the differences between a sectoral and an integrated approach and of the cross-sectoral integrations and pressure variables were analysed.

This section is divided into the study of the changes in the hydrological behaviour (Section 6.1), in the abstraction availability and water demand (Section 6.2) and in the influence of abstractions and discharges on the naturalised flows (Section 6.3).

6.1 The impacts of climate and socio-economic change on the hydrology

6.1.1 The impacts of climate change on QMED and the hydrological indicators

6.1.1.1 The impacts of climate change on QMED

The average regional change in winter half-year precipitation is very similar in both regions (Section 3.2.2) and therefore so is the regional change in QMED (Figure 6-1). Due to the relatively small standard deviation in the winter half-year precipitation (Section 3.2.2), the changes in the spatial patterns QMED are small, with the relative changes in QMED from baseline being greater in the west of East Anglia and in the south of the North West, with a gradual increase of QMED over the climate scenarios (Figure 6-1). Moreover, there are no significant absolute changes from baseline in the catchments of the regions.

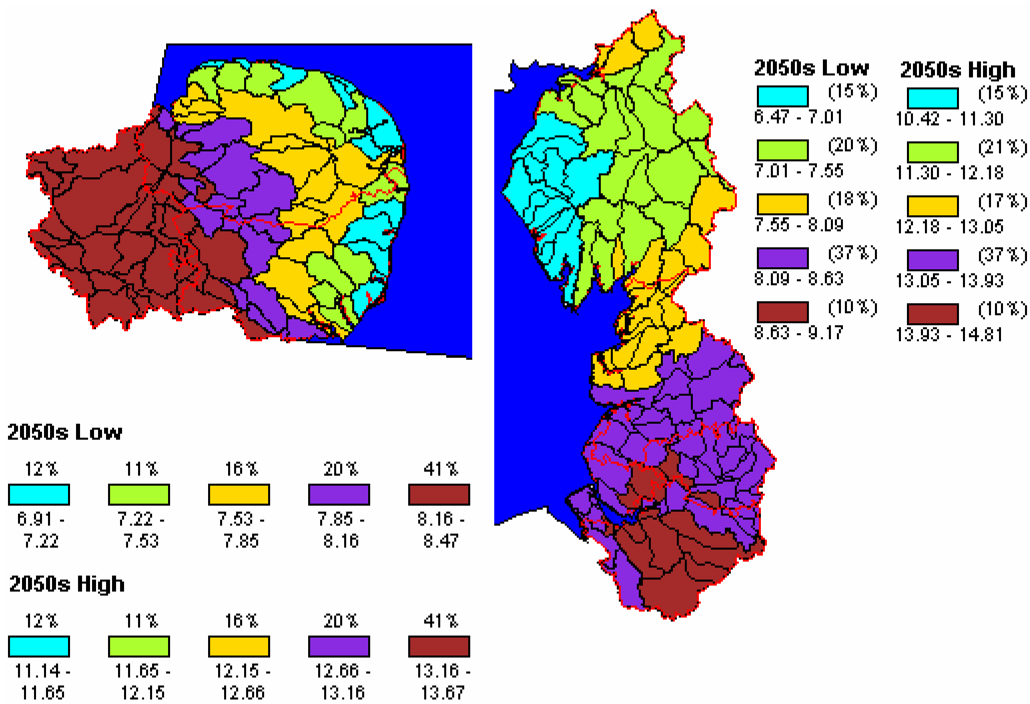


Figure 6-1: Change in QMED from baseline (%) under the baseline socio-economic scenario for 2050s Low and High emission scenarios (with different magnitudes of change but showing the same spatial patterns) for East Anglia (left) and the North West (right). The legend also indicates the percentage of the area within each range.

6.1.1.2 The impacts of climate change on the hydrological indicators

The impact of climate on the simulated hydrological indicators *i.e.* MF, Q95, MAM(7), flow range and groundwater recharge reflect the changes in hydrologically effective precipitation. This is a balance between the changes in average annual total precipitation rate due to climate change and evapotranspiration due to climate change and consequent changes in crop selection by farmers. All the estimated hydrological indicators change identically because the hydrologically effective precipitation is the only changed variable running these scenarios and is reflected on the estimated MF from which all the other hydrological indicators were derived (Section 4.1). This suggests that for estimating the impacts of climate change solely, the hydrological indicators could have been simulated simply adjusting the historical flow duration curve with the MF. That is due to the following limitation. Using the regression equation approach calibrated with past data for estimating the naturalised FDC from the MF (Section 4.1.2 and Section 4.1.3) for future time-slices assumes that the shape of the HOST-based FDC is constant. However, the hydrological behaviour of the soil types may change with climate given the generally wetter winters and substantially drier summers. Therefore, the impacts of climate change might have been underestimated, especially in flashy rivers; *i.e.* underestimating high flows and overestimating low flows. However, although the used method poses limitations, it provides a satisfactory broad scale mapping tool. Recommendations for further work are presented in Section 9.2.

From Figure 6-2 it can be observed that climate change gradually reduces those variables in the catchments and that Suffolk is the least impacted county in East Anglia.

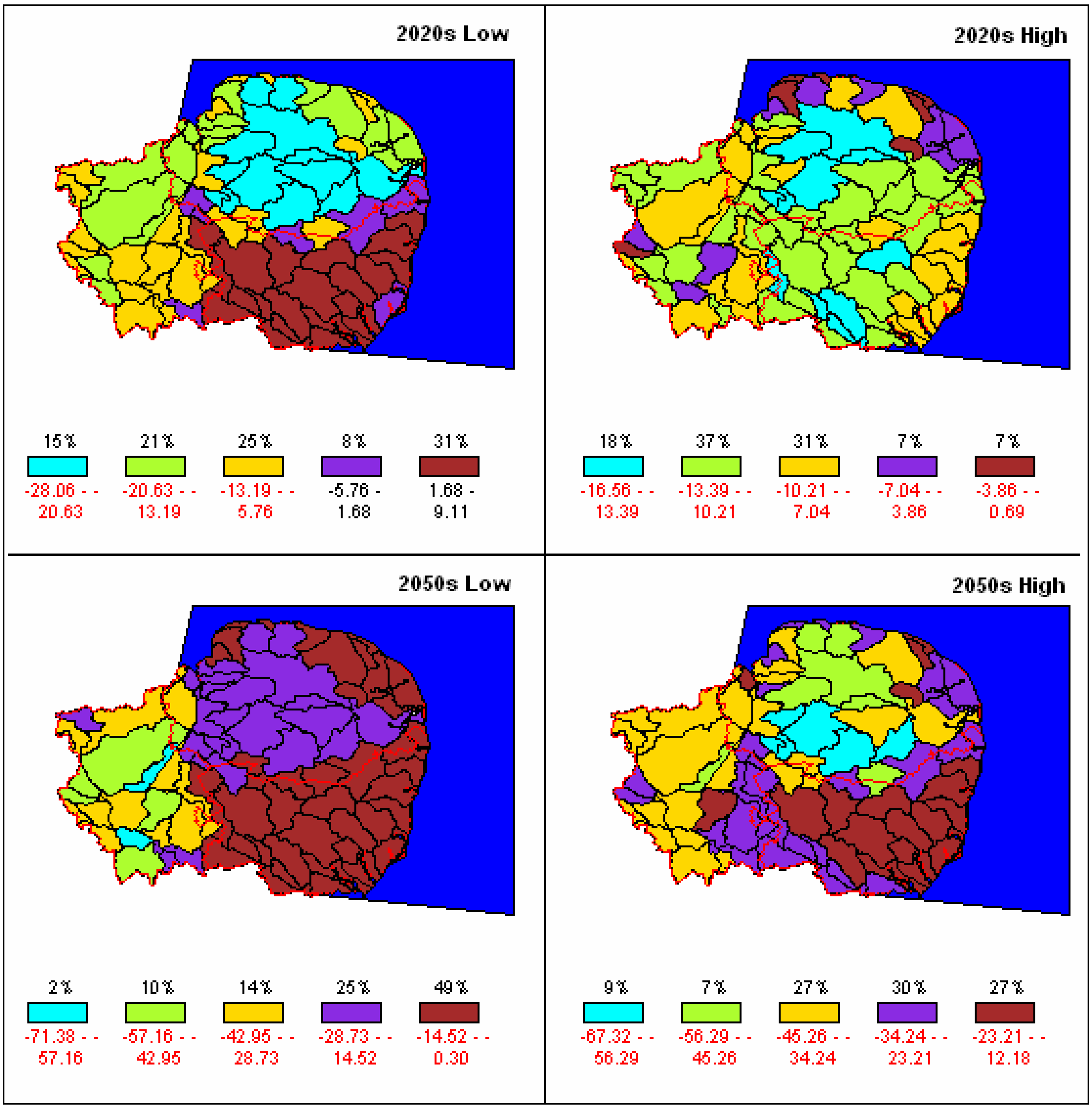


Figure 6-2: Change in the hydrological indicators (MF, Q95, MAM(7), flow range and groundwater recharge) from baseline (%) for 2020s (top) and 2050s (bottom) Low (left) and High (right) emission scenarios for East Anglia. The legend also indicates the percentage of the area within each range.

As a result of the reduction in hydrologically effective precipitation (manifested in the reduced MF), especially in Cambridgeshire and Norfolk, and the increase in the application of N-fertiliser mainly in Norfolk) due to changes in crop selection by farmers and higher yields (Audsley *et al.*, *Submitted*), nitrate leaching increases with climate change, mainly in Norfolk where it can increase by 200% under the 2050s High climate (Figure 6-3).

Figure 6-4 shows the change in the hydrological indicators from baseline, which behave identically, under the 2050s High climate assuming that agricultural practices remain as under baseline conditions *i.e.* with no autonomous adaptation. The hydrological impacts of agricultural changes are more significant in Norfolk, further reducing the hydrological indicators by around 10%, although they are much less significant than the direct impacts of climate change (as shown by a comparison of Figure 6-2 and Figure 6-4).

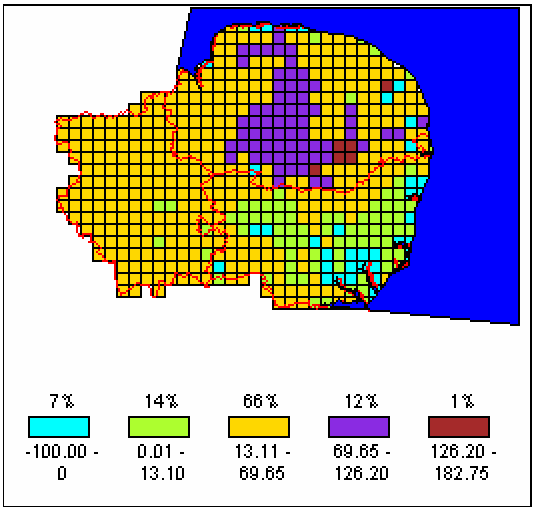


Figure 6-3: Change in nitrate leaching from baseline (%) under the baseline socio-economic scenario for the 2050s High emission scenario in East Anglia. The legend also indicates the percentage of the area within each range.

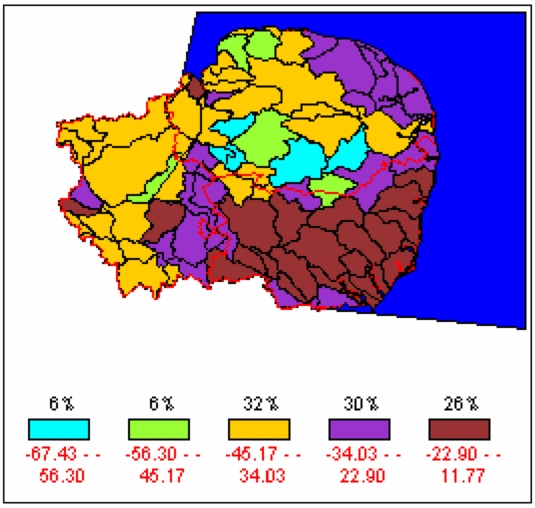


Figure 6-4: Change in the hydrological indicators from baseline (%) under the baseline socio-economic scenario assuming no response to climate from the agriculture sector for 2050s High emission scenarios in East Anglia. The legend also indicates the percentage of the area within each range.

In the North West the impacts of climate change on the hydrological indicators are less significant than in East Anglia (Figure 6-5) because the absolute flows are higher and therefore percentage changes are less significant. The change in mean nitrate concentration is also less significant in the North West (Figure 6-6) due to the smaller change in MF and the use of less fertiliser in this region.

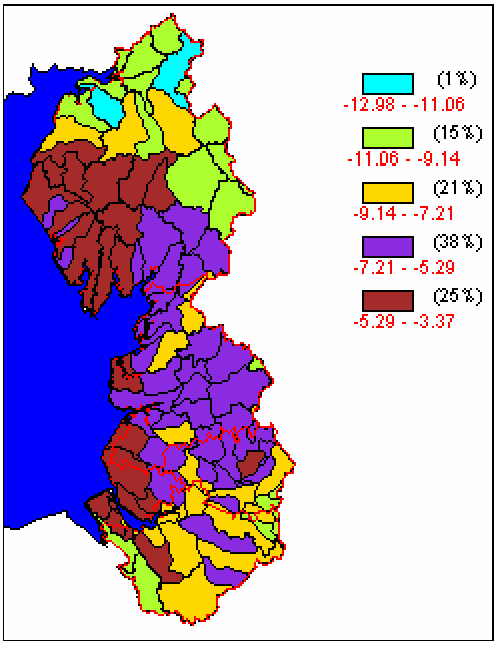


Figure 6-5: Change in the hydrological indicators from baseline (%) under the baseline socio-economic scenario for the 2050s High emission scenarios for the North West. The legend also indicates the percentage of the area within each range.

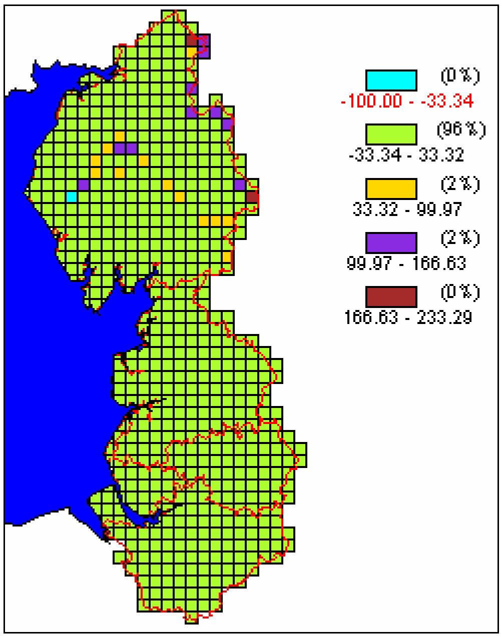


Figure 6-6: Change in nitrate leaching from baseline (%) under the baseline socio-economic scenario for the 2050s High emission scenario in the North West. The legend also indicates the percentage of the area within each range.

6.1.2 The impacts of climate and socio-economic change on QMED and the hydrological indicators

6.1.2.1 The impacts of climate and socio-economic change on QMED

Changes to the flood index within each catchment are a consequence of climate and the changing landscape. Regarding the latter, the model is only sensitive to changes in the urban development in urban areas (Section 5.1.3). Under the RS scenario, urbanisation decreases uniformly (*i.e.* URBEXT decreases by 6% in East Anglia and by 11% in the North West). Therefore, the increase of QMED due to climate (Figure 6-1) is uniformly reduced by the change in URBEXT in catchments by less than 5% in both regions under the 2050s High climate scenario. Under a GM scenario the impacts of climate on QMED are exacerbated in both regions (Figure 6-7) by the increase in urban and suburban areas (Figure 6-8). The impacts are more significant in catchments in the west of East Anglia and the south of the North West due to the combined greater change in urbanisation and winter half-year precipitation in these areas.

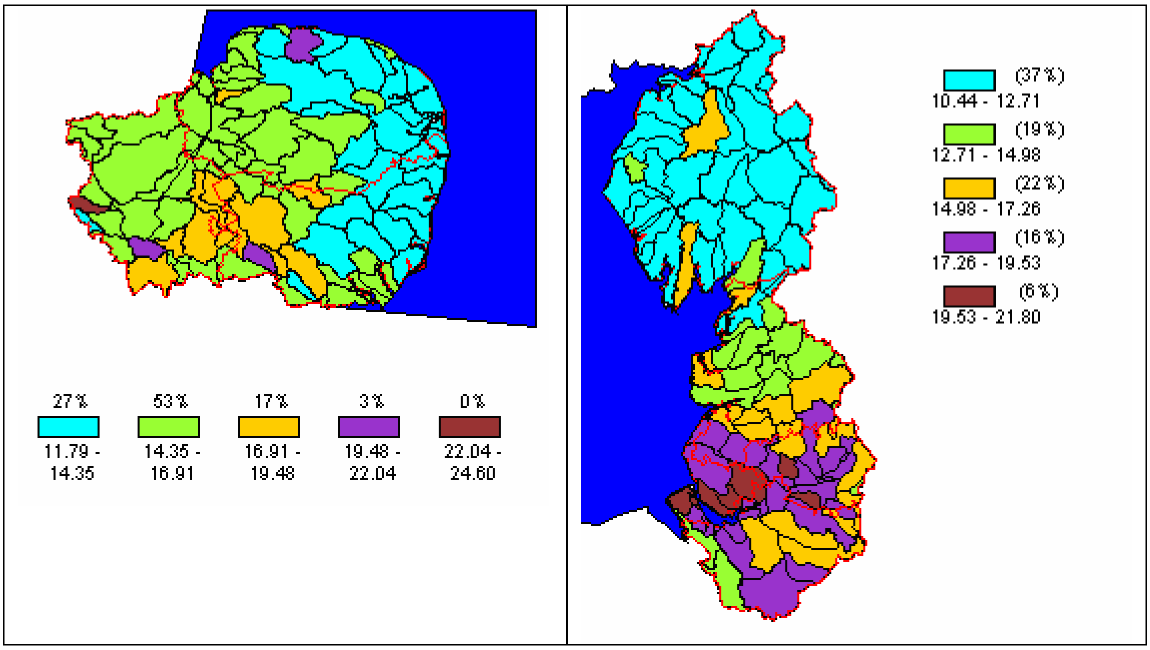


Figure 6-7: Change in QMED expressed as a percentage of change from baseline under the Global Markets scenario for 2050s High emission scenarios (right) for East Anglia (left) and the North West (right). The legend also indicates the percentage of the area within each range.

