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The impacts of climate change on severe droughts

Implications for decision making

Science Report: SC040068/SR3

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Steve Killeen Head of Science

Executive Summary

This report presents the final results of a collaborative study by the Environment Agency, Anglian Water Services and United Utilities on the impacts of climate change on severe droughts in England and Wales and implications for decision-making. The two companion reports for this study are *Major droughts in England and Wales from 1800 and evidence of impact* (Cole and Marsh, 2006) and *River flow reconstructions and implied groundwater levels* (Jones *et al*., 2006a).

The study shows that there were major droughts in the nineteenth century that were more severe than some of the drought scenarios used for planning water resources in the UK. In some cases, the reliable supply of water from different sources is estimated to be lower when earlier droughts are considered. The climate regime in the nineteenth century was not significantly different to today's climate. Therefore, major drought episodes (such as the Long Drought of 1890 to 1909 in the East of England) could occur again even without climate change. A return to these conditions would require year-on-year water restrictions to reduce demand, with far greater impacts than droughts experienced in the twentieth century and since 2003.

Future resource yields – that is, water supplied from sources such as reservoirs and lakes – were assessed using scenarios from three regional climate change models (ARPEGE, HadRM3H and HIRHAM). These show that future changes in precipitation are uncertain and the impact on water resources depends upon the amount of storage held by reservoirs and groundwater. Two case studies of reservoirs in the North West and East of England showed that both areas will be affected by climate change. In the North West of England there are likely to be reductions in water resources and lower average lake levels by the 2020s. In the East of England, river flows are very sensitive to changes in the balance between rainfall and evapotranspiration. Future scenarios with higher summer temperatures and evaporation losses lead to reductions in reservoir yield (ARPEGE model). Under future scenarios with lower rates of warming, large lowland reservoirs help to balance the changing seasonal pattern of rainfall and river flows and there is little change or even a small increase in reservoir yields (HadRM3H and HIRHAM models).

Future droughts may be more severe than those currently used for water resource and drought contingency planning. The analysis of nineteenth century droughts is one way that drought and water resource planning can encompass the full range of natural variability alongside projected changes in long-term climate. Operational and planning actions will be required to maintain water supplies and protect the environment through severe drought episodes. Operational measures may include drought forecasting, variable tariffs and stronger demand restrictions. Planning measures may include new water sources and long-term demand management.

Eight key findings from this study are explained below.

1. The analysis of long historical rainfall time series provides insights into the natural variation of climate from year to year, over decades and longer time periods. In particular, longer series can highlight the magnitude and frequency of multi-season droughts that have the greatest impacts on water resources. For example, the reconstructed flow for the River Ouse (East England) was on average around10 per cent less throughout 1841-1970 than present (1961-1990).

2. The East of England experienced severe droughts in the nineteenth century that would present a significant problem for current water resource systems. Inclusion of early nineteenth century droughts reduces predicted yields by as much as 16 per cent compared with estimates based on 1920-2004. In comparison, projected changes in long-term climate affects reservoir yields by ± two per cent by the 2020s.

3. In North West England droughts of the twentieth century were more severe than those of the nineteenth century, so reliable yields are unchanged. However, the climate change scenarios suggest a 13-18 per cent reduction in yield for one reservoir by the 2020s.

4. Climate change uncertainties, related to the use of different regional climate models, are significant. In the case studies, climate change generally had no impact or reduced source yields. Two of the climate models (HadRM3H, HIRHAM) produced similar results in terms of changes in source yield; a third model (ARPEGE) produced much larger reductions in source yields. This supports the view that predictions from more than one climate model should be considered in water resource planning.

5. The impacts of climate change on reservoir storage and yield was less than the impacts on river flow and on direct river abstractions reported in water company plans. This illustrates the potential role of storage and seasonally variable licence conditions to balance increases in winter flows with reductions in summer flows due to climate change.

6. The results also show that it is difficult to generalise on the potential impacts of climate change on water resources, as site specific factors (such as existing licences, infrastructure, catchment characteristics) are as important as changes in 'drivers' (such as precipitation). Even within the same region, results can vary from negative to positive depending on local factors.

7. In the worst case scenario (ARPEGE model outputs for this study), water companies would need to apply for drought powers much more frequently to maintain water supply and protect the environment. Policy, process and institutional changes would all be required to adapt to the more frequent drought conditions implied by some climate change scenarios. These include powers to reduce the demand for water, more advanced drought forecasting systems and flexible licensing conditions to benefit from projected increases in average winter rainfall.

8. Finally, both long-term natural variability and climate change should be considered in water resources planning, particularly for horizons up to the 2020s and 2030s, as natural variability will tend to dominate over these timescales. The methods explored in the study will be particularly useful in areas such as East Anglia, where there are good quality rainfall records back to the 1800s, and there are large lowland reservoirs that are vulnerable to droughts lasting over several seasons.