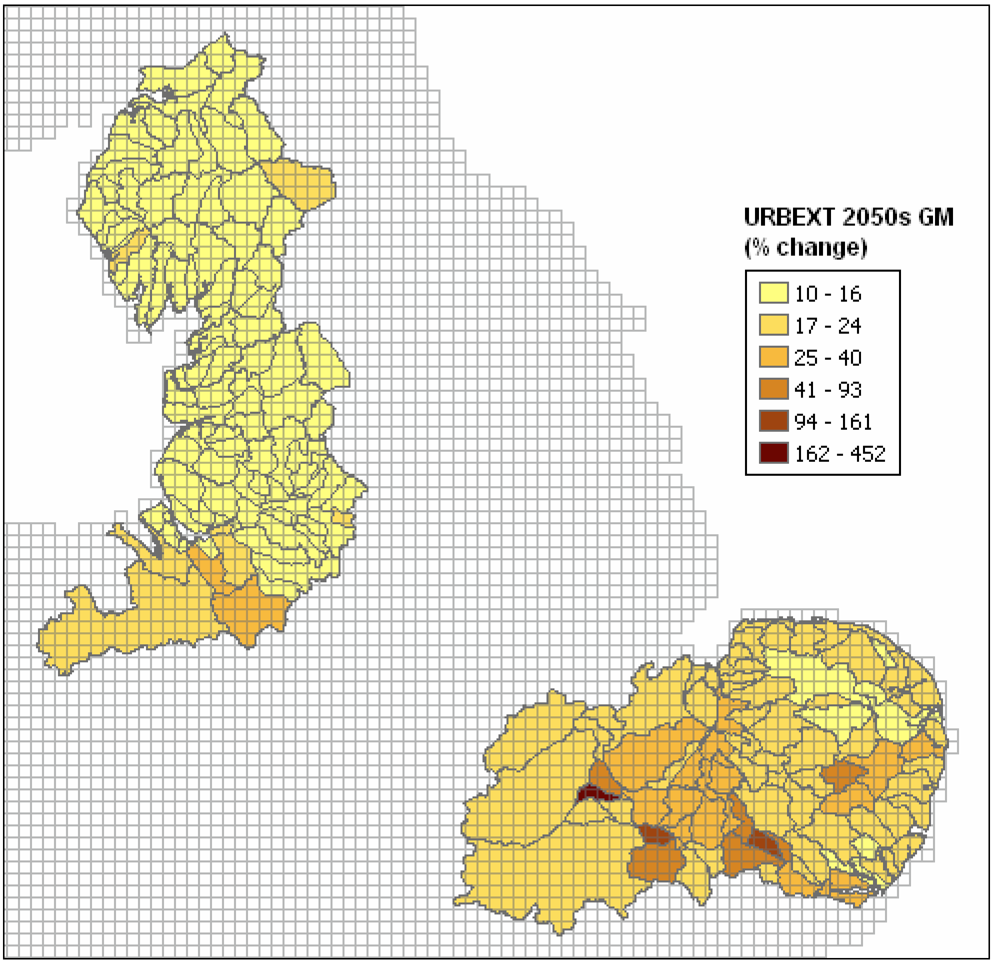


Figure 6-8: Change in URBEXT under the Global Markets scenario for 2050s for East Anglia and North West (expressed as % of change from baseline).

6.1.2.2 The impacts of climate and socio-economic change on the hydrological indicators

The socio-economic scenarios affect the hydrological behaviour by altering the landscape in two principle means. Firstly, future regional population and urban planning policy will determine the changes to the urban and suburban areas within the regions and consequent hydrological effects resulting from changed evapotranspiration and surface sealing. Secondly the agricultural policy within the socio-economic scenarios determines future changes to the agricultural landscape and the crops grown within it, which might result from (Henriques, *et al.*, *Submitted*):

- changes to agricultural policy *e.g.* farm subsidies, Common Agricultural Policy reform;
- changes in fuel/transport/climate change mitigation policy leading to large demands for non-food bioenergy crops, such as willow and *Miscanthus* grass plantations (MAFF, 2001).
- technical changes such as increased yields; and
- non-agricultural policy which affect agricultural labour and fertiliser costs.

The impacts of socio-economic changes under the 2050s High climate are analysed for the contrasting RS and GM scenarios. Under the 2050s High RS scenario, due to the uniform decrease of URBAN areas by 6% in all the catchments, the impacts of climate change on the hydrological indicators (represented in Figure 6-4) are further reduced by less than 5% (comparing Figure 6-4 and Figure 6-9). Coupling the impacts of climate and urban landscape change with the rural landscape changes, the hydrological indicators change more significantly in Norfolk and the south west of East Anglia where the impacts of climate are exacerbated by socio-economic changes although the former has a greater impact. The different modelled hydrological indicators show the same spatial patterns and magnitude of change compared to the baseline as illustrated in Figure 6-9 because the change in urbanisation is uniform over the catchment; the only variable modified is the hydrologically-effective precipitation reflected on the MF from which the other indicators have been derived. As a consequence of the decreased MFs and changes to agricultural practices, mean nitrate concentration increases in the region, especially in Cambridgeshire and Norfolk (Figure 6-10).

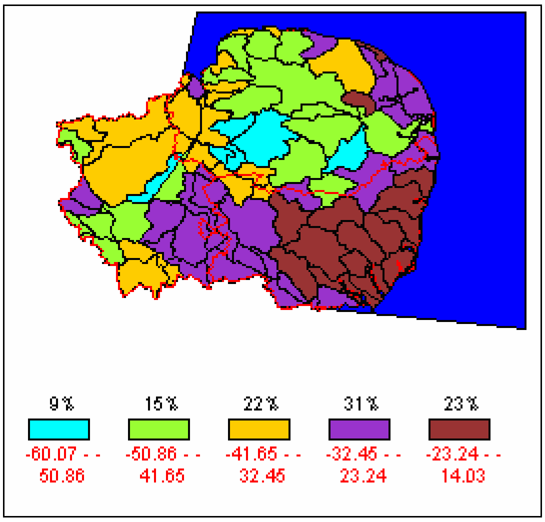


Figure 6-9: Change in the hydrological indicators from baseline (%) under the 2050s High Regional Stewardship scenario for East Anglia. The legend also indicates the percentage of the area within each range.

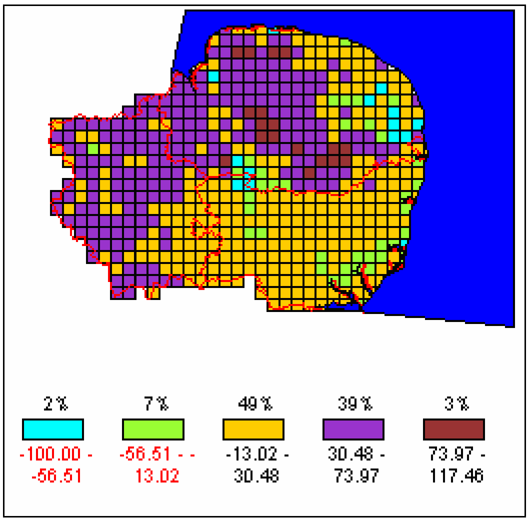


Figure 6-10: Change in mean nitrate concentration from baseline (%) under the 2050s High Regional Stewardship scenario for East Anglia. The legend also indicates the percentage of the area within each range.

Under the 2050s High GM scenario, urbanisation increases ameliorating the impacts of climate change on the hydrological indicators (comparing Figure 6-4 with Figure 6-12). In catchments with significant urban development (Figure 6-11) changes in urbanisation even leads to increases in the hydrological indicators from baseline. For the different hydrological indicators, different spatial patterns and magnitudes of change are observed due to the heterogeneous urbanisation that affect evapotranspiration (Section 4.1.1.4) and surface sealing (Section 4.1.2). Figure 6-12 illustrates the changes in MF and the naturalised Q95.

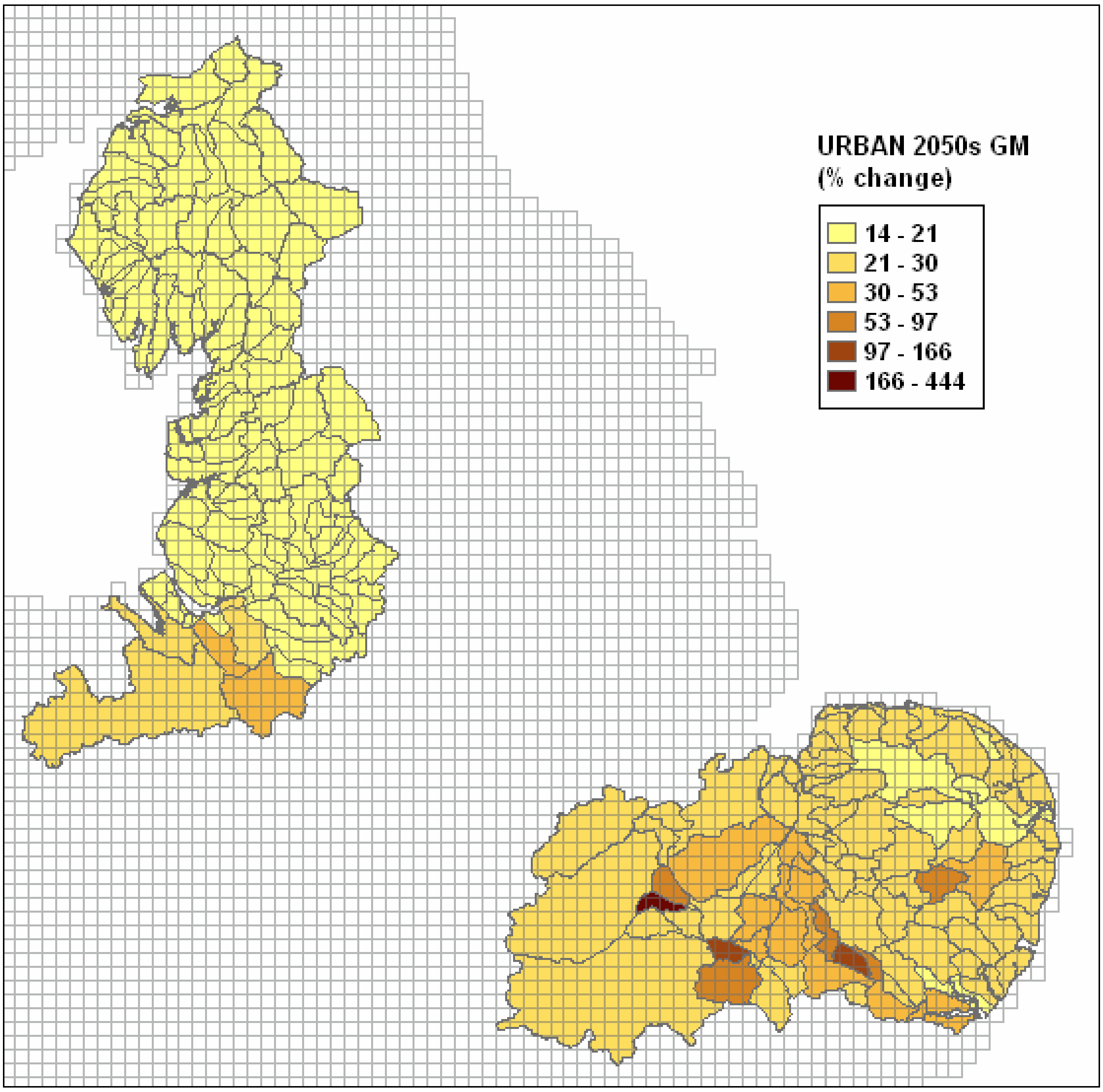


Figure 6-11: Change in URBAN under the Global Markets scenario for 2050s for East Anglia and North West (expressed as % of change from baseline).

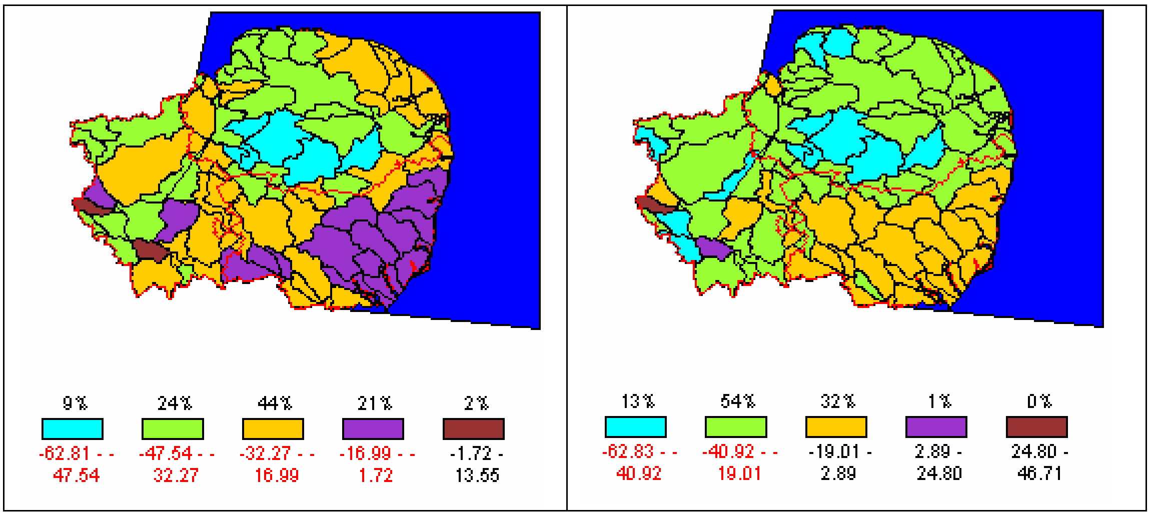


Figure 6-12: Change in Mean Flow (left) and Q95 (right) from baseline (%) under the 2050s High Global Markets scenario for East Anglia assuming no rural changes. The legend also indicates the percentage of the area within each range.

The impacts of rural changes have an opposite effect to the impacts of urban changes exacerbating the impacts of climate change, further reducing the hydrological indicators (example of MF comparing Figure 6-12 with Figure 6-13) leading to a very high increase in the mean nitrate concentration (Figure 6-13) due to decreased dilution. Therefore, for the 2050s High GM scenario, in catchments with moderate changes in urbanisation, the impacts of climate are greater than the impacts of socio-economic changes; however, in catchments with very high urban development, the impacts of socio-economic changes are greater.

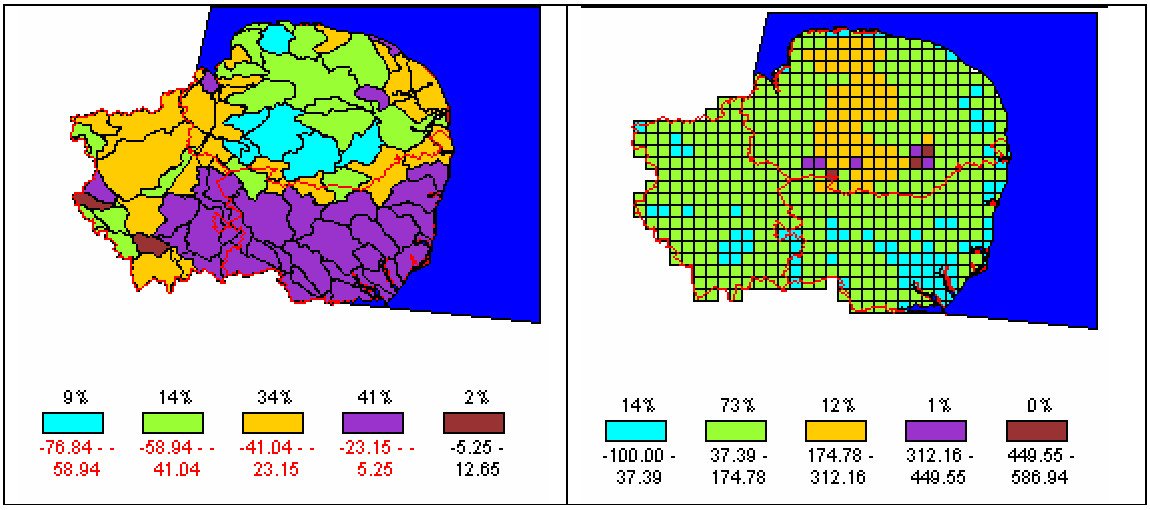


Figure 6-13: Change in Mean Flow (left) and mean nitrate concentration (right) from baseline (%) under the 2050s High Global Markets scenario for East Anglia. The legend also indicates the percentage of the area within each range.

The combined impacts of climate and socio-economic changes in East Anglia under the 2050s High GM scenario are generally smaller in the south and in catchments with high urban development (Figure 6-13). In the North West (Figure 6-14) the impacts of climate and socio-economic changes are smaller than in East Anglia and the impacts of climate are greater than the impacts of socio-economic change as catchments do not experience such large changes in urban development as in East Anglia.

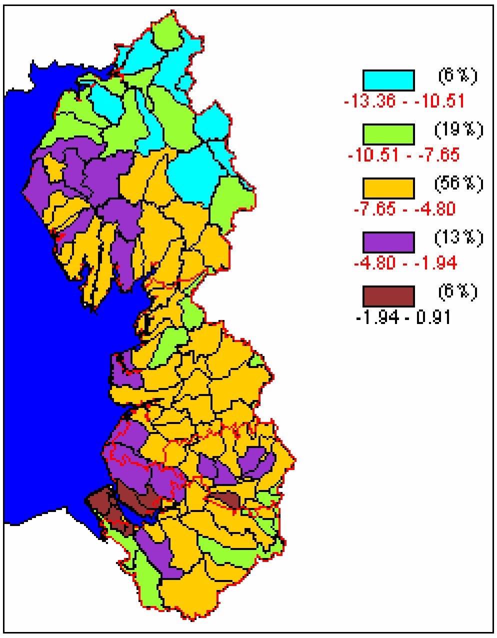


Figure 6-14: Change in Mean Flow from baseline (%) under the 2050s High Global Markets scenario for the North West. The legend also indicates the percentage of the area within each range.

6.2 The impacts of climate and socio-economic change on the abstraction availability and water demand

6.2.1 The impacts of climate change on abstraction availability and agricultural irrigation demand

Climate change impacts the naturalised flows on which the constrained and unconstrained abstraction availabilities are based. As a result of reduced river flows, under baseline socio-economic conditions less water is available for abstraction for all users under all climate scenarios (Figure 6-15, Figure 6-17). However, significant effects do not manifest themselves until the 2050s, as the reductions by the 2020s are approximately 10% of current levels in East Anglia; in the North West, due to the very high water availability, reductions are only around 2%. By the 2050s under a High climate change scenario, abstraction availability in East Anglia is reduced by over 300 Ml/d, a reduction of around 35% compared to current availability. Smaller reductions in abstraction availability, less than 250 Ml/d, are seen in the higher availability North West region, accounting for a reduction of approximately 5% only. The spatial distribution and the magnitude of the change from baseline on the abstraction availability due to climate change reflect the same changes as the hydrological indicators (Section 6.1.1).

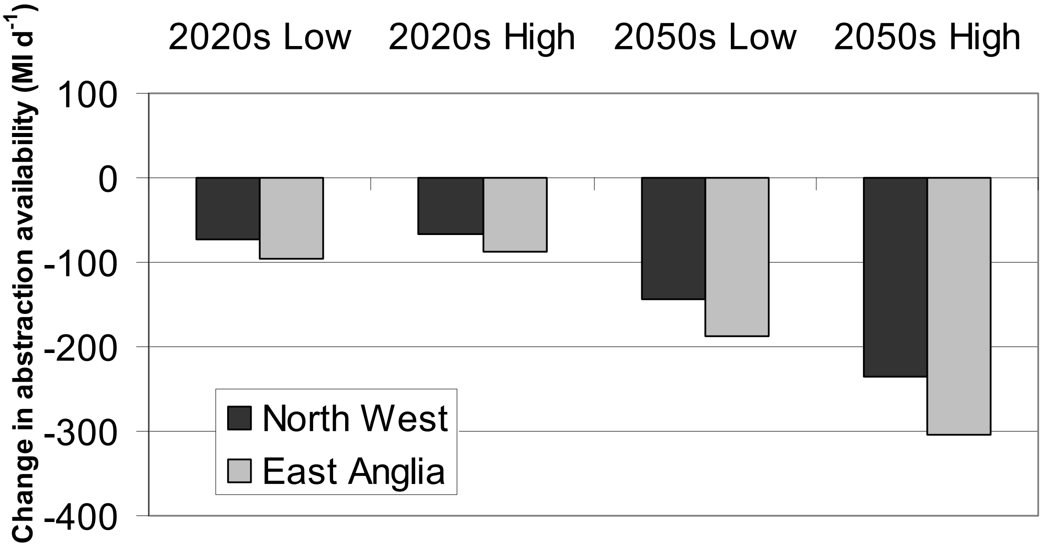


Figure 6-15: Change in abstraction availability in East Anglia and North West for different climate scenarios under current socio-economic conditions.

In parallel with the reduction in abstraction availability, there are variable changes in irrigation demand in both regions (Figure 6-16) as the simulated farms autonomously respond to the changes in relative crop profitability due to climate change-induced yield changes, although current licensed abstractions limits were assumed under baseline socio-economic conditions. In East Anglia, irrigation demand appears to remain relatively stable, apart from under a 2050s High climate scenario when it increases by about 40% (compared to the baseline). In the North West, irrigation demand increases by between 190 and 240 % under the 2050s Low and 2050s High, respectively, but the large percentage rise reflects the very low baseline irrigation demand. The changes in irrigation demand are as a result of (Henriques *et al.*, *Submitted*):

- the increase in water demand by the irrigated crops due to the warmer and drier growing season in all the climate scenarios;
- the relative changes in gross margins due to the differing yield response of all arable crops, leading to differing crop selection choices by farmers arising from autonomous adaptation, and;
- shifts in the relative irrigation of sugar beet and potatoes, due to water pricing and food production priorities of the socio-economic scenarios.

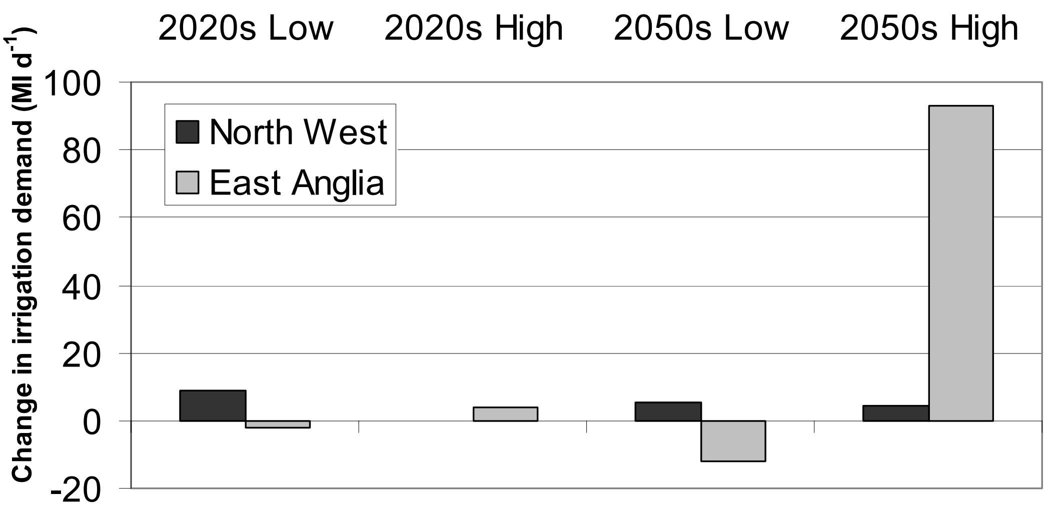


Figure 6-16: Change in irrigation water demand for agriculture in East Anglia and North West for the different climate scenarios under baseline socio-economic conditions.

6.2.2 The impacts of climate change on the abstraction availability and water demand under socio-economic changes

The socio-economic scenarios affect the hydrological behaviour, which in turn affects the abstraction availability; and influence the water availability through the policy arena. Table 6-2 separates out the changes in abstraction availability in East Anglia due to climate change (given by a 2050s High climate), rural landscape change, urban development changes and Regional Environmental Priority effects on the GM and RS futures at a regional level. These show that regional decrease in abstraction availability due to climate change is:

- exacerbated by the effects of land-use change in the agriculture landscape under both futures;
- under GM the increase in urban areas also leads to an increase in river flows, although by a small extent at a regional level as opposed to the locally greater extent in heavily urbanised individual catchments; and
- that the greatest effect is that caused by the choice of the environmental rights of the river systems to water (Figure 6-17). Under GM scenario, by accepting greater environmental stress the availability of water for human uses is increased and the impacts of climate change in reducing abstraction availability are ameliorated. Under RS scenario, with a high societal value placed on the environment and a consequent reluctance for environmental stress to be imposed on aquatic habitats and species, abstraction availability is further reduced.

Table 6-2: Contributions of scenario elements to the changes, *i.e.* climate and socio-economic effects, in the available water (change in Ml d^{-1} from the baseline) for East Anglia.

Scenario	Contribution	Available water
2050s High Global Market	Climate effect only	-305
	Socio-economic effect (rural landscape change)	-35
	Socio-economic effect (urban development change)	+1
	Socio-economic effect (Regional Environmental Priority)	+520
2050s High Regional Stewardship	Climate effect only	-305
	Socio-economic effect (rural landscape change)	-2.8
	Socio-economic effect (urban development change)	-0.2
	Socio-economic effect (Regional Environmental Priority)	-295

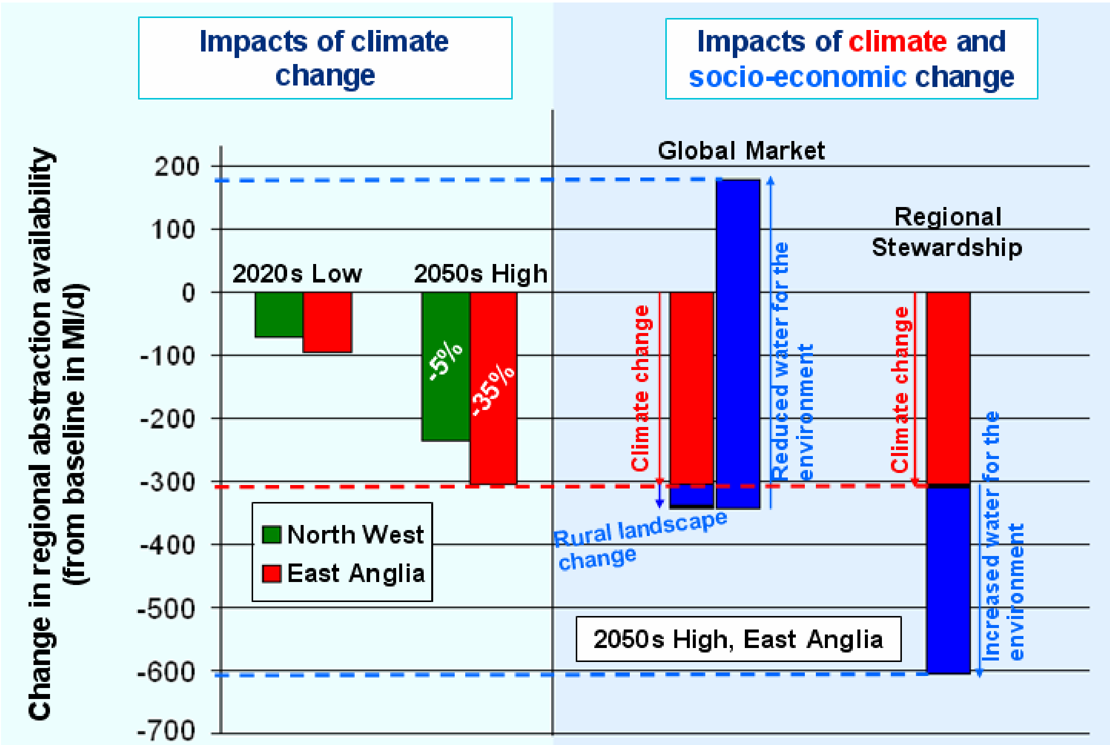


Figure 6-17: Change in the regional abstraction availability under climate change for East Anglia and the North West under 2020s Low and 2050s High (left); and under climate change and GM (left) and RS (right) socio-economic futures in East Anglia under 2050s High (right).

The impacts of climate and socio-economic changes on abstraction availability due to climate change and the change in urban and rural landscape reflect the same spatial patterns and magnitude of change as the change from baseline in MF Section 6.1.2). However, the sensitivity of abstraction availability to changes in the REP is more significant. For example, under the 2050s High RS scenario (comparing Figure 6-9 and Figure 6-18) and under GM scenario (comparing Figure 6-13 and Figure 6-18).

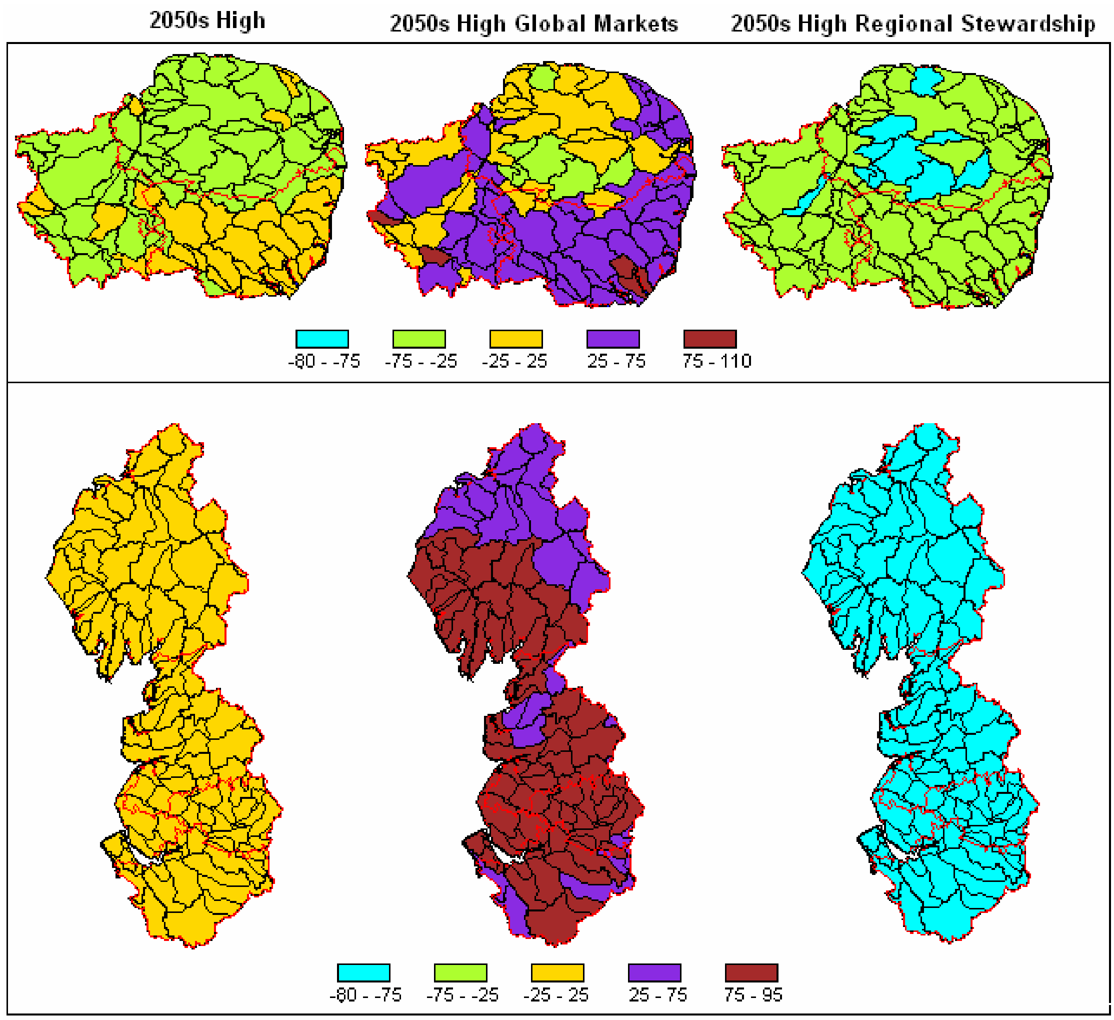


Figure 6-18: Change in abstraction availability (% change relative to baseline) in baseline (left), Global Markets (middle), and Regional Stewardship (right) futures under the 2050s High climate scenario for East Anglia (top) and the North West region (bottom).

Under environmentally-focused futures (Global Sustainability and Regional Sustainability), the REP is high and the necessary water is allocated to protect the river ecology at the expense of abstraction availability. The water demand is also reduced, by a lesser extent than abstraction availability (Table 6-3). The reduction in water demand in both regions is particularly from industry/commerce and due to leakage control. Leakage reduces by 50% in East Anglia under the GS and RS 2050s High scenarios (Figure 6-19) and is even further reduced in the North West (Figure 6-20). Under environmentally-focused futures for the 2050s High climate, in East Anglia the water demand is reduced for all sectors; however, in the North West agricultural irrigation demand increases as given by the agricultural model due to changes in water costs, demand for produce and gross margins (Henriques *et al.*, *Submitted*). However, this has little impact due to the small absolute demand.

Table 6-3: Change in regional water availability and water demand from the baseline for East Anglia and the North West under the 2050s High emission scenario and socio-economic change.

Climate and Socio-economic scenario	East Anglia				North West			
	Abstraction availability		Water demand		Abstraction availability		Water demand	
	Ml/d	%	Ml/d	%	Ml/d	%	Ml/d	%
2050s High baseline	-305	-36	+93	+10	-236	-6	+4	≈ 0
2050s High Global Sustainability	-605	-71	-387	-42	-2107	-57	-1658	-59
2050s High Global Markets	+182	+21	+396	+43	+2902	+78	+695	+25
2050s High Regional Stewardship	-602	-71	-327	-36	-2950	-80	-1485	-53
2050s High Regional Enterprise	+148	+17	+858	+94	+2209	+60	+1861	+67

Under economically-focused scenarios (Global Markets and Regional Enterprise) the lower priority that is given to the environmental flow requirements results in significantly increased availability of water. In East Anglia the water demand increases by a greater extent than abstraction availability as opposite to the case in the North West (Table 6-3). Abstraction availability increases more in the North West than in East Anglia for a given REP due to the higher river flows.

In all sectors, an increase in water demand is observed (Figure 6-19 and Figure 6-20). Under 2050s High GM futures, the greatest increases from baseline are in industrial/commercial water demand (58% in East Anglia and 34% in the North West) and in domestic water demand (77% in East Anglia and 37% in the North West). The water supplied by the mains increase; however, leakage does not increase as much because the leakage coefficient (leakage as a proportion of the water supplied) is significantly reduced due to the great emphasis on the market forces of competition in this scenario (Environment Agency, 2001).Under RE scenarios, the most significant change is in leakage, *i.e.* an increase of 440% in East Anglia and 190% in the North West, which is due to the increased losses as a proportion of the public water supply due to low levels of investment in the water industry (Environment Agency, 2001), but also due to the increase in the public water supply, as domestic water demand increases by 70% in East Anglia (compared to the baseline) and by 39% in the North West. Under the 2050s High RE in the North West a significant increase in water for irrigation was observed (from 2.2 to 19 Ml/d).

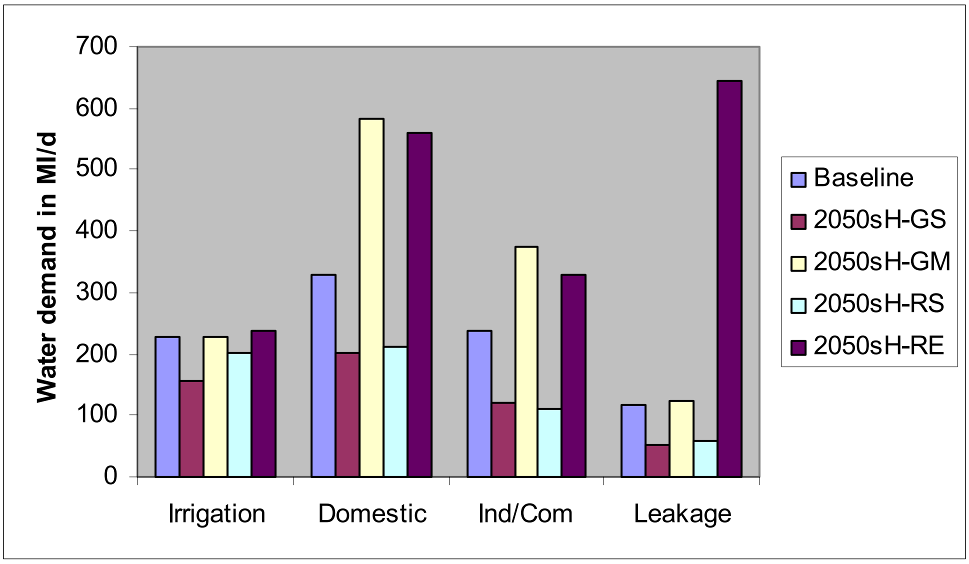


Figure 6-19: Allocation of water to the different demand components under baseline conditions and according to the different socio-economic scenarios for East Anglia under the 2050s High scenario.

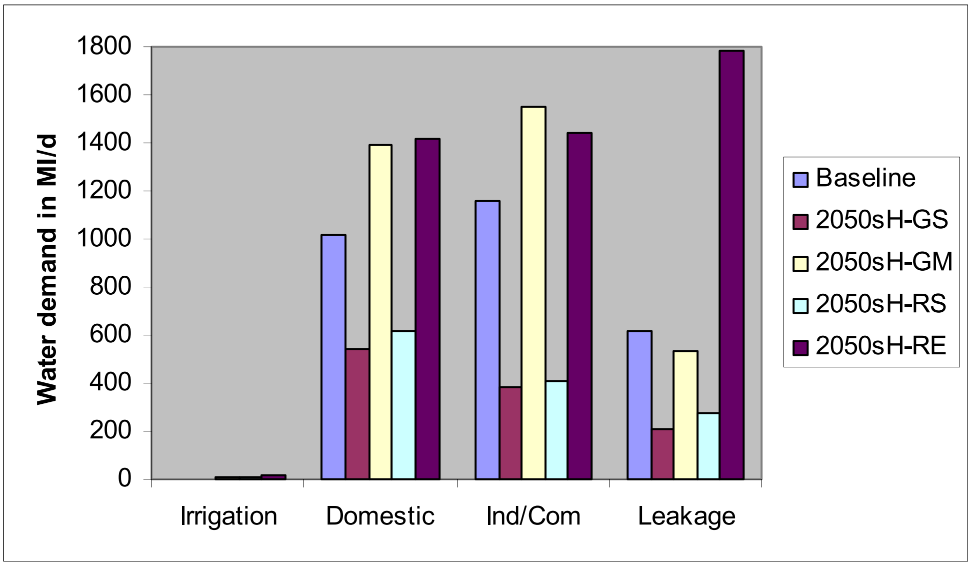


Figure 6-20: Allocation of water to the different demand components under baseline conditions and according to the different socio-economic scenarios for the North West under the 2050s High scenario.

6.2.3 The impacts of socio-economic factors in ameliorating or exacerbating the impacts of climate change on the balance between abstraction availability and water demand

The regional water demand can be met by the constrained and unconstrained abstraction availability under current baseline conditions in the North West, but not in East Anglia (Table 6-4). The supply-demand balance in East Anglia is negative given that the baseline reservoir supply (30 Ml/d)[6] and water transfers (19 Ml/d)[7] are smaller than the balance between abstraction availability and water demand. However, this current negative balance is due to an overestimation of the irrigation water demand by the agriculture model of Audsley *et al*. (*Submitted*) which assumes that a greater proportion of the licensed water for agricultural irrigation is actually abstracted *i.e.* 228 Ml/d instead of 169 Ml/d as in Environment Agency (2001c).