Short glossary of acronyms

AMP	Asset management plan (a review of water prices associated with an agreed infrastructure programme)
ARPEGE	A regional climate model
EA	Environment Agency
ET	Evapotranspiration (mm/day)
ETo	Reference evapotranspiration (mm/day)
GCM	Global climate model
HadCM3	Hadley Centre global climate model
HadRM3H	Regional climate model developed by the Met Office Hadley Centre for Climate Change Prediction and Research
HIRHAM	A regional climate model
LoS	Levels of service – determines the frequency of restrictions on demand, such as one in ten years for a hosepipe ban
LTA	Long-term average
MOSPA	An integrated simulation and dynamic programming approach for evaluating the performance of complex water resource systems and optimising operating policies
NR	'No restrictions' – a type of water resources model run where there are no restrictions imposed on customer demand
OSAY	Surface water yield assessment model
P	Precipitation (mm/day)
PET	Potential evapotranspiration (mm/day)
PR04	Periodic review of water pricing in England and Wales in 2004
PR09	Periodic review of water pricing in England and Wales in 2009
RCM	Regional climate model
SMD	Soil moisture deficit (mm)
UKCIP	United Kingdom Climate Impacts Programme
UKCIP02	United Kingdom Climate Impacts Programme climate change scenarios produced in 2002
UKCIP98	United Kingdom Climate Impacts Programme climate change scenarios produced in 1998
UKWIR	United Kingdom Water Industry Research
WHD	Worst historic drought
WRZ	Water resource zone

Contents

1 Introduction

1.1 Background

This report presents the results of an Environment Agency-funded study called the '*Impacts of climate change on severe droughts in England and Wales and implications for decision making'*. The aim of the project was to improve our understanding of the impact of past and possible future severe droughts on water resources, based on case studies from the East of England and from North West England.

The project was undertaken in partnership with Anglian Water Services, a company that supplies water to the East of England, and United Utilities, which supplies water to the North West of England. The study was carried out in four stages:

- a review of major droughts and evidence of impact in England and Wales (1800-2003);
- reconstruction of rainfall, temperature, evapo-transpiration and river flow records back to 1800 for two case study areas in the North West of England and East of England;
- water resources modelling to assess the impacts of past and future droughts on water source yields in the two case study areas.
- a review of adaptation options to provide guidance on appropriate adaptation strategies, including how drought risks should be communicated to policy makers and the public.

The first two stages are described in sister Environment Agency science reports: *Major droughts in England and Wales from 1800 and evidence of impact* (Cole and Marsh, 2006) and *River flow reconstructions and implied groundwater levels* (Jones *et al*., 2006a). This report reviews the previous research, describes the water resources modelling and discusses adaptation strategies based on the case studies.

Section 2 summarises the evidence of major droughts in England and Wales since 1800, focusing on climate indicators for the two case study regions. Section 3 summarises the methods used for reconstructing precipitation, evapotranspiration and river flows for the two case studies and the application of three different regional climate models (RCMs) to estimate changes in future river flows for the 2020s, 2050s and 2080s.

Sections 4 and 5 describe the East of England and North West of England case studies respectively. These sections include a description of the current water resources system, water resources modelling and estimates of the impacts of climate change on resource yields. Section 6 summarises the main conclusions from the study and options for adapting to future droughts in England and Wales.

Box 1: Drought definitions

The following definitions are used to describe drought and water resource terms:

- Deployable output (DO) - the output (that is, the amount of water released) of a source or group of sources as constrained by the environment, licence conditions, pump capacities, raw water losses, works capacity and water quality considerations. DO is normally reported as the average and critical period deployable output.
- Hydrological drought – changes in the catchment water balance (precipitation, evaporation and storage) leading to a deficit of run-off, recharge or low groundwater levels over a specific period. Severity can be classified in a similar way to rainfall drought (see below).
- Hydrological yield - The unrestricted output of a source (ignoring licence conditions) and other constraints.
- Levels of service (LoS) – the standard and reliability of water supply expressed in terms of the frequency of specific drought management measures such as hosepipe bans, restrictions on non-essential use and emergency supplies. The LoS is set by water companies and the Water Customer Council. In water resources modelling, a LoS run simulates the behaviour or a system operating according to specific LoS and other system constraints to meet demand.
- No restrictions (NR) – a water resources model run that excludes any restrictions on water use in order to determine yield or deployable output.
- Rainfall drought – a deficit of rainfall over a specific period significantly below the long-term average. The drought severity can be classified used statistical indices, such as the Standardised Precipitation Index (SPI).
- Water resources drought – a shortage of water available to meet normal demands (for water supply, industry or the environment) due to a combination of hydrological drought and socio-economic factors affecting water resources.
- Worst historic drought (WHD) – the most severe drought on record in terms of its impact on water resources. Drought and water resource plans in the UK have typically considered the WHD based on a period from 1920. In some cases only the period of observed hydrological records, that is from the 1950s or 1960s for most UK catchments, is considered.
- Yield – the reliable output of a water source considering (current) licence and other specified constraints. In England and Wales the constraints include a customer level of service. (The constraints considered should be clearly stated when comparing yields between sources, catchments or regions).
- Assessment of hydrological yield – a calculation of the maximum average annual demand that can be met by the source, subject to specific constraints. Depending on the method used, yield searches identify the demand that can be met in the WHD or alternatively for a specific return period of drought (such as one in 50 years). In Scotland, the latter method is used to assess hydrological yields of reservoirs.