Under the 2050s High climate, with no change in the socio-economic factors, abstraction availability reduces and water demand increases for irrigation purposes (Section 6.2.1) and therefore the balance between abstraction availability and water demand is reduced comparing to baseline conditions (Table 6-4). In the North West, the balance is positive indicating that the increased irrigation demand should be able to be met from the available resource. However, for the 2050s High climate in East Anglia the balance is negative (Table 6-4). This indicates that current water resource management practices would become unsustainable and that adaptation from the supply and/or demand sides are needed, given that current reservoir storage capacity and net water transfers (as under baseline socio-economic conditions) are not sufficient for meeting the demand.

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[6] assuming that Grafham Water reservoir (Section 3.1.5.1) does not benefit East Anglia assumed to consist solely of Anglian Water Services Eastern zone.

[7] assuming that East Anglia solely consists of Anglian Water Services Eastern zone and that transfers between Essex Water Co and the Eastern zone are intra-regional, according to the water transfers presented in Section 3.1.5.1.

Table 6-4: Balance between the unconstrained (UNC) and constrained (CON) abstraction availability and water demand for East Anglia and the North West under the different socio-economic scenarios and the 2050s High climate scenario, in Ml/d.

Regions	Scenarios	Abstraction availability		Water demand	Balance (UNC + CONS – demand)
		UNC	CONS		
East Anglia	Baseline	114	739	914	-61
	2050s High	78	470	1007	-459
	2050s High GS	45	202	527	-279
	2050s High GM	170	865	1310	-276
	2050s High RS	47	204	587	-336
	2050s High RE	125	876	1772	-771
North West	Baseline	557	3146	2792	911
	2050s High	521	2946	2796	671
	2050s High GS	313	1282	1134	462
	2050s High GM	1169	5436	3487	3118
	2050s High RS	102	651	1307	-554
	2050s High RE	771	5141	4653	1259

In East Anglia, under the 2050s High climate, for the different socio-economic scenarios the balance between abstraction availability and water demand is negative (Table 6-4). Under GS, GM and RS the impacts of climate change are moderated by socio-economic factors, although the situation is less sustainable than under baseline conditions (Table 6-4). Under RE scenario the impacts of climate are exacerbated due to the very high leakage, further reducing the balance between demand and abstraction availability (Table 6-4). In the North West, under environmentally-focused futures, the impacts of climate change are further exacerbated and under RS the balance between demand and abstraction availability is negative (as opposite to all the other scenarios) (Table 6-4) due to the very high REP that significantly reduces abstraction availability. Under economically-focused futures, the impacts of climate change are moderated (Table 6-4) due to the very high abstraction availability and the balance shows a surplus even greater than under baseline socio-economic conditions.

Under the different futures not only abstraction availability changes, but there is also potential for increase in reservoir storage and net water transfers in order to meet the demand in East Anglia. These are analysed in the context of each socio-economic scenario under the adaptation options considered in Section 7.1.

6.3 The impacts of socio-economic change on altering the naturalised flows due to abstractions and discharges

Changes to the high and low non-naturalised flows within each catchment are a consequence of the changing naturalised flows but also depend on the socio-economic factors, specifically abstractions and discharges. In catchments where there are no dramatic changes in urbanisation, the hydrological response of the catchments is not greatly affected by the socio-economic future, as illustrated with the case for 2050s High RS. In that scenario urbanisation in East Anglia uniformly decreases by only 6% (compared to the baseline) and per capita domestic water demand decreases to 95 $l.d^{-1}$), producing large decreases in abstractions and discharges. Figure 6-21 and Figure 6-22 show the naturalised and non-naturalised Q5 and Q95 flows.

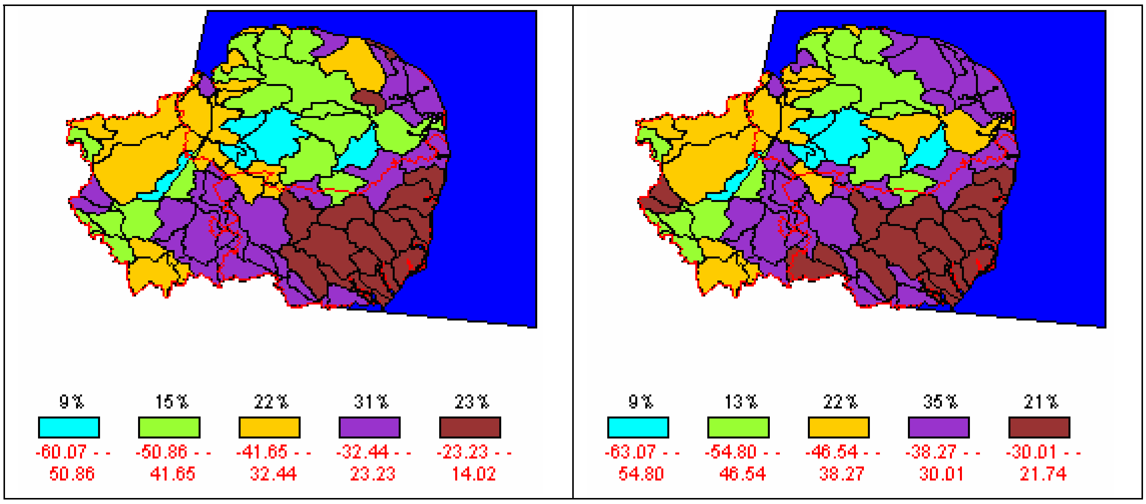

Figure 6-21: Percentage change from baseline in naturalised (left) and non-naturalised (right) Q5 for the 2050s High RS scenario. The legend also indicates the percentage of the area within each range.

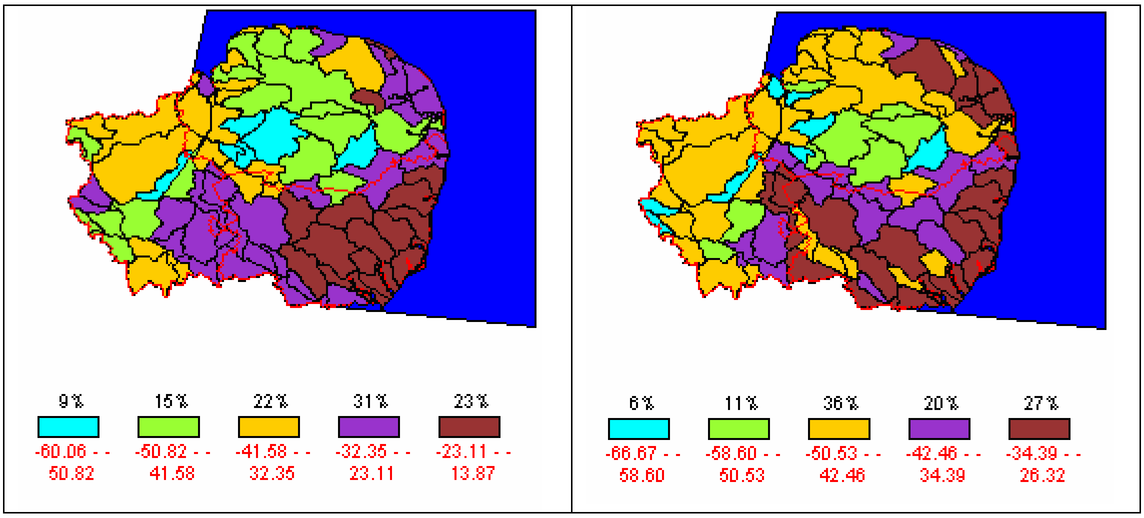

Figure 6-22: Percentage change from baseline in naturalised (left) and non-naturalised (right) for Q95 for the 2050s High RS scenario. The legend also indicates the percentage of the area within each range.

Comparing the naturalised and non-naturalised Q5 (Figure 6-21), it is apparent that there is very little difference in both the spatial patterns of change and the absolute percentage changes. The decreases in non-naturalised Q5 are therefore mainly driven by the climate with very little influence from the changes in urban areas.

A slightly different situation is apparent when comparing the naturalised and non-naturalised Q95 (Figure 6-22). However, although elements of the spatial pattern are still visible in the non-naturalised Q95 flows, indicating that in those catchments the main driver is the climate impacting upon the naturalised flows, significant local changes occur in the spatial pattern which result from relative changes in discharges and unconstrained abstraction availability that differs between catchments depending on the naturalised flow. Under this RS scenario, effluent returns are reduced because of the decreased consumptive water demand arising from a reduced population and lower per capita usage, whilst unconstrained abstraction availability is also reduced because of the high REP. As the reduction in urbanisation within this scenario is a uniform decrease of 6%, the greatest absolute changes in urban areas and population will occur in the larger towns. In the south east of the region, the non-naturalised Q95 decreases from the naturalised Q95 as discharges decrease more than the abstractions. Nevertheless, in all catchments the non-naturalised Q95 is reduced from the baseline.

The increase in urbanisation from baseline to the GM scenario in the 2050s High (Figure 6-8) is higher than the decrease for RS, and spatially heterogeneous, with some catchments experiencing very large increases in urbanisation of more than 100% (relative to the baseline). As a result, the regional variability of the percentage of change of non-naturalised Q95 with the 2050s High climate is higher than under the RS scenario. Under the 2050s High GM scenarios, the magnitude of change of non-naturalised Q95 from the baseline is extremely high in catchments experiencing very large new urban development associated with new towns. In these catchments, the impacts of the socio-economic changes are clearly evidenced by increased effluent returns resulting from the higher population and per capita water usage.

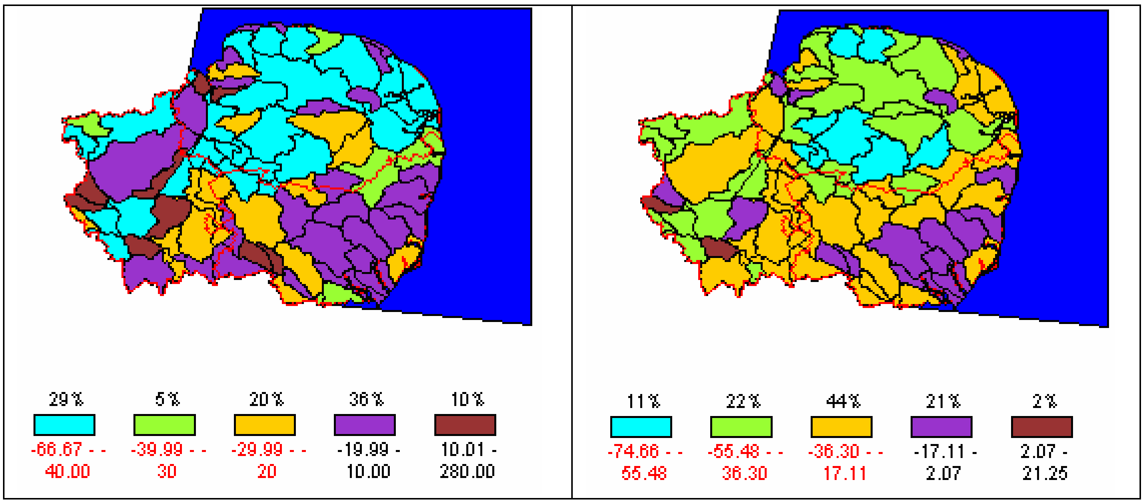

Figure 6-23: Percentage change form baseline in non-naturalised Q95 (left) and non-naturalised Q5 (right) for the 2050s High GM scenario. The legend also indicates the percentage of the area within each range.

Whilst non-naturalised Q5 decreases in East Anglia by up to 65% under the RS scenario (Figure 6-21), under the GM scenario it decreases by up to 75%, which is explained by changes in the naturalised Q5, but increases in some catchments by up to 20% in East Anglia (Figure 6-23) due to the above mentioned reasons. However, the non-naturalised Q5 flows increase relative to the baseline in fewer catchments than for the non-naturalised Q95.

The regional variability in the change in non-naturalised Q95 between the 2050s High RS and GM scenarios and the baseline (Figure 6-22 and Figure 6-23) are higher than for the non-naturalised Q5 (Figure 6-21 and Figure 6-23). This arises because the Q95 is a smaller absolute flow that is impacted by abstractions and discharges to a greater relative proportion that the larger Q5 flow.

The non-naturalised Q5 and Q95 flows are sensitive to the regional consumptive water demand which determines the effluent returns (from domestic, industrial/commercial purposes and leakage from the mains). The consumptive water demand regionally increases by 58% for 2050s GM and decreases by 44% for 2050s RS socio-economic scenarios in East Anglia due to a change in water usage and population (Table 6-5). The impact on the non-naturalised Q95 of the change in effluent returns is partially offset by a change in the unconstrained abstraction. For example, the effect of the 378 Ml/d increase in effluent returns due to the GM scenario, resulting from the higher non consumptive water demand, is partially cancelled by an increase of 91 Ml/d in the unconstrained abstraction availability due to the very low REP under the GM future (Table 6-5).

Table 6-5: Non-consumptive demand, domestic water demand, industrial/commercial water demand, population and unconstrained abstractions availability for East Anglia 2050s High scenario and baseline, GM and RS socio-economic scenarios.

	Non-consumptive demand (Ml/d)	Domestic water demand ($l.p^{-1}.d^{-1}$)	I/C water demand (Ml/d)	Pop (x1000)	Unconstrained abstraction availability (Ml/d)
2050s High Base	685	150	238	2513.6	78
2050s High GM	1083	190	376	3068.3	169
2050s High RS	383	95	112	2237.8	47

Comparing the 2050s High RS and GM scenario results, the impacts of climate and socio-economic changes are evident, with the latter being more significant in the more urbanised areas. The GM scenario with the 2050s Low and High emission scenarios have been compared to show the impacts of climate change under the same changed socio-economic conditions as, since the same time slice is analysed, urbanisation, domestic and industrial water demand and effluent returns are constant. However, the naturalised flows change due to the climate scenario and the changes in the cropping as a result of the climate. As a consequence of the change in naturalised flows, abstraction availability also changes even though the REP remains the same.

The non-naturalised Q95 indicator is analysed because of its greater susceptibility to changes. From Figure 6-24 under a GM scenario it can be observed that although the non-naturalised Q95 flows are generally reduced under the 2050s Low scenario (compared to the baseline) due to a decrease in the annual rainfall, the flows are higher than under the 2050s High climate. However, in areas in the south west of East Anglia, where urbanisation most increases (Figure 6-8), it is observed that the non-naturalised flows increase (compared to the baseline). This suggests that the increase in effluent returns under the 2050s GM scenario are greater than the reduction in Q95 flows under the 2050s Low climate scenario but are less than the equivalent change under the 2050s High climate.

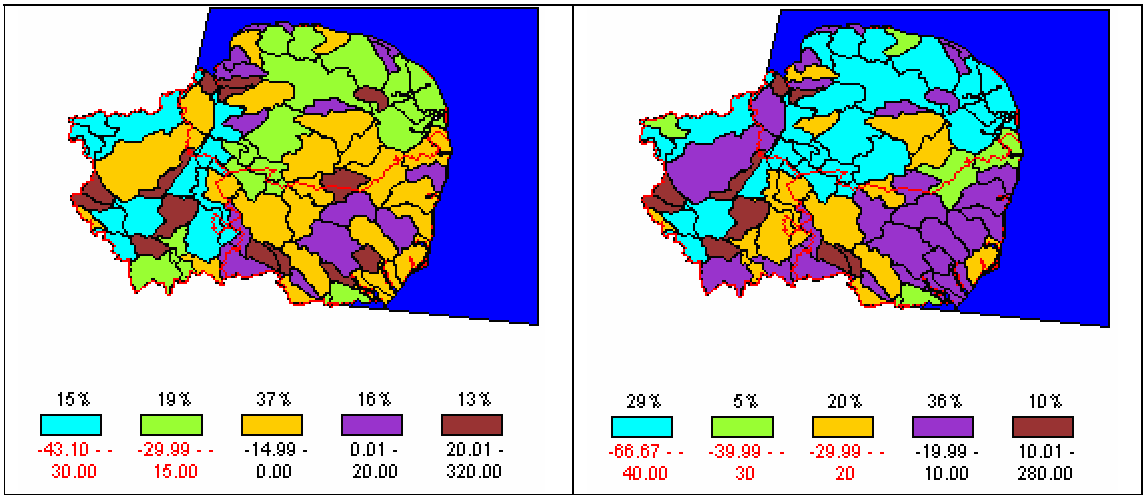

Figure 6-24: Percentage change from baseline in the non-naturalised Q95 for GM scenarios under the 2050s Low (left) and 2050s High (right) emission scenarios. The legend also indicates the percentage of the area within each range.

In the North West the impacts of socio-economic scenarios are smaller than for East Anglia because the urbanisation for the different scenarios does not change as much (*e.g.* for 2050s GM, Figure 6-8 and Figure 6-25), and, at a regional level, the actual non-consumptive water demand is not so affected (Table 6-6) because demand can be satisfied by the supply of water and therefore the potential and actual non-consumptive water demand are the same.

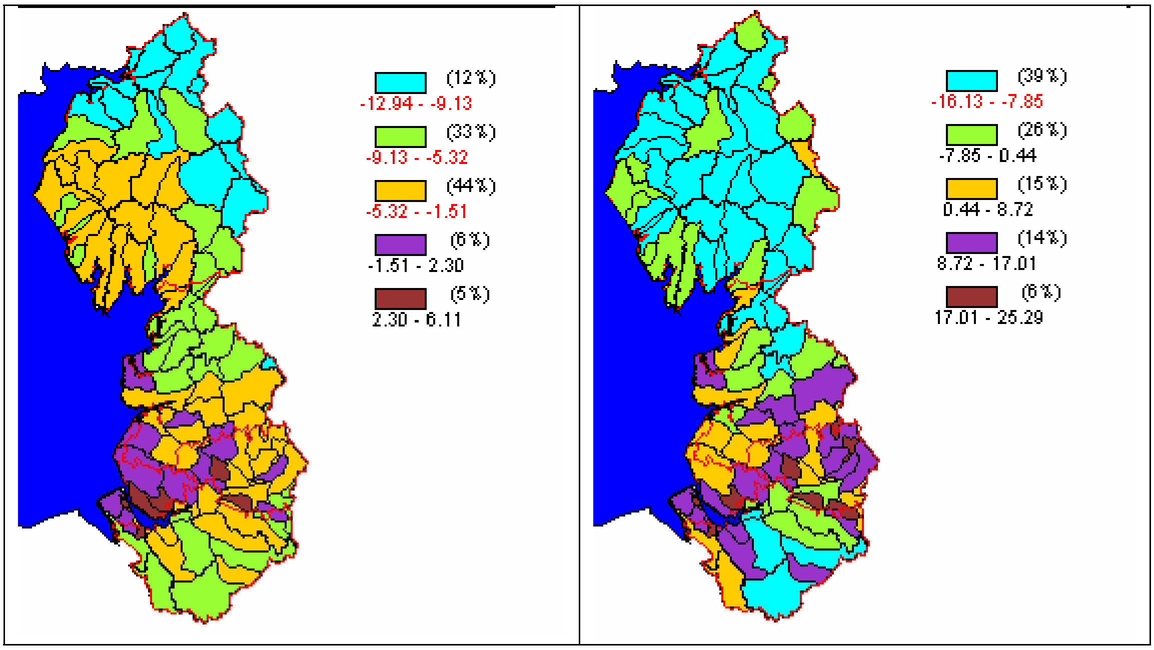

Figure 6-25: Percentage change from baseline in the naturalised (left) and non-naturalised Q95 (right) for 2050s High for the GM scenario. The legend also indicates the percentage of the area within each range.