Droughts are a natural and recurrent feature of the UK climate that can develop over short periods or several seasons and years with a wide range of consequences for the environment, water supply and agriculture. Rainfall droughts occur during periods of low rainfall significantly below long-term averages and, if prolonged, can develop into ‘agricultural droughts’ with persistently low soil moisture affecting crops, and ‘hydrological droughts’ reducing river flows and groundwater recharge. Rainfall or hydrological drought severity can be quantified in statistical terms but severe ‘agricultural’ or ‘water resources’ droughts are more difficult to define. These occur due to a combination of intense and long-lasting events and the vulnerability of agricultural or water resource systems to drought situations.

The multi-faceted nature of drought means that it is difficult to define a ‘severe drought’ and no attempt has been made to provide an exact definition as part of this research. Rather, ‘major droughts’ have been identified using meteorological information supported by additional historical evidence (Cole and Marsh, 2006). In addition, care has been taken to distinguish ‘rainfall droughts’ from ‘hydrological’ and ‘water resources’ droughts. In particular, the latter occurs due to socio-economic factors as well as natural variation in rainfall and river flows.

In parts of England and Wales, particularly where the Environment Agency has indicated that there is an ’unsustainable or unacceptable abstraction regime’ or that there is ‘no additional water available’ (Environment Agency, 2001), hydrological droughts can have impacts on:

- public water supplies, leading to drought orders, permits or licences to manage the demand for water, increase abstraction or reduce the amount of ‘compensation flows’ from reservoirs that are in place to protect the environment;
- the environment, where reduced river flows and groundwater levels can damage aquatic habitats, and low flows reduce the amount of dilution in river systems and contribute to fish-kills and excessive algal growth;
- agriculture, with high soil moisture deficits, increased irrigation costs or insufficient water available for irrigation;
- industry, if direct abstractions or public water supplies are interrupted due to water shortages or poor water quality and high temperatures;
- recreation and navigation due to low river levels, and indirectly due to environmental impacts such as higher plant and algal growth;
- tourism in cases where low river, reservoir and lake levels affect landscape quality.

In several of these sectors, policies and management approaches have been developed to manage drought risk. For example, the Water Resources Act (1991) and Water Act (2003) makes provisions for the use of drought permits, drought orders and emergency drought orders to manage demand, maintain public water supply and protect the environment during droughts. Water resource planners take a long-term view (30 years plus) to develop supply and demand-side schemes to meet specific levels of service for water supplies, while farmers plan irrigation based on dry year conditions and for high value crops, may switch to public water supply to meet the crops' requirements.

Planning for future droughts, including those under climate change scenarios, requires a risk management approach with measures to both reduce the probability of a drought (through water resources planning) and the consequences of drought (through contingency plans, insurance policies and so on). Good drought planning requires long-term climate and hydrological data to determine the probability of specific drought situations; effective forecasting, warning and communications systems; hydrological and environmental monitoring systems; information on water use; methods to quantify drought impacts; clear policy and management responses to different stages of drought and information on the effectiveness of different drought management actions.

The Environment Agency published revised guidelines for drought planning in England and Wales in 2005 (Environment Agency, 2005). The guidance states that *"*water companies must prepare for a wide range of drought situations that might threaten the ability to provide secure supplies*"*, including single dry summers, single dry winters and a range of multi-season droughts. The guidance does not consider climate change. However, the plans are updated every three years and the scenarios considered can change to reflect more recent severe droughts.

In a changing climate, a more proactive approach is needed to ensure that water plans consider the uncertainties related to natural variability and climate change. For example, the development of model drought conditions based on the severe droughts of the early nineteenth century and climate change would provide a test for water company drought plans. Possible changes to current policy and planning processes are discussed in Section 6.

1.2 Methods

This stage of the study involved an impacts and adaptation assessment based on case studies in the North West and East of England. The methods were developed to gain an understanding of the impacts of natural climate variation and future climate change scenarios on the yield of individual and groups of water sources.