Table 6-6: Percentage change from baseline in potential non-consumptive water demand and actual non-consumptive water demand (which differ from the former in case demand cannot be met by the supply) for East Anglia and North West.

	Change in potential non-consumptive demand from baseline (%)		Change in actual non-consumptive demand from baseline (%)	
	East Anglia	North West	East Anglia	North West
2050s GM	+58	+24	+58	+24
2050s High RS	-44	-54	-59	-54

For the North West, more water is available and the demand is not restricted by limited supply as in East Anglia for 2050s High RS scenario (Table 6-6). Adding this to the change in non-consumptive demand (from the baseline) for the socio-economic scenarios analysed, it is observed that changes in the effluent returns in the North West are smaller than for East Anglia. In the North West, compared to East Anglia, not only are the impacts of the socio-economic scenarios smaller, but so also are the impacts of climate change (Figure 6-25).

The non-naturalised Q95 changes less in the North West than in East Anglia (relative to the baseline). This is because the naturalised flows in the North West are larger than for East Anglia in absolute terms, and therefore the change from baseline is smaller despite the magnitude of climate change in both regions being similar. Moreover, the variability of change of the non-naturalised flows is much lower in the North West for the abovementioned reason and due to the socio-economic scenarios being associated with smaller changes (in urbanisation and water demand changes).

Figure 6-25 shows that non-naturalised Q95 flows under a 2050s High GM future in the north of the North West are further reduced by the socio-economic scenarios compared to the rest of the region. Whilst non-naturalised Q95 decreases by up to 15% in the north, it increases by up to 25% in the south, which reflects the heterogeneity of urbanisation and population density in the region – the effects of abstraction in the north are not offset by discharges because of the low population density, whereas in the south the high population leads to discharges being greater than the abstractions such that the non-naturalised Q95 increases.

6.4 Summary

The method used to estimate the hydrological indicators provides a satisfactory broad scale mapping tool although it should be recognised that the use of regression equation approach pose limitations. The simulated impact indicators are mainly determined by the climate scenario as hydrologically effective precipitation drives the hydrological behaviour of the catchments, *i.e.* the reduced annual average rainfall and increased evapotranspiration results in reduced flows and groundwater recharge. Moreover, the increased winter precipitation results in increased flooding. The changes from baseline are generally greater in East Anglia than in North West. To a lesser extent, these indicators are also determined by socio-economic changes such as land uses: cropping classes and urbanisation. However, if urban development is very high, such as the case for 2050s GM scenario in some catchments in East Anglia, the impacts of climate change on the hydrological indicators can even be totally ameliorated as urban areas generate higher runoff (compared to most soil types), however exacerbating the impacts of climate change regarding the increase in flooding events and further deteriorating the water quality.

In a future under current socio-economic factors, the model shows that the significant effects of climate change are not manifested until the 2050s in East Anglia under a high emission scenario, where abstraction availability is reduced and water demand is increased for irrigation purposes leading to the need for adaptation options as supply does not meet demand. The socio-economic futures cause even larger changes in the abstraction availability, primarily due to the Regional Environmental Priority that determines the environmental flow allocation for the river. The volumes of water that can be abstracted are determined by the value that society places on the environment and the consequent reluctance (or willingness) for environmental stress to be imposed on aquatic habitats and species. By accepting greater environmental stress, particularly at times of low flow, a future society can significantly increase the availability of water for human uses. Socio-economic factors also impact on water demand and include population growth, leakage management, increased water saving and efficiency arising from technology improvements and changed irrigation demand due to changes in water costs, demand for produce and gross margins.

The balance between the abstraction availability and water demand in each region is impacted through interactions of differing importance with the hydrological and policy environments. In East Anglia, under environmentally-focused futures the decrease in abstraction availability is greater than the decrease in water demand, resulting in a negative supply-demand balance for the 2050s High climate. The deficit is likely to lead to further restrictions on water demand, particularly in drier than average years, unless adaptation responses are implemented or a relaxation of the environmental allocation becomes inevitable. Under economically-focused futures, the increase in water demand, especially for industrial/commercial and domestic water demand under GM and due to leakage under RE, is greater than the increase in abstraction availability for the 2050s High climate scenario resulting in a deficit which is greater than under baseline conditions. In the North West, under all socio-economic futures, changes in abstraction availability are greater than in demand. Apart from the RS scenario with very high protection of aquatic ecosystems, the water available for abstraction is sufficient to meet the demand. Under environmentally-focused futures the impacts of climate on the balance between abstraction availability and water demand are exacerbated and under economically-focused scenarios the balance has a greater surplus than under baseline conditions.

The non-naturalised low and high flows (as given by the non-naturalised Q95 and Q5 flows respectively) show the significant influence of future urbanisation, population water requirements and regional environmental allocation of water on the hydrological responses of catchments to future change. Whether the effects of the socio-economic scenario moderate or amplify the reduction on the naturalised flows due to climate change depends on the characteristics of the socio-economic scenario and the region. In those catchments with low levels of urbanisation (in much of the northern and central parts of the North West and much of East Anglia to a greater extent) and under environmentally-focused futures with low consumptive water demand, the non-naturalised flows will be little affected by these socio-economic factors being mainly determined by the changes in the naturalised flows. In those catchments with low levels of urbanisation and under economically-focused scenarios in which consumptive water demand is high, increased abstraction will lead to the reductions in naturalised flows caused by the impacts of climate change being amplified. In those catchments with significant urbanised areas (such as the south of the North West), the influence of urbanisation and population water requirements can be highly significant, especially in East Anglia. Decreases in low flows, will be partially or in some cases completely moderated by the effects of returns. High flows, may increase to a lesser extent than the low flows due to the increased returns.

7 Responses to the impacts of climate change in the context of different socio-economic futures

In order to tackle the impacts of climate change, suitable adaptation options from the supply and demand side under each of the socio-economic scenarios for East Anglia and the North West are presented in Sections 7.1.1, 7.1.2 and 7.1.3. These adaptation options were assessed given the range of the impacts resulting from the quantified uncertainty associated to the climate and water demand changes. In Section 7.1.4 the relevant model results are interpreted in the light of the model limitations. In Section 7.1.5 relevant adaptation options regardless the future scenario are presented for each of the regions. In Section 7.2 the ability to deliver the current environmental legislative requirements under the Water Framework Directive, Habitats Directive and Nitrates Directives is analysed in the context of the different socio-economic futures.

7.1 Adaptation options to tackle climate change

The balance between the water supply and demand provides a measure of the robustness of the system and significantly differs between the regions. The water supply is considered for a first analysis to be the sum of the regional abstraction availability and the reservoir storage capacity and inter-regional net water transfers as for baseline conditions (Section 3.1.5.1 and Section 3.1.5.2). In East Anglia, the balance is reduced from the baseline and is generally negative, apart for the GM socio-economic scenario with 2020s Low and High and 2050s Low climate scenario (Figure 7-1). In the North West, the balance is only reduced from the baseline under the environmentally-focused futures (for all climate scenarios), but still maintains a positive value (Figure 7-2). Adaptation options are therefore required when the supply-demand balance is negative or potentially when water availability is reduced from baseline conditions.

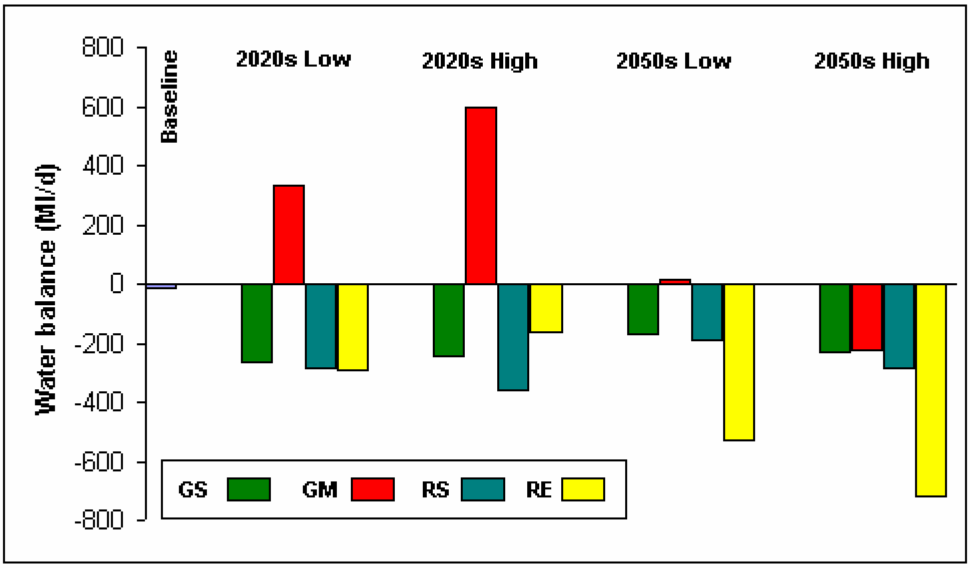

Figure 7-1: Balance between water supply (with baseline net water imports and reservoir storage capacity) and water demand for East Anglia under the different climate and socio-economic scenarios.

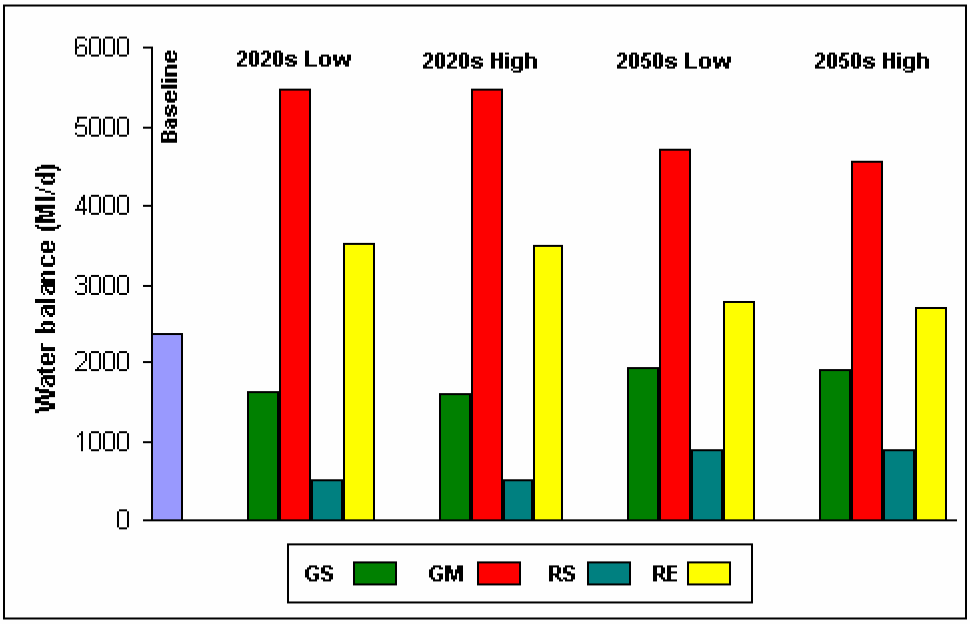

Figure 7-2: Balance between water supply (with baseline net water imports and reservoir storage capacity) and water demand for the North West under the different climate and socio-economic scenarios.

7.1.1 Adaptation in East Anglia under environmentally-focused futures

In East Anglia under environmentally-focused futures, adaptation is likely to be focused on water supply management. In order to decrease the abstraction availability to protect the aquatic ecosystems a strong effort has already been achieved in significantly decreasing the water demand. Under the GS scenario, the water industry is subject to strong regulation and high investment is placed in new technologies. Improved leakage targets reflect technical solutions, efficient water use significantly reduces domestic water demand, and industrial water use minimisation is regulated. Under the RS scenario, high water using industrial sectors go into decline or might relocate and most implement voluntary measures. Householders instigate simple changes in their behaviour. Moreover, despite the decentralised decision making, aggressive campaigns to reduce water leakage reflect the political priority.

Assuming no supply adaptation measures (so that reservoir storage and net water transfers are as under baseline conditions), the total water demand would have to be reduced by 30 or 35% under 2050s Low scenario and by 40 or 50% under the 2050s High scenario, under GS and RS respectively for the supply to meet the demand. This is in addition to the scenario reductions in domestic, industrial/commercial, leakage and agricultural of 39-35, 50-53, 56-50 and 32-10% under the GS and RS 2050s High scenario, respectively.

These supply-demand changes reflect the default scenarios and do not consider the effects of uncertainties in many of the parameters associated with each scenario. For example, considering the scientific uncertainty margins in the climate variables only (Table 7-1; Hulme *et al.*, 2002) for the GS 2050s High scenario, the supply-demand balance of -230 Ml/d given by the default values of change in temperature and in precipitation has an uncertainty range from -341 to +145 Ml/d. The best case and worst case changes in climate variables are within the uncertainty margin of the scenario and therefore as probable as the default value given. Moreover, for the same scenario, if considering the uncertainty margins on the variables of water demand change (Table 7-2) *i.e*. domestic and industrial/commercial water demand (Appendix 1), water available for irrigation (Appendix 1) and population (from RegIS2 socio-economic scenarios), the balance ranges from -376 to -97 Ml/d. Combining the uncertainties in the climate and demand change variables, the balance ranges from -492 to +240 Ml/d and from Table 7-3 it can be observed that the effect of uncertainty in the climate variables is more significant than the uncertainty in the demand variables.

Table 7-1: The effects of uncertainty of the climate scenarios variables on the supply-demand balance under the GS 2050s High scenario.

<table>
<tr><th colspan="2"></th><th>Default values</th><th>Worst case</th><th>Best case</th></tr>
<tr><td rowspan="3">Change from baseline</td><td>Temperature (˚C)</td><td>+ 2.3</td><td>+ 3.5</td><td>+ 1</td></tr>
<tr><td>Winter half-year precipitation (%)</td><td>+ 8</td><td>- 4</td><td>+21</td></tr>
<tr><td>Summer half-year precipitation (%)</td><td>- 18</td><td>- 20</td><td>+ 10</td></tr>
<tr><td colspan="2">Supply-Demand balance (Ml/d)</td><td>- 230</td><td>- 341</td><td>+ 145</td></tr>
</table>

Table 7-2: The effects of uncertainty of the variables of demand change on the supply-demand balance under the GS 2050s High scenario.

	Default values	**Worst case**	**Best case**
Domestic water demand (Ml/d)	80	95	65
Ind./Comm. water demand (Ml/d)	119	145	95
Water available for irrigation (Ml/d)	200	285	120
Population ('000 inhabitants)	2513.6	2780.0	2175.0
Supply-Demand balance (Ml/d)	- 230	- 376	- 97

Table 7-3: The effects of uncertainty of the climate and demand change variables on the supply-demand balance under the GS 2050s High scenario for a combination of 'best' and 'worst' cases.

	Best climate	**Default climate**	**Worst climate**
Best demand	+ 240	- 97	- 196
Default demand	+ 145	- 230	- 341
Worst demand	+ 10	- 376	- 492

In East Anglia, under the 2050s High environmentally-focused futures, it is apparent that the water supply cannot meet the anticipated demand and adaptation will therefore be required. Moreover, no further reductions on water demand seem plausible. Although UKCIP (2001) refers that under GS scenario, no new sources of water supply are not expected to be required, the results shown the opposite.

Under GS scenario, the water resources are seen from a national perspective with the aim being an equitable sharing of the resource according to need. Therefore, water-rich regions are expected to provide water to water-poor regions through a new national water network (Shackley and McLachlan, 2005). Under the RS scenario, when supply difficulties arise, the exchange of water resources between regions in the UK becomes more difficult as the concept of national water transfers is rejected. Instead, demand is met by increased local reservoir storage capacity.

Under the 2050s GS scenario, the water supply-demand balance is approximately -150 and -250 Ml/d under the Low and High emission scenarios and under RS the deficit is greater and is approximately -200 and -300 Ml/d respectively (with reservoir and net water transfers as for baseline conditions and for the scenario default variables).

Regarding net water transfers, under the baseline, 19 Ml/d of water are transferred into East Anglia (Section 6.2.3). The water transfers for 2024/25, according to the Anglian Water Services Ltd (1999) are expected to remain as under baseline conditions, whilst Environment Agency (2001a) suggests a strategy to increase the public water supply by extending the Ardleigh Reservoir for Anglian Water and Tendring Hundred Water Services with a resource value of 5-15 Ml/d (Environment Agency, 2001c).

The existing reservoir storage capacity is 30 Ml/d (Section 6.2.3) under baseline conditions According to the National Rivers Authority (1994), the regional needs would best be served by a reservoir in the order of 40-50 Ml/d at Great Bradley, and when demand rises so that more than 60 Ml/d is required, the only acceptable site would be a bunded reservoir in the Fens, the Feltwell Reservoir, that could follow with a resource value of 80-150 Ml/d (Environment Agency, 2001c). However, this is not certain as Essex and Suffolk Water may look for other alternatives and there is a potential increase to Alton yield that is unproven but could equal to 36 Ml/d in wet years. Another adaptation option to increase water availability is to build winter storage reservoirs, although with a little contribution for the deficit (Environment Agency, 2001a). For instance, Anglian region has worked with Defra to create a strategy to promote the rural enterprise scheme providing grants to farmers for winter storage reservoirs (Environment Agency, 2003).

From the abovementioned adaptation options, and given the supply-demand balance given by the default scenario, it would be possible to achieve a positive supply-demand balance under the GS scenario (Table 7-4). However, under RS (Table 7-4), due to the greater deficit, in order to adapt, a relaxation of the environmental allocation may be required if the net water transfers planned for the 2020s are not significantly increased.

Table 7-4: Potential for adaptation under the 2050s Low and High emission scenarios given the negative supply-demand balance for the Global Sustainability and Regional Stewardship default scenarios, and potential for increased reservoir storage capacity and net water imports.

	Global Sustainability	**Regional Stewardship**
Supply-demand balance (Ml/d)	-150 to -230	-200 to -300
Increased reservoir storage capacity (Ml/d)	40 to 50 Great Bradley 80 to 150 Feltwell reservoir Winter storage reservoirs	
Net water imports (Ml/d)	5 to 15 due to extending the Ardleigh Reservoir	Not consistent with scenario

7.1.2 Adaptation in East Anglia under economically-focused futures

In East Anglia, under economically-focused futures, there is scope for adaptation on the demand and supply sides because under the default scenario there is little demand management in place and no consideration for potential increases in reservoir storage capacity and net water transfers. Under the 2050s High economically-focused futures, the supply-demand balance for the 2050s High and Low emissions scenario is -227 and +15 under GM and -722 and -528 under RE, respectively (Figure 7-2; given by baseline reservoir storage and net water transfers).

For the RE scenario, where the deficit in the supply-demand balance is greater than under GM, an uncertainty analysis were carried out. Given the scientific uncertainty in the climate variables, the supply-demand balance may range from -1209 to +507 Ml/d (Table 7-5, Hulme *et al.*, 2002) and given the uncertainty in the demand variables, it varies from -1208 to -253 Ml/d (
Table 7-6). Coupling the uncertainties in the climate and demand change variables the supply-demand balance ranges from -1665 to +916 Ml/d (Table 7-7). The uncertainty range was defined as a percentage of the water demand (Appendix 1) and given that under RE scenario the water demand is higher than under GS, the uncertainty in the climate and demand change variables similarly affect the supply-demand balance as opposed to what happens under GS (Section 7.1.1). Moreover, the effects of uncertainty under RE are greater than under GS.

Table 7-5: The effects of uncertainty of the climate scenarios variables on the supply-demand balance under the RE 2050s High scenario.