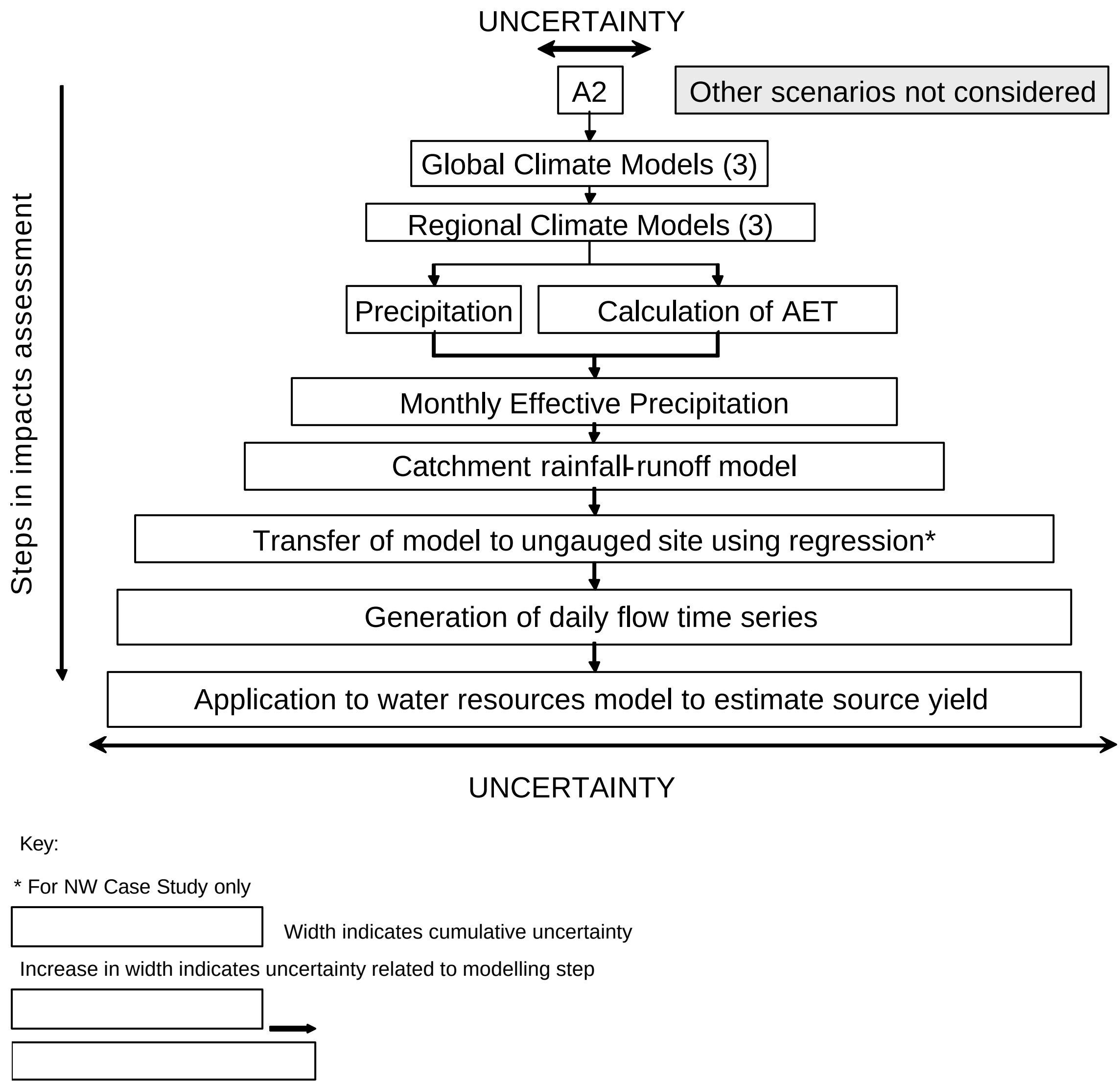
The impact assessment method involved the following steps:

- a review of the long-term river flow series for the period 1801 to 2000 based on a hydrological regression model (Jones, *et al*., 2006a; Section 3);
- the development of climate change scenarios based on three regional climate models and the 'A2' emissions scenario (Appendix 1);
- application of the climate change scenarios to the hydrological model to produce 'perturbed' river flow time series (Appendix 1);
- input of observed or 'water company estimated' river flows and reconstructed and 'perturbed' river flows into reservoir models to quantify the potential impacts on source yield (Sections 4 and 5);

- a similar analysis of groundwater levels to provide information on all the major resource types: groundwater, direct surface water abstraction and reservoirs (Jones *et al*., 2006a; Section 3).

Box 2 shows how uncertainty enters each stage in the methodology. The following two sections provide more information on the choice of climate change scenarios and case studies. The case study chapters provide more information on the modelling methods.

Box 2: The cascade of uncertainty affecting future water resource scenarios



1.3 Climate change scenarios

This project used one emissions scenario and three RCMs to develop future scenarios for the 2020s, 2050s and 2080s (see Box 3). The emissions scenario chosen was the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) “A2” scenario. It corresponds to one of the four standard UK Climate Impacts Programme (UKCIP) scenarios (medium high emissions, Hulme *et al*. 2002). As the Box 2 shows that the choice of emission scenario and RCM are just two components within a much larger ‘cascade of uncertainty’ affecting projections of future river flow and hence estimates of changing water resource yields.

Box 3: Regional climate change scenarios

In order to estimate future changes in climate, the development of society also needs to be considered. The IPCC, through the Special Report on Emissions Scenarios (SRES – see discussion in Hulme *et al*., 2002), devised a set of possible future scenarios which quantify possible pathways of societal development and thus future greenhouse gas emissions through to the year 2100. Estimates of greenhouse gas emissions in each of these scenarios are based upon important social and economic factors such as global population, degree of globalisation, investment and use of sustainable energy sources.

The A2 scenario used here envisages a world slow to globalise, where regional preservation is emphasised and the underlying theme is self-reliance. Fertility patterns are slow to homogenise across the planet and the global population continues to rise. Although economic growth and technological advancement continues, they do so regionally and are more fragmented than in other scenarios. This scenario therefore results in a high anthropogenic forcing of the future climate. A2 is the most widely applied SRES scenario used to force global climate model (GCM) integrations.

GCMs provide us with a reliable and internally consistent method for assessing the response of the climate system to changes in forcing. They are based upon the fundamental laws of physics (such as fluid flow, radiation emission, absorption and scattering), though only represented approximately within the constraints of the model (always a simplified representation of the real climate system). In essence, GCMs are modified versions of weather forecast models, simplified for use in the majority of studies because of computer constraints. The most serious limitation is the limited spatial detail resolved in the relatively coarse grid (~250 km by 250 km at present) of a GCM. This limitation carries over to difficulties in simulating short-timescale variability, since events on timescales of days or less typically occur at very small spatial scales. Overcoming these limitations requires a variety of techniques to provide information at the appropriate scales (particularly spatial).

Higher-resolution scenarios (50 km by 50 km at present) can be developed with regional climate models (RCMs). The ability of an RCM to simulate the correct climate change signal will depend in part on the ability of the driving GCM to simulate the correct signal at larger spatial scales (this cannot easily be assessed, so using a number of different

GCMs within which to embed the higher resolution models is recommended). RCMs require intensive computational resources and are only now being used to simulate time-dependent responses of the climate system. Previously they have been used to simulate climate within specific time horizons (such as the 1961–1990 and 2070–2099 periods).

Simulations by currently available GCMs and RCMs will differ. To encompass as many of these differences (uncertainties) as possible, it is necessary to use integrations from a number of GCMs and RCMs. As yet, there is no agreed way of ranking GCMs and RCMs, and a common approach is to consider each as an equally plausible future for a given scenario such as A2. In this project, we explore uncertainty by using three different RCMs driven by three different GCMs to encompass the range of the currently available integrations. The three GCMs have been developed at the Hadley Centre, Met Office (HadCM3/HadAM3H), Meteo-France (ARPEGE) and the German Climate Modelling Centre (DKRZ) in Hamburg (ECHAM4). Each of the three main climate modelling centres in Europe has also developed an RCM (HadRM3H, ARPEGE and HIRHAM, respectively). A number of other smaller modelling centres have developed RCMs, but they are nearly all driven by one of the three GCMs listed above. As the driving model determines much of the RCM climate, a greater range of possible futures is covered by having different GCMs as opposed to RCMs. All the RCM results from this project have been taken from the PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) project website (http://prudence.dmi.dk/; see also Christensen *et al*., 2006). This project transformed all model grids (all of which differ from each other) into a common 0.5° by 0.5° latitude/longitude resolution. Data was extracted from this grid for the Ouse and Eden case study regions.

For this study, regional climate changes projected by three RCMs were chosen to span the range of future RCM variability as well as three different driving general circulation models (GCiMs).

The three models selected were:

- HadRM3 driven by HadAM3.
- ARPEGE RCM driven by ARPEGE GCM.
- HIRHAM driven by ECHAM4.

These models provide a fairly good sample of the range of possible RCM futures represented by the full set of RCMs inter-compared within the PRUDENCE project. An in-depth discussion of regional climate modelling can be found on the PRUDENCE project web pages and in Christensen *et al.* (2006).

The method used to estimate future monthly flows based on changes in future precipitation and potential evapotranspiration (PET) is outlined in Appendix 1 and described in detail in Jones *et al*., (2006a,b). It involved several steps including the use of a simple Penman model to estimate actual evapotranspiration (AET), the use of monthly precipitation and AET change factors with the regression models of the Ouse and Eden, analogue selection of months from the historical record in order to develop daily time series and finally regression to estimate flows at specific abstraction sites (Appendix 1).

Sections 4 and 5 summarise the changes in precipitation, PET and flows based on each model for the case studies.

In addition, predictions by the selected RCMs and the UK Climate Impacts Programme climate change scenarios (UKCIP02) (Hulme *et al*., 2002) for the 2020s are compared using the following data sets:

- UKWIR, 2005. *Effect of Climate Change on River Flows and Groundwater Recharge, A Practical Methodology: Use of Climate Change Scenario Data at a Catchment Level*. UKWIR Report 05/CL/04/3. This report includes changes in precipitation and potential evaporation for Catchment Abstraction Management Strategy catchments in England and Wales.
- UKWIR, 2003. *Effect of Climate Change on River Flows and Groundwater Recharge UKCIP 02 Scenarios*. UKWIR Report 03/CL/04/2. This report includes regional changes in precipitation, PET, run-off and recharge and is used to compare run-off factors currently used in the water sector with the research results.

Some differences will be due to hydrological modelling uncertainties and methods of spatial interpolation as well as genuine differences between the RCMs, in particular:

- the data sets are for slightly different catchment areas and were derived using different methods of interpolation from RCM grids;
- PET was calculated using different methods: a form of the Penman-Monteith equation was used in the UKWIR studies, whereas this project estimated PET based on temperature only;
- the differences between these two case studies does not imply a consistent difference across the UK or even within the same region. National assessments are required to place the UKCIP02 scenarios in the context of other models.

However, the comparison helps to put the research results in the context of current approaches used in water resources planning to account for climate change.

1.4 The case study regions

The study considered two contrasting regions: the North West, based on the Rivers Eden, Ehen and Cocker and Ennerdale Water and Crummock Water, and the Anglian Region, based on the Great Ouse, River Nene and Welland and water supply reservoirs at Grafham, Rutland, Pitsford and Ravensthorpe and Hollowell.