		Default values	Worst case	Best case
Change from baseline	Temperature (˚C)	+ 2.3	+ 3.5	+ 1
	Winter half-year precipitation (%)	+ 8	- 4	+ 21
	Summer half-year precipitation (%)	- 18	- 20	+ 10
Supply-Demand balance (Ml/d)		- 722	- 1209	+ 497

Table 7-6: The effects of uncertainty of the variables of demand change on the supply-demand balance under the RE 2050s High scenario.

	Default values	Worst case	Best case
Domestic water demand (Ml/d)	200	240	160
Ind./Comm. water demand (Ml/d)	328	400	260
Water available for irrigation (Ml/d)	420	600	250
Population ('000 inhabitants)	2806	3125	2550
Supply-Demand balance (Ml/d)	- 722	- 1208	- 253

Table 7-7: The effects of uncertainty of the climate and demand change variables on the supply-demand balance under the RE 2050s High scenario for a combination of 'best' and 'worst' cases.

	Best climate	Default climate	Worst climate
Best demand	+ 916	- 253	- 783
Default demand	+ 497	- 722	- 1209
Worst demand	+ 13	- 1208	- 1665

Firstly, adaptation options from the supply side are analysed under these economically-focused futures. Under GM, the high water prices and increases in water demand encourages the development of new sources of supply and there is little resistance to the development of new reservoirs, except where significant recreational opportunities are threatened. Under RE, the increased demand is met by extending traditional water sources such as reservoirs and by the development of inter-regional transfers that are seen as a marketable commodity. Given the scope for increased reservoir storage capacity and net water transfers presented in Section 7.1.1, the supply-demand balance has potential to become positive under the GM scenario; however, under RE, adaptation also from the demand side is essential (Table 7-8).

Table 7-8: Potential for adaptation under the 2050s Low and High emission scenarios given the supply-demand balance for the Global Markets and Regional Enterprise default scenarios, and accounting for the potential increase in reservoir storage capacity and net water imports.

	Global Markets	**Regional Enterprise**
Supply-demand balance (Ml/d)	-227 to +15	-722 to -528
Increased reservoir storage capacity (Ml/d)	40 to 50 Great Bradley 80 to 150 Feltwell reservoir Winter storage reservoirs	
Net water imports (Ml/d)	5 to 15 due to extending the Ardleigh Reservoir	

Although under GM the supply-demand balance is positive after adaptation from the supply side, there is also scope for further demand management increasing the flexibility of the water resources system. Options would be consistent with the storylines incorporated in the scenario, such as follows:

- market forces of regulation and investment result in efficient operation of water companies and leakage control. Moreover, virtually all households are metered due to the importance of competition in the water industry and low level of political concern for social equity;
- decline of primary manufacturing sectors that cannot complete with world prices leads to reduced direct abstraction;

- increase in water for industry and commerce due to high level of economic growth despite the growth in the service and high technology sectors (which are less water intensive systems) and high levels of investment that results in uptake of low cost water use minimisation measures;
- High levels of personal affluence result in an increase of household demand despite the improvements of water efficiency of white goods due to high levels of investment.

Under RE, in order to obtain a positive supply-demand balance, water demand would need to reduce approximately by 250 and 500 Ml/d under the 2050s Low and High emission scenario (Table 7-8) after allowing for adaptations from the supply side. The priority adaptation option from the demand side is on leakage control as from baseline, leakage has increased by 526 Ml/d under the 2050s. To manage leakage, it is necessary an active leakage control, infrastructure management, and improving the speed and quality of repairs and the pressure management (Trow and Farley, 2006; Environment Agency, 2001b). The necessary investment would possibly be covered by the value of water being lost in the distribution system that would be saved. Other adaptation options include higher capital investment in water efficiency such as in white goods to reduce household demand and household metering enhancing the system of water company regulation. In case the abovementioned adaptation options do not suffice, it might be necessary to increase abstraction availability imposing further stress on aquatic habitats and species (Table 7-9).

Table 7-9: Change in the Supply demand balance due to increased abstraction availability from reduced REP (from low as given for baseline to very low) in East Anglia under RE 2050s High default and worst and best cases regarding the uncertainty of demand change variables.

	Default	Worst case	Best case
Low REP	- 722	- 1208	- 253
Very low REP	- 576	- 1061	- 108

7.1.3 Adaptation in the North West

In the North West, under all scenarios there is a surplus in the supply-demand balance (Figure 7-2; assuming baseline net water transfers and reservoir storage capacity); nevertheless, adaptation is important given the uncertainty in the estimates, climate variability, and the fact that there is scope to protect the aquatic ecosystems. Under economically-focused futures, given the high regional water availability and the big surplus in the supply-demand balance, abstraction could be reduced, raising the environmental concern to protect the aquatic environment. For instance, the GM scenario default value is a 'very low' REP; however, if the REP is increased to a 'medium' as under baseline conditions, there is still a surplus of 1443 Ml/d under the 2050s High climate. Another option would be to export the surplus water from the region to other parts of England which suffer from water shortages (*e.g.* under RE scenario).

Under environmentally-focused futures, adaptation could increase the robustness of the water management system in drier than average years given that the balance between water supply and demand is reduced from baseline conditions, especially under RS (Figure 7-2). Environment Agency (2001a) presents alternatives such as raising Stocks Reservoir by 2025 and building a major reservoir in the longer term in case leakage control and industrial waste minimisation initiatives are unsuccessful in order to increase the regional storage capacity that has a reliable yield of 700 Ml/d under baseline conditions (Section 3.1.5.2). However, United Utilities is not planning to increase reservoir storage capacity; instead, the source of water in case there is a deficit in the balance is increased groundwater abstraction (Mark Smith from United Utilities, *Pers. Comm.*). Net water transfers, which are not favoured under a RS scenario, are not considered as an adaptation option in the North West (Environment Agency, 2001a; Mark Smith from United Utilities, *Pers. Comm.*) although a transfer of water from Northumbrian Water started in 2004 but is very small at 256 Ml/year (Janet Bromley from United Utilities, *Pers. Comm.*). Therefore, the current 735 Ml/d of water imported (Section 3.1.5.2) should suffice in the future.

7.1.4 Assessing changes in abstraction availability

Evaluation of the regional water availability is the most difficult component of a regional study as no simple figure can be given for the environmental flow requirements of rivers (Acreman and Dunbar 2004). In the past, such assessments were based on simple hydrological methods (Tharme, 2003) such as fixed-percentage or look-up table methodologies in which a minimum flow based upon set proportion of the dry weather flow represented by the Q95 was maintained. Acreman and Dunbar (2004) suggest that where many catchments need to be assessed, rapid methods such as look-up tables are appropriate. However, the modified-RAM approach adopted in this study, using a REP, produces an ecologically acceptable FDC which retains many characteristics of the flow regime such as the basic magnitudes of droughts, low flows and floods, which are not given by the simple methods.

The approach taken to derive abstraction availability in this study bases the availability of water on the naturalised flow duration curve *i.e.* the flows that would occur in the absence of abstractions and discharges. Abstraction is therefore allowed based upon the potential impacts of abstraction on river flow (and hence on the aquatic ecosystem) without considering the potentially moderating influences of abstraction returns, such as if sewage treatment works would always discharge to the sea or to a tidal watercourse. Therefore, it does not allow for re-use of water directly through grey water use (Diaper *et al.*, 2001) or indirectly through recharge of aquifers by leaking water supply pipes (Yang *et al.*, 1999; Hooker *et al.*, 1999) or river flow augmentation from sewage treatment works which return about 95% of water used for domestic purposes to the river system. In East Anglia and the North West, where significant volumes of water are abstracted from groundwater or are provided by imports or water transfers, water returns will significantly increase the availability of surface water in receiving catchments, especially during summer low flow periods. Therefore, the impacts of climate change on water availability have been estimated for a ‘worst case’ situation. On the other hand, ignoring the effluent returns for estimating abstraction availability maximises the dilution capacity of the receiving water body and therefore minimises the impacts on the water quality due to effluent returns.

7.1.5 Adaptation options for East Anglia and the North West given the uncertainty in the future conditions

The impacts of future change have been explored using four socio-economic scenarios and two global emission scenarios for two time-slices. Although these future conditions are contrasting, trends were evidenced for each region. The following preventive no-regret management options have been identified as the general adaptation options required now to tackle climate change.

In East Anglia, adaptation is essential for supply to meet the demand and to avoid conflicts between the water users. Strong demand management is required using price or regulatory mechanisms to reduce the domestic water consumption (*e.g.* water saving and efficiency measures). If necessary, restrictions might apply on agricultural irrigation water use (Section 7.2.1). The increased reservoir storage capacity is an important supply management strategy in this dry region (Section 7.1.1 and Section 7.1.2). However, in the future, increasing reservoir storage capacity may be a limited option due to the deterioration of the water quality as a result of urbanisation and agricultural practices which will be exacerbated by increased winter rainfall. The reservoirs will need to be prepared to collect water between periods of drought and flooding; *i.e.* the higher pumping rates during smaller periods of time. Moreover, suitable locations for building reservoirs should be identified and current adaptive management should not limit potential future reservoirs.

In the high water availability region of the North West, adaptation options are also important. Demand management is a no-regret option that saves water, chemical and energy for its treatment. Moreover, surplus water from this region can be transferred to water scarce regions.

7.2 The implications of future change for delivering EU environmental legislative requirements

There is an extensive list of EU environmental legislation to which the UK is permitted to adhering to (http://ec.europa.eu/environment/enlarg/handbook/handbook.htm). Examples of water protection legislation include the Urban Wastewater Treatment Directive, the Nitrates Directive, the Bathing Water Directive, the Directive on Surface Water for Drinking Water Abstraction,, the Groundwater Directive, the Freshwater Fish Directive, the Drinking Water Directive, and the Water Framework Directive. Climate and socio-economic changes may pose risks to delivering the objectives under those Directives. For example, Wilby *et al* (2006a) analyses the consequences of projected changes on water quality and water resources for delivering the WFD; Wilby *et al*, 2006b assesses the impacts of climate change on key phases of the river basin management process that underpin the WFD; Latham *et al.*, 2004 studies changes due to climate on forest habitat networks protected under the Habitats Directive; and Hsieh *et al.* 2005 projected increases in nitrous oxide emissions due to climate change being far greater than the decrease expected from reduced fertiliser applications, which compromises the Nitrates Directive.

7.2.1 The Water Framework Directive and the allocation of water to the environment

Freshwater is vital to human life and societal well-being, and so its utilisation for consumption, irrigation, and transport has long taken precedence over the services and functions provided by freshwater ecosystems. With a limited resource, water has to be shared or allocated between competing uses, principally public water supply, the environment, irrigation and industrial water supply. The relative weights which society puts upon these different uses will affect the mode of resource allocation. There is growing recognition that fluvial ecosystems are legitimate users of water (Naiman *et al*., 2002) and that functionally intact and biologically complex aquatic ecosystems provide many economically valuable services and long-term benefits to society (Baron *et al*., 2002). Increasingly, therefore policy is placing greater or greatest priority on the environment; for example, the Water Framework Directive (WFD) in Europe aims to ensure that all water bodies achieve *good ecological status* which requires the hydromorphological conditions (including flows) to be close to pristine. To achieve these aims, it is necessary to ensure that the environmental needs are identified (Tharme, 2003; Acreman and Dunbar, 2004) and met. The four possible socio-economic futures reflect, however different degrees of commitment to meeting these flow needs.

Under environmentally-focused futures, the requirements of the WFD regarding the protection of low flows and flow variability are met through a strong demand management. As the surplus of water is reduced from the baseline for both regions (Section 6.2.3), water resources need careful management. Moreover, further restrictions on water demand might be necessary, particularly in East Anglia in drier than average years, unless significant adaptation responses are implemented (Section 7.1.1) or a relaxation of the environmental allocation becomes inevitable. Under these futures with water resource shortfalls, it is important to avoid conflicts between the water users. Restrictions on agricultural irrigation can be achieved directly through regulatory approaches (*e.g*. licence restrictions) or indirectly via economic instruments (principally volumetric abstraction costs) depending on the socio-economic scenario (Henriques *et al.*, *Submitted*). The WFD will introduce the cost recovery for water services, including the costs of environmental protection (Gómez *et al.*, 2004). According to Henriques *et al.* (*Submitted*), under economically-focused futures agricultural demand is sensitive to water pricing; however under environmental futures where local sustainable agricultural production is a priority, constraints on irrigation demand are best managed through volumetric restrictions on the abstraction licences, and trigger limits on summer abstraction.

Under economically-focused futures, increases in water demand for human consumption can only be satisfied in both regions if less water than required under the WFD is allocated to the environment. The WFD flow needs are therefore compromised; under GM there is an unrestricted water market and under RE the situation is also worse than the current where a pre-WFD can be assumed as in Morris *et al.* (2004a). However, the abstraction availability was estimated from the naturalised FDC without considering the potentially moderating influences of abstraction returns (Section 7.1.4). In both regions, where significant volumes of water are abstracted from groundwater or are provided by reservoirs or water transfers, water returns will significantly increase the availability of water for abstraction in receiving catchments. The spatial distribution of abstractions and discharges will therefore affect the ability of catchments to meet the WFD flow needs. Where returns from STW or industrial effluents are higher than abstractions, the river ecology might be protected assuming a high quality of effluent. Where abstractions are greater than returns, the impacts of climate change (and socio-economic changes under economically-focused futures) in reducing river flows are exacerbated.

The ability to achieve a *good ecological status* is also dependent on the water quality, which is evaluated in Sections 7.2.2 and 7.2.3 for the different socio-economic futures in the context of other EU legislative requirements.

7.2.2 The Habitats Directive and the health of future aquatic ecosystems

Climate change also challenges the Habitats Directive, which aims at protecting and improving the environment, including the conservation of natural habitats and of wild fauna and flora. Climate warming is expected to lead to a drying of wetlands, mainly through alterations in water level (Gorham, 1991), which is closely linked to the hydrology. Under all futures, groundwater recharge and naturalised low flows are reduced, which, might be significantly exacerbated by the socio-economic scenarios depending upon the location of abstractions and returns (Section 6.3).

A simplistic spatial distribution of future abstractions and discharges has had to be used in the absence of detailed data for future scenarios. However, the locations of these human influences will have important site-specific implications leading to potentially significant changes in the suitability of the regions for fen and bog species due to increased drought stress (Harrison *et al*., *Submitted*). Actions which lead to decreased water usage under environmentally-focused futures, where there are no significant discharges, lead to stressing of species or loss of suitable space, while increases in non-consumptive demand under economically-focused futures led to considerable improvements for species in urbanised catchments as more water was imported through the water supply network into these catchments to satisfy demand and which in turn leads to increased return flows into the rivers at times of low flow (Section 6.3; Harrison *et al*., *Submitted*). Suitable adaptation options would be based on increasing water demand and supply that could be difficult to meet, especially in East Anglia, and assuming high quality effluent returns which is particularly significant at times of low flows due to the reduced dilution capacity. Adaptation options are therefore limited leading to a concern for the conservation of both the habitat and individual species.

However, in the modelling approach used there is a lack of integration between the water quantity and quality. Urbanisation futures also leads to increased nutrient stresses, especially in winter given the increase in flooding events (Section 6.1.2; Mokrech *et al., Submitted*). Unless there is an equivalent improvement in storm water management due to increased urbanisation, increased winter rainfall will lead to increased likelihoods of combined sewer overflows leading to decreased water quality and increased nutrient loads. The deterioration of the water quality, which is likely to be more significant under economically-focused futures (due to urban development and increased water demand and use of fertiliser, Section 7.2.3), will also impact the aquatic ecosystems.

7.2.3 The Nitrates Directive and future agricultural practices

The Nitrates Directive aims to protect water quality with respect to eutrophication, particularly from agricultural sources. Under environmentally-focused futures, simulated mean nitrate concentration in the water bodies was similar or slightly lower than under baseline conditions due to changes in crop selection by farmers and reduced application of fertilisers, which ameliorates the impacts of climate on reducing dilution capacity. However, under the economically-focused futures, fertiliser use increases (Audsley *et al*., *Submitted*) to meet demand for either local production or the global market, so that nitrate leaching increases which is coupled with decreased dilution from reduced recharge and river flows (Section 6.1.1 and Section 6.1.2). Moreover, the impacts of fertiliser application on the water quality will be exacerbated by climate change due to possible increase overland flow arising from increased flooding events (Section 6.1.1; Mokrech *et al., Submitted*) and rainfall intensity.

The situation is more critical in East Anglia where areas are already not complying with the Nitrates Directive. Moreover, it can compromise ability to meet the 50 mg/l drinking water standard set by the EU Drinking Water Directive. Potential options include changing agricultural practices for instance related to soil compaction or fertiliser application techniques, changing land-uses, which has implications for food production, or enforcing more severe nutrient input restriction.

7.3 Summary

The need for adaptation and the adaptation options to be considered vary according to the socio-economic scenario and the region in question. In the drier region of East Anglia, there is a greater need to adapt than in the North West where supply meets the demand. That trend was shown even in the light of the wide uncertainty associated with the estimated supply-demand balance. The effects of climate and demand change variables uncertainty depends upon the socio-economic scenario in question.

The choice of preventive non-regret adaptation options is important in both regions. In East Anglia, under environmental futures, adaptation is focused on the supply side whilst under economically-focused futures, the emphasis in on demand and supply side strategies. Although the supply side adaptation would suffice under the 2050s High Global Markets future, under the Regional Enterprise, demand is also necessary, namely for leakage control. Under most of the scenarios there is scope for adaptation on the regional water resources to moderate the impacts; however, under Regional Enterprise or under an environmentally-focused future in a drier that average year, it might be required to increase abstraction availability causing failure of current policy objectives (*e.g*. Water Framework Directive) and compromising the beneficial ecosystem services which rivers provide. Under economically-focused futures the Water Framework Directive flow requirements are unrealistic and cannot be achieved because economic development takes priority and not enough water can be allocated to the environment. Moreover, it may not be possible to comply with the Habitats and the Nitrates Directives because the socio-economic factors exacerbate the negative impacts of climate change regarding the water quality.

In the North West, there is a surplus of water, and adaptation options under economically-focused futures include the move towards a sustainable development protecting the aquatic ecosystems and increasing water use efficiency. Moreover, surplus water can be exported to regions with water scarce.

Whilst future hydrological changes will impact the water resources and environment in both regions, maintaining the ability to satisfy the water demand and to meet the requirements of the EU legislative requirements represents a policy and societal choice.

8 Conclusions

For future sustainable water resource management, it is important to begin planning for climate change and adapting to those changes, namely implementing anticipatory adaptation by reducing vulnerabilities to its effects and enabling reactive adaptation to happen more efficiently. Consequently, it is important to understand the implications of climate change for water resources. In this research study, the possible impacts of global climate change and regional socio-economic change in the contrasting regions of East Anglia and North West England for land management, hydrology and water environment were holistically explored in its regional context given that a changing climate is only one of the pressures on the regions.

8.1 Methodology for assessing the impacts of climate and socio-economic changes on the water resources

In order to simulate the impacts of future change, a model was developed and integrated with the UKCIP02 climate scenarios, regionalised scenarios of socio-economic change and agricultural changes within the RegIS2 integrated assessment modelling framework.

Pre-existing modelling approaches that allow the development of a computational simple model were used given the fast running time constraint posed by RegIS2 project. Criterion for the model selection include catchment scale regionalised models that have been calibrated and validated over a wide range of conditions, and the use of adaptable models that can be sensitive to the relevant pressures variables and that output impact indicators.