The locations of the study areas and catchments are shown in Figure 1.1 and the characteristics of each water resource system are summarised in Table 1.1. The study areas were chosen because of their distinctly different hydrological responses as well as their location in UK regions with different rates of warming under future climate scenarios. The Ouse catchment is dominated by base flows and consequently river flows are a function of rainfall over seasons and years, whereas the catchments in the

North West have a much faster response to shorter periods of rainfall and/or snowmelt (Section 3).

The different catchment response times affect the nature of management responses to severe droughts. In West Cumbria, the rapid onset of a water resources drought will leave insufficient time for hosepipe and sprinkler bans to be effective and planning should focus on preparing drought permit applications simultaneously with demand management measures. The longer lead time between rainfall deficits and reductions in river flow in the East of England means that a more sequential approach can be taken, beginning with demand management measures before considering drought permits.

Table 1.1: Characteristics of the two case study regions: (a) regional water balance and (b) case study catchments, reservoirs and lakes

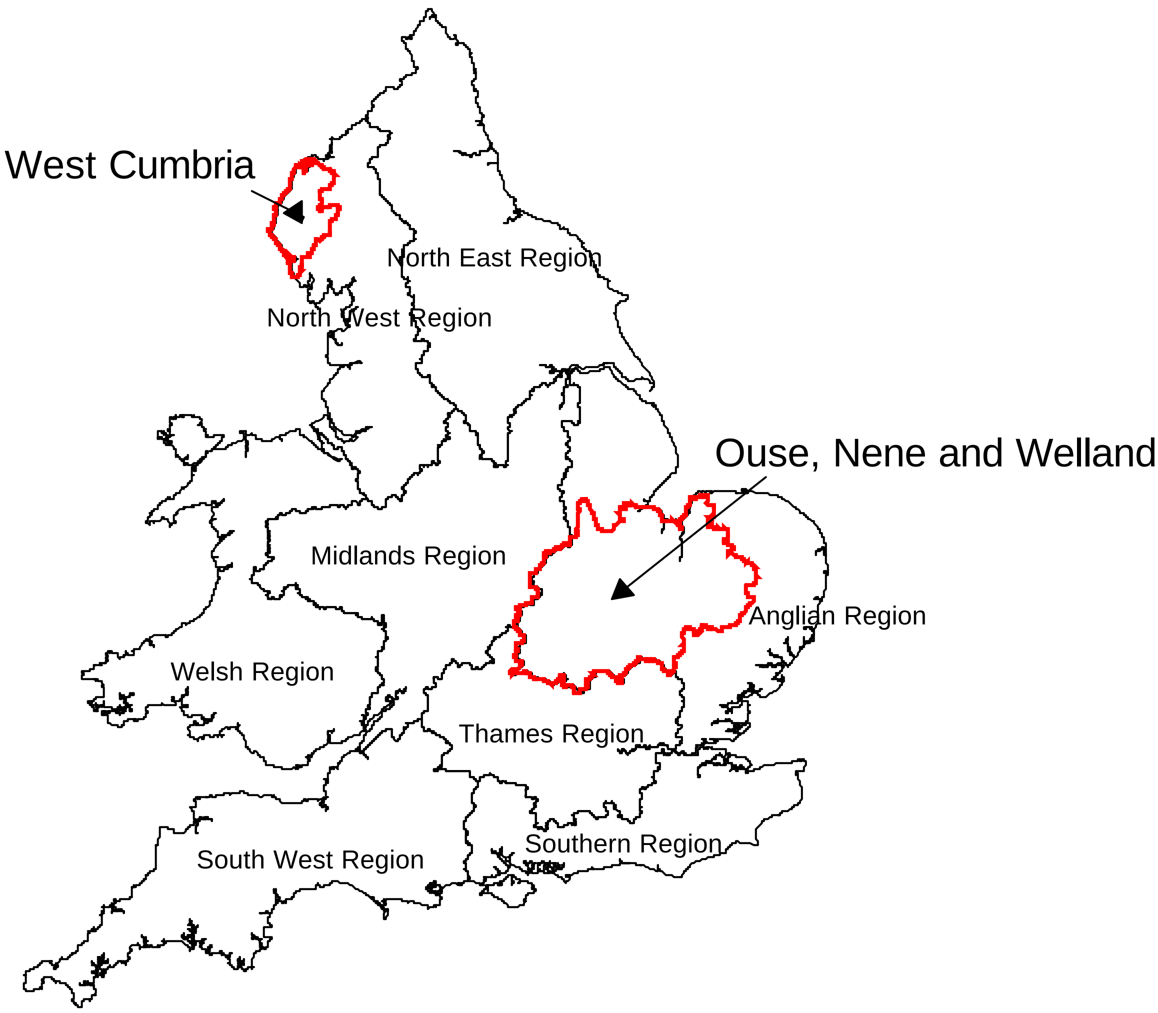
(a)