1. A catchment scale hydrological model was developed from climatological and physical descriptors based upon regionalised methods that allow for spatial variability .Estimated impact indicators include the flood index, mean flows, low flows and groundwater recharge. As a part of the methodological development, *the method of Gustard et al. (1992) that estimates the naturalised Flow Duration Curve was improved to be sensitive to changes in land-use that affect runoff and evapotranspiration*, *i.e*. urbanisation and cropping classes, and *the Catchment Descriptors method of Robson and Reed (1999) was improved to account for future seasonal distribution of rainfall in estimating the flood flow index*. The hydrological model was successfully spatially validated against measured river flow statistics from 30 and 48 catchments in East Anglia and North West England, respectively. The concordance correlation coefficient obtained was 0.9851 and 0.9815 for the Mean Flow, 0.9433 and 0.9675 for Q95, and 0.9779 and 0.9791 for Q10, for East Anglia and the North West, respectively. QMED was validated against measured flow statistics from 15 catchments in East Anglia and 39 in the North West, and the concordance correlation coefficient obtained was 0.6403 and 0.9487, respectively. Although QMED tends to be overestimate in East Anglia, the results for baseline conditions are generally within the 95% confidence intervals presented for the method. QMED also provided plausible results for the climate change scenarios compared to other studies.

2. *The catchment abstraction availability was estimated using an approach based on the Resource Assessment Management framework (Environment Agency, 2002) from the estimated naturalised flow duration curve and a socio-economic indicator which represents the willingness of society within a socio-economic scenario to allocate water to aquatic ecosystems* to prevent abstraction-related hydrological stress by protecting the low flows and flow variability of the catchments. This approach produces an ecologically acceptable flow duration curve which retains many characteristics of the flow regime such as the basic magnitudes of droughts, low flows and floods, which are not given by other rapid methods used to assess abstraction availability in many catchments.

3. The model estimated the regional balance between water supply and demand as an indicator of the robustness of the water management system under the different futures. The regional water supply was calculated as the sum of the regional abstraction availability, net water imports from other regions and reservoir storage capacity and the regional water demand from the domestic, industrial/commercial, and irrigation purposes accounting for leakage as a proportion of the public water supply, all of which are linked to the socio-economic scenarios.

4. *The impacts of human influences on the naturalised flows were simulated as abstractions and effluent returns impact the catchment hydrological behaviour and are sensitive to future socio-economic change such as population, urbanisation and water consumption*. A simplistic future spatial distribution of abstractions and discharges was assumed, as its spatial patterns are unknown under significantly different socio-economic futures. It has been assumed that discharges are related to urbanisation and a more distributed abstraction system in which all catchments contribute towards supply. The estimated non-naturalised Q95 was validated against measured flow statistics from 30 catchments in East Anglia and 48 in the North West, and the concordance correlation coefficient obtained was and 0.9303 and 0.9585, respectively.

The model allowed to explore holistically the impacts of climate and socio-economic change on the hydrology and water resources management for different time-slices, global greenhouse gas emission scenarios, and regional systems of governance and social values. The choice of the contrasting East Anglia and North West regions allowed a diversity of problems to be examined and the development of a robust approach with potential for wider application. The major results are presented as follows.

8.2 The relative importance of climate and socio-economic changes for the future water resources management

8.2.1 Hydrological indicators and abstraction availability

The estimated naturalised hydrological indicators and the flood index are primarily determined by the hydrologically effective precipitation given by the climate scenario which drives the hydrological behaviour of the catchment. The impacts on the hydrology are greater in East Anglia than in the North West region which has higher river flows similarly prone to flood flows. Although the sensitivity of socio-economic factors such as agricultural land-use change are generally not so significant, the negative impacts of climate change on reducing the naturalised mean and low flows are ameliorated under economically-focused futures in highly urbanised catchments (such as in the south of the North West) due to the higher generated runoff, but flood flows are increased as well as urban pollution. This effect of urbanisation in ameliorating the impacts of climate change is even more critical when allowing for abstractions and discharges under economically-focused futures. The population water requirements are significantly higher in these futures and the effects of effluent returns on urbanised catchments can in some cases in East Anglia under the 2050s High climate completely counteract the decreases in low flows due to the climate. The high flows, may increase due to effluent returns, but in a lesser extent. In those catchments with low levels of urbanisation (in much of the northern and central parts of the North West and much of East Anglia to a greater extent) the non-naturalised flows will be little affected by these socio-economic factors being mainly determined by the changes in the naturalised flows, which are in turn mainly determined by climate change.

Abstraction availability also reduces due to reduced river flows mainly due to climate change; however, the results showed that the impacts of climate change on abstraction availability are is not greater than 10% until the 2050s in East Anglia under a high emission scenario and that the socio-economic futures cause larger changes, primarily due to the Regional Environmental Priority that determines the environmental flow allocation for the river. Under these economically-focused futures, the increased water demand is met by increased abstraction availability as a consequence of reduced allocation of water to the river ecosystems. The situation can be particularly critical, compromising the WFD flow requirements, in those catchments with low levels of urbanisation due to the increased abstraction which will lead to the reductions in flows that will not be compensated by effluent returns amplifying the impacts of climate change. On the other hand, in heavily urbanised catchments, the higher effluent returns from increased non-consumptive water demand may be beneficial for the suitability of aquatic ecosystems and some species under the Habitats Directive. However that is only beneficial if the effluent has a high quality, otherwise it may deteriorate the water quality, especially at times of low flows where the receiving water body has less dilution capacity. Moreover, in these urbanised catchments the increase in flood flows by climate change is exacerbated by socio-economic changes, which may further deteriorate the water quality. Moreover, under economically-focused futures, nitrate leaching is a continuing problem due to agricultural practices and reduced mean flows which can worsen the water quality and compromise the requirements of the Nitrates Directive, especially in East Anglia.

Under environmentally-focused futures, with low consumptive water demand and decreased urbanisation level from baseline, the naturalised hydrological indicators, the flood index and the non-naturalised flows are little affected by the socio-economic factors being mainly determined by climate change. Abstraction availability is also mainly influenced by the socio-economic factors, being further reduced to protect the aquatic environment, which is met by a strong water demand management.

The use of an integrated assessment at the regional scale allowed the importance of climate and socio-economic changes on the hydrology and water resources of these two regions to be evaluated. It could be concluded that *the hydrological behaviour is primarily determined by climate scenario; however, the hydrological response of catchments to future socio-economic change can be significantly influenced by future increased urbanisation which generates higher runoff and potentially greater effluent returns, and the non-consumptive water requirements of the population. The volumes of water to be abstracted are mainly determined by the value that society places on the environment and the political willingness to protect ecological river ecosystems, which varies significantly across the socio-economic futures*. By accepting greater environmental stress a future society can significantly increase the availability of water for human uses, but risks losing the valuable ecosystem functions and services provided by rivers and wetlands. *Whilst future hydrological changes will impact the water resources and environment, to a greater extent in East Anglia, maintaining the ability to meet the requirements of the EU legislative requirements represents a policy and societal choice.*

8.2.2 The ability for the water supply to meet the demand

The balance between abstraction availability and water demand in each region is impacted through interactions of differing importance with the hydrological and policy environments. The balance between the supply (assuming baseline net water imports and reservoir storage capacity) and the demand was analysed as an indicator of the robustness of the water management system in the regions. The socio-economic factors that impact on the water demand include population growth, leakage management, increased water saving and efficiency arising from technology improvements for domestic and industrial/commercial purposes and changed irrigation demand due to changes in water costs, demand for produce and gross margins.

In East Anglia there is a deficit between water supply and demand under almost all futures for the different time-slices. The exception is the Global Markets future where supply meets increased demand under 2020s Low and High and 2050s Low emission scenario due to the unrestricted water market. Under environmentally-focused futures, the changes in abstraction availability are greater than those in water demand, in contrast with the economically-focused futures. In the North West, the balance is always positive, although it is reduced from the baseline under environmentally-focused futures and increased from the baseline under economically-focused futures; under all the scenarios, the changes in abstraction availability are greater than in demand. *It can be concluded that the socio-economic pressures on the water resources management are very significant and were shown to moderate or exacerbate the effects of climate change* to which East Anglia is more vulnerable than the North West region.

The estimated supply-demand balance is associated with error due to the uncertainty in input model variables and model limitations. The quantified uncertainty in climate and demand change input variables plays a major role in significantly affecting the estimates of future supply-demand balance; however, the abovementioned trends on the impacts were confirmed. Moreover, the supply-demand balance was underestimated because the abstraction availability was estimated without considering the potentially moderating influences of abstraction returns that could be significant if with high quality effluent during summer low flows, but maximises the dilution capacity minimising the impacts due to effluent returns.

8.3 Potential adaptation options

Different adaptation options (acting upon the socio-economic variables) were considered in order to reduce the impacts on individuals, society and the environment caused by the changes in the water resources. Those options represent an anticipatory adaptation (*i.e.* acting upon the pressures now in order to minimise the impacts by the time-slice they are being analysed) addressing climate variability in the shorter term and preparing for a longer term climate change. *The adaptive strategies allowed by policy scenarios which vary according to the socio-economic future in question generally allow the impacts on the supply-demand balance to be moderated, but sometimes at the cost of the environment or the society and the economy.*

In East Anglia, adaptation is crucial given the negative supply-demand balance within its uncertainty range. Under environmentally-focused futures adaptation is focused on the supply side given that a strong demand management has already been achieved in the default scenario; however, in drier than average years it may be necessary to increase the pressure on aquatic ecosystems in order to increase abstractions. Under economically-focused futures, the emphasis of adaptation is both on the decreasing water demand (*e.g.* using price and regulation mechanisms) and increasing water supply. The supply side adaptation would suffice under the 2050s High Global Markets future, however, under the Regional Enterprise, demand strategies are also necessary, namely for leakage control. A significant adaptation measure is the increased reservoir storage capacity both by water companies and farmers associations; however this strategy needs to be evaluated in the context of future deterioration of water quality, such as increased nitrates.

In the North West, the water availability is high with potential for new water transfers to water scarce areas. Demand strategies are also important protecting the aquatic ecosystems and to preserving resources.

8.4 Key message

The use of an integrated assessment allowed the identification of significant pressure variables and cross-sectoral linkages from the socio-economic pressure variables on the impacts. Moreover, it allowed different adaptation options to be explored in a consistent and coherent manner across the different linked sectors. *It was concluded that East Anglia is more vulnerable to the impacts of climate change and that in both regions, the changes in hydrological behaviour are mainly determined by the global climate change whilst the water resources are mostly impacted by the local/regional socio-economic changes. This emphasises the need for integrated impact assessments accounting for socio-economic changes, which has not been widely done.*

9 Suggestions for further work

The suggestions for further work are mainly concerned with improved modelling methodologies. The need for further research has already been mentioned, such as on integrating the impacts of water quality and water quantity and estimating the abstraction availability considering the effluent returns. In this section, some other suggestions are presented in order to improve the estimated flow duration curve and water availability.

9.1 Improve the method to estimate abstraction availability

To estimate the abstraction availability within the RAM methodology (Environment Agency, 2002), the environmental weighting band defines the flow regime based on the ecological sensitivity of the reach upstream of the assessment point to abstraction impacts. In the absence of such data regionally, within the Water Resources model, the Regional Environmental Priority (REP), which reflects the willingness of society within a socio-economic scenario to allocate water to aquatic ecosystems, is used to define the environmental flow regime at the catchments' outlet.

The REP ranges from high for environmentally-focussed futures to low for market-driven futures, with the Baseline being given medium. This is applied to all the catchments within a region equally, regardless the sensitivity of the ecological status of each catchment. Although this is considered to be reasonable to estimate the regional abstraction availability, it implies that in more sensitive catchments water is over-abstracted and in less sensitive ones it is under-abstracted.

Therefore, it is suggested for further work to develop a methodology to derive a REP for each catchment from indicators based on the current biological and chemical General Quality Assessment for the river reaches and flows, given the regional REP trend for the future time-slices consistent with the socio-economic storylines. The purpose would be to provide a contrast for the modelled catchments and to better estimate the abstraction availability at a regional and catchment levels given that the impacts of the latter are important for aquatic ecosystems, namely at times of low flows.

9.2 Improve the method to estimate the naturalised flows

The method of Gustard *et al.* (1992) has been modified to be sensitive to land-use changes, namely cropping classes. For each crop, a coefficient, k, relating the actual evapotranspiration of the crop to ETp was derived (Section 4.1). However, there is scope for further improvements, such as follows:

- The derived coefficient k differs as a consequence of changing temperature and precipitation for each of the different scenarios; however, it is suggested that it could be improved to be sensitive to precipitation and temperature changes within each climate scenario in order to better assess the effects of uncertainty due to climate on the estimated indicators of climate change. A method that relates temperature with ETp as derived by Tim Hess (*Pers. Comm.*, Cranfield University) could be used to derive new coefficients.
- A new coefficient k could be derived to be applied to other land-uses, such as forests from which interception also occurs.

In order to improve the estimation of the naturalised FDC, the following is recommended:

- An annual time-step was used to estimate MF. Instead, the water balance and the coefficient k could have been applied seasonally capturing the seasonal characteristics of UKCIP02 data and improving the estimation of the MF.
- The method used to estimate the FDC assumes that climate change does not impact the hydrological behaviour of the soils (Section 6.1.1), which exemplifies the limitations posed by using regression equation approaches. It is suggested to carry out a further temporal validation assessing how the model responds to wetter and drier than average past 30-year periods. Past river flow data could be obtained from Jones and Lister (1998) that have reconstructed monthly-mean river flow data for some catchments within the regions of interest from precipitation records for the period since the 1860s.

9.3 The impacts of climate change on reservoirs

Climate change increases the importance of reservoirs given that they are the most important component for risk and uncertainty management of water resources systems (Takeuchi, 2002). Moreover, reservoir management is also impacted by socio-economic changes (Takeuchi, 2002). In this study, it was assumed that reservoirs are refilled at times of high flows and that they do not impact the river flows. As further work, it is suggested to account for the impacts of climate change on reservoir management and storage capacity, which are, for example:

- the distribution of rainfall changes from year to year and during the year as a result of changes in effective rainfall and in the seasonal distribution of precipitation;
- the deterioration of water quality due to increased flood flows and runoff from urban and agricultural areas;
- the increased temperatures will lead to problems such as algae growth in the reservoirs (Arnell and Liu, 2001);
- the increased sedimentation problems (Takeuchi, 2002).

Vogel *et al.* (2002) developed a general methodology suitable for use in regional scale assessments of the impact of climate change on water supply. This and other studies could be reviewed and implemented in the developed water resources model.

A1 Water demand pressure variables

Estimates of quantified socio-economic drivers related to the water demand management strategies were necessary as inputs to the developed models. These pressure variables were derived based upon the key assumptions and narratives that describe the future scenarios according to the specific quantitative water demand scenarios developed by the Environment Agency (2001b) that provides qualitative indicators on water demand, level of leakage, metre penetration and water efficiency.

A1.1 Domestic water demand

The average regional water consumption for domestic purposes divided by head of population increases under economically-focused futures (RE and GM) and decreases under environmentally-focus futures (GS and RS) (Table A1-1).

Table A1-1: Domestic water demand default values (in litres per person per day) for East Anglia and the North West regions.

Scenarios		**Baseline**	**Regional Enterprise**	**Global Sustainability**	**Global Markets**	**Regional Stewardship**
Baseline	Default values	150				
2020s	Default values	150	180	100	170	115
	Credible limits	120-180	145-215	80-120	135-205	90-140
2050s	Default values	150	200	80	190	95
	Credible limits	120-180	160-240	65-95	150-230	75-115

The household per capita water consumption of water was 140-160 $l.p^{-1}.d^{-1}$ in 1997/98 in both East Anglia and North West regions (Environment Agency, 2001a pp.32), thus a baseline value of 150 $l.p^{-1}.d^{-1}$ was assumed for both regions. To estimate the future domestic water demand, the Environment Agency's (2001b pp.39) national average measured per capita household consumption was considered. For the 2020s data for 2025 was used and the default values for both regions were extrapolated to be equal. That is valid because the results are within a 10% error range from the total regional public water supply household demand presented by Environment Agency (2001b) divided by the population from RegIS2 socio-economic scenarios. For the 2050s, due to the lack of information, a further 20 $l.h^{-1}.d.^{-1}$ was assumed following the trend from the 2020s. The credible limits were assumed to deviate by 20%.

A1.2 Industrial and commercial water demand

The industrial and commercial water demand is presented for East Anglia and the North West regions in Table A1-2 and Table A1-3 respectively. The industrial and commercial water demand for the baseline and for the 2020s under the different socio-economic scenarios were obtained from Environment Agency's (2001b) values for 1997/98 and 2025 respectively of direct abstraction for industry and commerce and public water supply for non-household demand for Anglian and the North West regions, that were summed. Industrial and commercial water demand was assumed to consist of 36% of the one in the Anglian region, based on the proportion of the populations. This assumption was validated as the ratio between the industrial and commercial water demand in Norfolk county and Anglian region is only overestimated by 15% to the ratio of correspondent populations (data from Environment Agency, 1999). For the 2050s, due to the lack of information, it was assumed that water demand increases by 20% under economically-focused futures and decreases by 30% under environmentally-focused futures from the estimates for the 2020s following the trend from the baseline to the 2010 and 2025 (Environment Agency, 2001b). The credible range was defined as being a 20% deviation from default values.

Table A1-2: Industrial and commercial water demand default values (in mega litres per day) for East Anglia.

Scenarios		**Baseline**	**Regional Enterprise**	**Global Sustainability**	**Global Markets**	**Regional Stewardship**
Baseline	Default values	238				
2020s	Default values	238	273	171	314	159
	Credible limits	190-285	220-325	135-205	250-375	130-190
2050s	Default values	238	328	119	376	112
	Credible limits	190-125	260-395	95-145	300-450	90-135

Table A1-3: Industrial and commercial water demand default values (in mega litres per day) for the North West.

Scenarios		**Baseline**	**Regional Enterprise**	**Global Sustainability**	**Global Markets**	**Regional Stewardship**
Baseline	Default values	1160				
2020s	Default values	1160	1202	551	1292	588
	Credible limits	930-1390	960-1440	440-660	1035-1550	470-705
2050s	Default values	1160	1440	385	1550	410
	Credible limits	930-1390	1150-1730	310-460	1240-1860	330-490

A1.3 Water available for agricultural irrigation

The licensable water to meet the agricultural demand was estimated. The actual regional direct abstraction for spray irrigation data for the baseline and for the 2020s' different socio-economic scenarios was obtained from Environment Agency (2001b) for 1997/98 and 2025 respectively. It was assumed that:

- In 1997/98, 67% of the actual water used for agriculture in the Anglian region is used in East Anglia (E Suffolk, Norfolk and Cambridgeshire, Pauline Jowett from Environment Agency, *pers. Comm.*), which was assumed to happen under baseline conditions and for the 2020s;
- in E Suffolk and Norfolk & Cambridgeshire 40% of the licensed water is actually abstracted (for the years 1997/98, Pauline Jowett from Environment Agency, *pers. Comm..*), which was assumed for baseline conditions; for the 2020s that figure was assumed to be 50-60%.
- in the North West, the actual baseline abstraction of water for spray irrigation is 31% of the licensed, according to the national average for the years 1997/98 (Defra, 2005: Table 22); for the 2020s, abstractions were assumed to be 40-50% of the licenses.