	1961-1990 average for the Ouse or Eden (Marsh and Lees, 2003)			Regional estimate for water company supply area	
Region	Average precipitation (mm)	Average actual evaporation (mm)	Average annual run-off (mm)	Surface water (reservoir/run-of-river)	Groundwater
Anglian	600	465	151	50%	50%
West Cumbria	1170	432	738	85%	15%

(b)

Region	Long-term synthetic flow series derived for:	Abstraction points/Inflows	Reservoir Water resources models
Anglian	River Ouse at Denver Sluice (1801-2002)	Rivers Ouse, Welland and Nene and individual reservoir inflows	Grafham Rutland Pitsford Ravensthorpe & Hollowell
West Cumbria	River Eden at Temple Sowerby and Warwick Bridge (WB) (1800 – 2002)	Rivers Ehen and Cocker	Ennerdale Water Crummock Water

Figure 1.1: Map showing Environment Agency regions and case study areas



2 Evidence of major droughts since 1800

Evidence of major droughts in England and Wales, particularly for the two case study regions, was described in the project's first report (Cole and Marsh, 2006). Key points from this report are summarised in Box 4 and notable drought years, in terms of rainfall, evaporation and run-off are summarised in Tables 2.1, 2.2, and 2.3.

Box 4: Historic Droughts (from Cole and Marsh, 2006)

- Drought has been a recurring feature of the UK climate, with recent drought events by no means exceptional in terms of their intensity or duration. A notable feature is the repeated tendency for dry years to cluster together, resulting in multi-year droughts of shorter, more intense periods. The extended drought periods from 1780-90, 1798-1808, 1854-60, 1890-1909, 1990-92, 1995-97 are all evidence of this.
- As many 'drought clusters' predate most observed river flow and groundwater time series, there is a clear danger that contemporary data sets (post-1950) may be unrepresentative of the full historical series. In particular, they do not capture the hydrological impact of the sequences of dry winters which are a feature of the pre-1920 rainfall series. Thus, drought risk (particularly in relation to protracted events) may be underestimated.
- When examining drought in an historical context, one must also be aware of possible changes in climatic variability over the historical record, the changing ability of a region to cope with drought and less documentary evidence for earlier periods.

Table 2.1 lists major droughts across England and Wales and for the two case study regions in chronological order. These are based on climate and hydrological records and historical evidence. The years that are currently used by each water company for water resources and drought planning including the 'worst drought on record' (1920-2004) are highlighted in Table 2.1[1]. Table 2.2 ranks the critical run-off deficits for the Ely Ouse and shows that 1803 had the lowest run-off, just 33 per cent of the long-term average. Table 2.3 shows similar data for the Eden, the critical period being six months.

[1] Following the Water Summit in 1997, water companies were asked to reassess the yields of all their water sources; typically, these assessments considered climate and hydrological records from approximately 1920 to 1996 (based on data availability). The assessments are updated periodically but the major droughts from 1798 to 1919 are not factored into current plans. The impact of this on design conditions depends upon water resource zone characteristics and the number of droughts pre- and post-1920 and their severity. In simple terms, if there are 'record-breaking' dry periods in the pre-1920 period, estimates of yield are likely to be reduced if a longer time period is considered.

Table 2.1: Preliminary selection of major drought events from Cole and Marsh (2006) and scenarios currently used for water resources and drought planning

England & Wales	Anglian	North West
1798-1808	1802-3?	1854-60
1854-60	1854-60	1869?
1887-88	1873-75	1887-88
1890-1909	1890-1909	1915
1921-22	1921-22	1933-34?
1933-34	1933-34	1976
1959	1959	1984
1976	1943-44?	1995-97
1990-92	1976	
1995-97	1990-92	
	1995-97	

Key

	Considered to be the worst droughts in the reconstructed rainfall series or current plans for one or more reservoirs. (Note that 1963 was a critical year for sources in West Cumbria due to local conditions that were not reflected in the regional historical records).
	Considered in current yield estimates and drought planning (years between 1920 – 2004)
	Droughts that are not considered in current plans (years between 1798 to 1919)
?	Conveys difficulties in fully assigning 'major' status to the event, due to its spatial and temporal variability (see Cole and Marsh, 2006)

Table 2.2: **Maximum 18-month run-off deficiencies for the Ely Ouse at Denver (synthetic naturalised series 1801-2002)**

Rank	Run-off (mm)	Per cent of long-term average	End month	Year
1	69.1	33.5	Nov	1803
2	80.5	39.0	Nov	1934
3	86.6	42.8	Oct	1922
4	90.1	43.7	Nov	1991
5	90.3	43.8	Nov	1815
6	94.7	46.8	Oct	1944
7	97.2	48.0	Oct	1997
8	100.7	49.7	Oct	1894
9	101.9	49.4	Nov	1973
10	103.5	50.2	Nov	1902
11	106.6	51.2	Sep	1855
12	107.4	51.6	Sep	1808
13	109.6	53.1	Nov	1976
14	112.1	53.9	Sep	1865
15	112.9	55.7	Oct	1871

Table 2.3: Minimum six-month run-off totals for the River Eden at Warwick Bridge (synthetic naturalised series 1800-2002)