For the 2050s, based on the trends (Environment Agency 2001a and 2001b), it was assumed that the actual abstraction for spray irrigation increases by 30% under economically-focused futures; decreases 20% under GS and remains constant under the RS scenario, comparing with the estimates for the 2020s. It was also assumed that approximately 60% of the licensed water is abstracted in both regions under the different scenarios. That reflects a more effective use of water licenses than under baseline conditions in the line of the Water Act 2003 where all new abstraction licences have time-limits and are easier to trade (Environment Agency, 2004; Howarth, 2006). The credible range was defined as being a 20% deviation from default values.

The default values of the water available for irrigation are presented in Table A1-4 and Table A1-5 for spray irrigation. It was assumed that other direct abstractions for general agriculture and irrigation using public water supply are negligible in both regions.

Table A1-4: Water available for irrigation in East Anglia (in mega litres per day).

Scenarios		Baseline	Regional Enterprise	Global Sustainability	Global Markets	Regional Stewardship
Baseline	Default values	420				
2020s	Default values	420	420	300	420	350
	Credible limits	336-504	336-504	240-360	336-504	280-420
2050s	Default values	420	420	200	420	300
	Credible limits	336-504	336-504	120-280	336-504	180-420

Table A1-5: Water available for irrigation in the North West (in mega litres per day).

Scenarios		Baseline	Regional Enterprise	Global Sustainability	Global Markets	Regional Stewardship
Baseline	Default values	32				
2020s	Default values	32	32	17	27	25
	Credible limits	26-38	26-38	14-20	22-32	20-30
2050s	Default values	32	30	10	23	20
	Credible limits	26-38	18-42	6-14	14-32	12-28

A1.4 Leakage from the mains

Leakage was calculated as a proportion of water provided by the Public Water Supply (as opposed to direct abstraction by users). The demand for domestic water, non-household demand, DSOU and water taken unbilled was obtained for the baseline and for 2025, assumed to represent the 2020s, from Environment Agency (2001b). For the 2050s, the same proportion was assumed as for the 2050s. The proportion of leakage from the mains was assumed not to change with climate as Downing *et al.* (2003) shows no climate impact factors on leakage. The scenario-specific leakage coefficient (Table A1-6) increases from baseline under the RE characterised by low levels of investment in the water industry, and most decreases under the GM scenario where a great emphasis is placed on market forces of competition (Environment Agency, 2001b). To obtain the total leakage, for the modelling purposes, the leakage coefficient is multiplied by the estimated domestic water demand and estimated industrial/commercial water supplied by the mains.

Table A1-6: Leakage as a percentage of the public water supply for the different socio-economic scenarios for all the time slices in East Anglia and the North West regions.

Region/Scenarios	Baseline	Regional Enterprise	Global Sustainability	Global Markets	Regional Stewardship
East Anglia	23	79	17	14	19
North West	39	83	26	24	32

A2 Model validation and statistical techniques

Part of the model development process is the model validation, which is defined by Sargent (1994) as the substantiation that a computerised model within its domain of applicability processes a satisfactory range of accuracy consistent with the intended application of the model. The model can be validated using a conceptual model validity and operational validity (Table A2-1).

Table A2-1: Conceptual model validity, and operational validity approaches definition and method for model validation (Sargent, 1994), and relevant validation techniques (Sargent, 1994 and Kleijnen, 1999).

Conceptual model validity	Determines that the theories and assumptions underlying the conceptual model of the new derived or improved methodologies are correct and that the model representation of the problem entity and the model's structure, logic and mathematical and casual relationships are reasonable for the intended purpose of the model.
Operational validity	Determines that the behaviour of the outputs of the model have the accuracy required for the model's intended purpose over the domain of its intended applicability.
Example of validation techniques	Comparison with observed data or with results of other valid models using graphical displays and statistical test and procedures. Sensitivity analysis - changing the values of the input and internal parameters of a model to determine the effect upon the model behaviour and its output. The same relationships should occur in the model as in the real system. This analysis further shows which factors are important, and, in case they are controllable, how to change them to optimise the real system. Uncertainty analysis - performed when input parameters values of the simulation model are not accurately known. Expert knowledge - to check whether the simulation model's input/output behaviour is reasonable based on knowledge about the system. Strong validation claims are impossible; however, if it violates the qualitative knowledge the model should be questioned.

In order to statistically validate the Water Resources and the High River Flow models (Section 4.6 and 5.3) the geometric mean regression and the concordance correlation coefficient were used and are explained as follows.

A2.1 The geometric mean regression

In order to validate the estimated flows, these were compared with the gauged flows (*e.g.* gauged MF and Q95 for validating the naturalised estimates from the Water Resources model) or with calculated ones (*e.g.* QMED calculated using the peak over threshold method from gauged data). Both variables (the simulated and 'expected') are subject to error in the data and the method. For most of these situations a geometric mean regression line, that minimises the errors on x and y as both variables are subject to error, is more suitable than an ordinary predictive regression that is usually employed according to Draper and Smith (1998), Draper (1992) and Ricker (1973).

The functional regression line can be calculated from the geometric mean of one predictive regression and the reciprocal of the other. The two predictive regression lines are $\hat{x}$ on y (in green in Figure A2-1) that minimises the error on y (simulated variable), and $\hat{y}$ on x plotted on a graph of the usual sort (in red in Figure A2-1) that minimises the error on x ('expected' variable). From these predictive regression lines, the slope and the intercept of the geometric mean or functional regression line (in blue in Figure A2-1), that is the line in between the predictive regression lines, can be calculate as described in Draper and Smith (1998) and Draper (1992).

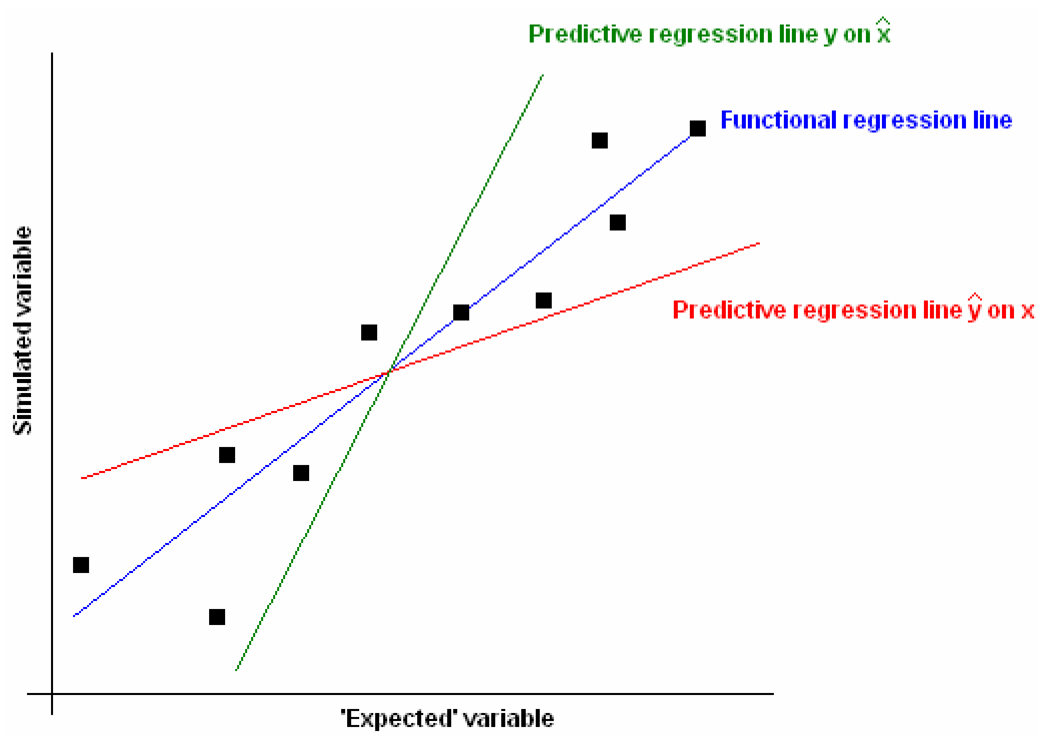

Figure A2-1: Diagrammatic representation of the geometric mean regression principle and calculation method.

One disadvantage of the geometric mean functional relationship is that no easy calculations are available for conducting tests on the parameters or constructing confidence intervals for them (Draper, 1992). However, by comparing the slopes and intercepts of the predictive and functional regression lines with the hypothesis of slope = 1 and intercept = 0, it is possible to get an initial impression of the validity of the model in question (Draper and Smith, 1998; Draper, 1992). This is carried out in Section 5.3.1 to validate QMED; that was required because QMED was the parameter more difficult to validate in this study. For all the simulated variables, the concordance correlation coefficient was used to analyse the slope (=0) and the intercept (=1) as suggested by Pat Bellamy (*Pers. Comm.*).

A2.2 The concordance correlation coefficient

In order to evaluate the agreement between two readings (from the same sample) by measuring the variation from the 45º line through the origin Lin (1989) developed the concordance correlation coefficient, which was after corrected in Lin (2000). In 2002, Lin *et al.* confirmed that the method could be applied to characterise agreement between the observed measurements and the theoretical (expected) values, which is of interest in order to compare the gauged flows with the simulated ones.

The concordance correlation coefficient measures how far the observations deviate from the concordance (symmetry) line in the scale of 1 (perfect agreement to 0 (no agreement) to -1 (perfect reversed agreement) through a measure of precision and accuracy. The measure of precision evaluates how far the observations deviate from the best-fit linear line using the Pearson correlation coefficient. The measure of accuracy evaluates how far the best-fit line deviates from the concordance line (Lin, 1992).

A3 Gauging stations used for the statistical model validation

A3.1 Data for the validation of the Water Resources model

For the validation of the Water Resources model (Section 4.6) data on the Mean Flow, Q95 and Q10 was available from the NRFA website, which also provided information about the gauging stations.

A3.1.1 East Anglia

The 31 selected gauging stations in East Anglia (hydrometric areas HA31-HA36) are:

Gauging station number	Watercourse	Location	Grid Reference
31004	Welland	Tallington	53 (TF) 095 078
32001	Nene	Orton	52 (TL) 166 972
33001	Bedford Ouse	Brownshill Staunch	52 (TL) 369 727
33003	Cam	Bottisham	52 (TL) 508 657
33012	Kym	Meagre Farm	52 (TL) 155 631
33013	Sapiston	Rectory Bridge	52 (TL) 896 791
33019	Thet	Melford Bridge	52 (TL) 880 830
33021	Rhee	Burnt Mill	52 (TL) 415 523
33023	Lea Brook	Beck Bridge	52 (TL) 662 733
33024	Cam	Dernford	52 (TL) 466 506
33026	Bedford Ouse	Offord	52 (TL) 216 669
33029	Stringside	Whitebridge	53 (TF) 716 006
33053	Granta	Stapleford	52 (TL) 471 515
34004	Wensum	Costessey Mill	63 (TG) 177 128
34005	Tud	Costessey Park	63 (TG) 170 113
34007	Dove	Oakley Park	62 (TM) 174 772
34008	Ant	Honing Lock	63 (TG) 331 270
34010	Waveney	Billingford Bridge	62 (TM) 168 782
34012	Burn	Burnham Overy	53 (TF) 842 428
34013	Waveney	Ellingham Mill	62 (TM) 364 917
34018	Stiffkey	Warham All Saints	53 (TF) 944 414
34019	Bure	Horstead Mill	63 (TG) 267 194
35001	Gipping	Constantine Weir	62 (TM) 154 441
35002	Deben	Naunton Hall	62 (TM) 322 534
35004	Ore	Beversham Bridge	62 (TM) 359 583
36001	Stour	Stratford St Mary	62 (TM) 042 340
36002	Glem	Glemsford	52 (TL) 846 472
36003	Box	Polstead	52 (TL) 985 378
36004	Chad Brook	Long Melford	52 (TL) 868 459
36007	Belchamp Brook	Bardfield Bridge	52 (TL) 848 421
36013	Brett	Higham	62 (TM) 032 354

Information about the stations: http://www.nwl.ac.uk/ih/nrfa/station_summaries/op/EA-Anglian1.html

Map of the stations: http://www.nwl.ac.uk/ih/nrfa/station_summaries/op/EA-Anglian_map.html

A3.1.2 North West

The 48 selected gauging stations in the North West (hydrometric areas HA69-HA76) are:

Gauging station number	Watercourse	Location	Grid Reference
68002	Gowy	Picton	33 (SJ) 443 714
68003	Dane	Rudheath	33 (SJ) 668 718
68007	Wincham Brook	Lostock Gralam	33 (SJ) 697 757
69002	Irwell	Adelphi Weir	33 (SJ) 824 987
69003	Irk	Scotland Weir	33 (SJ) 841 992
69005	Glaze Brook	Little Woolden Hall	33 (SJ) 685 939
69006	Bollin	Dunham Massey	33 (SJ) 727 875
69008	Dean	Stanneylands	33 (SJ) 846 830
69013	Sinderland Brook	Partington	33 (SJ) 726 905
69015	Etherow	Compstall	33 (SJ) 962 908
69020	Medlock	London Road	33 (SJ) 849 975
69023	Roch	Blackford Bridge	34 (SD) 807 077
69024	Croal	Farnworth Weir	34 (SD) 743 068
69027	Tame	Portwood	33 (SJ) 906 918
69030	Sankey Brook	Causey Bridge	33 (SJ) 588 922
69031	Ditton Brook	Greens Bridge	33 (SJ) 457 865
69037	Mersey	Westy	33 (SJ) 617 877
70002	Douglas	Wanes Blades Bridge	34 (SD) 476 126
70004	Yarrow	Croston Mill	34 (SD) 498 180
70005	Lostock	Littlewood Bridge	34 (SD) 497 197
71001	Ribble	Samlesbury	34 (SD) 587 314
71004	Calder	Whalley Weir	34 (SD) 729 360
71006	Ribble	Henthorn	34 (SD) 722 392
71008	Hodder	Hodder Place	34 (SD) 704 399
71014	Darwen	Blue Bridge	34 (SD) 565 278
72001	Lune	Halton	34 (SD) 503 647
72002	Wyre	St Michaels	34 (SD) 463 411
72005	Lune	Killington New Bridge	34 (SD) 622 907
72008	Wyre	Garstang	34 (SD) 488 447
72009	Wenning	Wennington	34 (SD) 615 701
72011	Rawthey	Brigg Flatts	34 (SD) 639 911
72014	Conder	Galgate	34 (SD) 481 554
73001	Leven	Newby Bridge	34 (SD) 371 863
73015	Keer	High Keer Weir	34 (SD) 523 719
74005	Ehen	Braystones	35 (NY) 009 061
74006	Calder	Calder Hall	35 (NY) 035 045
74007	Esk	Cropple How	34 (SD) 131 978
75002	Derwent	Camerton	35 (NY) 038 305
75003	Derwent	Ouse Bridge	35 (NY) 199 321
75004	Cocker	Southwaite Bridge	35 (NY) 131 281
75017	Ellen	Bullgill	35 (NY) 096 384
76002	Eden	Warwick Bridge	35 (NY) 470 567

Gauging station number	Watercourse	Location	Grid Reference
76003	Eamont	Udford	35 (NY) 578 306
76004	Lowther	Eamont Bridge	35 (NY) 527 287
76005	Eden	Temple Sowerby	35 (NY) 605 283
76007	Eden	Sheepmount	35 (NY) 390 571
76008	Irthing	Greenholme	35 (NY) 486 581
76010	Petteril	Harraby Green	35 (NY) 412 545

Information about the stations: http://www.nwl.ac.uk/ih/nrfa/station_summaries/op/EA-NorthWest1.html

Map of the stations: http://www.nwl.ac.uk/ih/nrfa/station_summaries/op/EA-NorthWest_map.html

A3.2 Data for the validation of the High River Flows model

For the validation of the High River Flow model (Section 5.3) the peak-over-threshold and annual maxima data series were available from the High Flows UK website, which also provided information about the gauging stations.

A3.2.1 East Anglia

The 15 selected gauging stations in East Anglia are as follows:

Gauging station number	Watercourse	Location	Grid Reference
31004	Welland	Tallington Total	53 (TF) 095 078
33012	Kym	Hail Weston	52 (TL) 155 631
33013	Sapiston	Rectory	52 (TL) 896 791
33019	Thet	Melford	52 (TL) 880 830
33021	Rhee	Burnt Mill	52 (TL) 415 523
33023	Kennett	Beck Bridge	52 (TL) 662 733
33029	Stringside	Whitebridge	53 (TF) 716 006
34004	Wensum	Costessey Mill	63 (TG) 177 128
34005	Tud	Costessey Park	63 (TG) 170 113
34008	Ant	Honing Lock	63 (TG) 331 270
34012	Burn	Burnham	53 (TF) 842 428
36002	Glem	Glemsford	52 (TL) 846 472
36003	Box	Polstead	52 (TL) 985 378
36004	Chad Brook	Long Melford	52 (TL) 868 459
36007	Belchamp Brook	Bardfield Bridge	52 (TL) 848 421

Map of the stations: http://www.environment-agency.gov.uk/hiflowsuk/maps/anglian/

A3.2.2 North West

The 39 selected gauging stations in the North West are as follows:

Gauging station number	Watercourse	Location	Grid Reference
68003	Dane	Rudheath	33 (SJ) 668 718
68007	Wincham Brook	Lostock Gralam	33 (SJ) 697 757
69002	Irnwell	Adelphi Weir U/S	33 (SJ) 824 987
69003	Irk	Scotland Weir	33 (SJ) 841 992
69005	Glaze Brook	Little Woolden Hall	33 (SJ) 685 939
69006	Bollin	Dunham Massey	33 (SJ) 727 875
69015	Etherow	Compstall	33 (SJ) 962 908
69020	Medlock	London Road	33 (SJ) 849 975
69023	Roch	Blackford Bridge	34 (SD) 807 077
69024	Croal	Farnworth	34 (SD) 743 068
69027	Tame	Portwood	33 (SJ) 906 918
69030	Sankey Brook	Causey Bridges	33 (SJ) 588 922
70002	Douglas	Wanes Blades Bridge	34 (SD) 476 126
70004	Yarrow	Croston	34 (SD) 498 180
70005	Lostock	Littlewood Bridge	34 (SD) 497 197
71001	Ribble	Samlesbury Pgs	34 (SD) 587 314
71004	Calder	Whalley Weir	34 (SD) 729 360
71006	Ribble	Henthorn Fms	34 (SD) 722 392
71008	Hodder	Hodder Place	34 (SD) 704 399
71014	Darwen	Blue Bridge	34 (SD) 565 278
72002	Wyre	St Michaels Fms	34 (SD) 463 411
72005	Lune	Killington	34 (SD) 622 907
72011	Rawthey	Brigflatts	34 (SD) 639 911
72014	Conder	Galgate	34 (SD) 481 554
73015	Keer	High Keer Weir	34 (SD) 523 719
74005	Ehen	Braystones	35 (NY) 009 061
74006	Calder	Calder Hall	35 (NY) 035 045
74007	Esk	Cropple How	34 (SD) 131 978
75002	Derwent	Camerton	35 (NY) 038 305
75003	Derwent	Ouse Bridge	35 (NY) 199 321
75004	Cocker	Southwaite Bridge	35 (NY) 131 281
75017	Ellen	Bullgill	35 (NY) 096 384
76002	Eden	Warwick Bridge	35 (NY) 470 567
76003	Eamont	Udford	35 (NY) 578 306
76004	Lowther	Eamont Bridge	35 (NY) 527 287
76005	Eden	Temple Sowerby	35 (NY) 605 283
76007	Eden	Sheepmount	35 (NY) 390 571
76008	Irthing	Greenholme	35 (NY) 486 581
76010	Petteril	Harraby Green	35 (NY) 412 545

Map of the stations: http://www.environment-agency.gov.uk/hiflowsuk/maps/northwest/

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