Rank	Run-off (mm)	Per cent of long-term average	End month	Year
1	110.2	44.2	Sep	1995
2	113.0	45.2	Sep	1826
3	115.2	46.19	Sep	1984
4	128.4	45.2	Oct	1989
5	129.2	51.78	Sep	1996
6	134.5	47.48	Oct	1919
7	137.3	54.9	Sep	1806
8	140.1	40.48	Nov	1915
9	141.0	56.4	Sep	1870
10	142.7	50.2	Oct	1887
11	143.2	57.38	Sep	1955
12	144.9	53.2	Aug	1869
13	145.2	58.1	Sep	1941
14	150.2	60.1	Sep	1976
15	151.0	53.2	Oct	1901

Additional observations based on the naturalised flow time series and recent drought periods (2003 and November 2004 to March 2006) include:

- Major drought periods in the nineteenth century, in terms of run-off on the Ely Ouse and Eden (1803 and 1826 respectively), were more severe than the drought scenarios currently used in water resources and drought planning.
- The 2003 drought showed that UK water supply systems are generally resilient to short, intense droughts. However, a succession of dry winters (often followed by dry summers) may present a bigger problem for our supply systems. Prolonged drought periods have been relatively rare in the recent past but were much more common in the nineteenth century (1798-1808, 1854-60,1890-1909) when drought conditions continued for many years.
- The current drought in the South East of England that started in November 2004 is due to two successive, exceptionally dry winters. This drought bears some similarities to the prolonged drought periods of the early nineteenth century. The 1798-1808 example shows that these conditions can last for a decade – a situation that would require year-on-year restrictions to water use.
- Consideration of longer term climate and hydrological records should reduce the uncertainty in estimates of drought probability and improve our understanding of natural variability, both of which can contribute to better drought planning.

The climate regime in the early nineteenth century was not significantly different to today's climate. Therefore major drought episodes, such as the long drought of 1890-1909 in the East of England, could occur again even without climate change. A recurrence of these conditions would require year-on-year water restrictions to reduce demand, with far greater impacts than droughts in the twentieth century and those of 2003 and since November 2004.

The impact of these extended drought episodes on reservoir yields are described in Sections 4 and 5 for the two case studies.

3 Long-term river flow reconstructions

The method for constructing long-term river flow sequences for the two case studies was described in the project's second report (Jones *et al*., 2006a). Key points from this report are summarised in Box 5 and features of the reconstructions that provide information on natural variability are summarised in Figures 3.1 to 3.4. When following the methodology it is important to keep in mind that uncertainty is being introduced at each stage of the analysis (Box 2). For example, transposing river flow reconstructions for the River Eden to the 'donor' sites of Ennerdale and Crummock Water involved the use of imperfect regression relationships.

Box 5: Reconstructing river flows

- Rainfall records for the Eden and Ouse were extended back on a monthly basis to 1800 and checked for consistency and homogeneity.
- Monthly average river flows were hindcast using empirical models to estimate flow as a function of rainfall.
- These synthetic run-off sequences were analysed in terms of low flows of six month and 18 month duration for the Eden and Ouse respectively.
- For the Eden, three of the four most severe hydrological droughts (based on the above definition) were within the instrumental period (1960s onwards). These were 1989, 1995 and 1996. The second most severe drought was 1826.
- For the Ouse, the most severe drought was 1803 and a number of other notable droughts pre-date the instrumental flow record that started in 1920. Six of the worst 12 droughts occurred in the instrumental period.
- The synthetic monthly flow sequences were transferred to 'donor' sites at abstraction points using (a) one or two stage regression of the logarithm of flows and (b) an analogue approach to create daily river flow series for water resources modelling by re-sampling observed flow records.
- The monthly Central England Temperature (CET) record was adjusted for location and elevation to provide an estimate of historical temperatures and potential evapotranspiration.
- Empirical models were developed to hindcast annual minimum groundwater levels for two sites. These also indicated a number of severe drought events pre-dating the instrumental records.

Figure 3.1 shows an example of a reconstruction of annual minimum groundwater levels for Washpit Farm. Figures 3.2 (a) and (b) show the differences in the 'critical period' flow deficits for the Ouse and Eden with respect to the 1961-1990 period that is used as a standard reference period in many climate studies (such as Hulme *et al*., 2002). For the Ouse the prevalence of low flows in the early nineteenth century can be clearly identified and compared to more recent events. For the Eden there is an absence of low flows in the same period, with clusters in the second half of the nineteenth century and the most severe hydrological droughts occurring in the instrumental period as described in Box 5.

Figures 3.3 and 3.4 summarise some of the characteristics of different historical periods (defined as 30-year periods, centred on the listed decades). For the Ouse, late spring and early summer periods (April, May and June) appear to have had significantly lower flows in the past compared to 1961-1990 and both the 1820s and 1850s appear to have been significantly drier than the reference period. For the Eden, summers in the past appear to have been wetter than 1961-90 and only the 1850s were drier than the reference period. The statistical significance of these differences has not been tested, but the influence of natural variability is an important issue for the development of technical methods for climate change impact assessment within the water sector (for example, UKWIR, 2005b). The 1961-1990 period does not appear to be representative of long-term natural variability, which reinforces the need for (a) good quality, long-term climate and hydrological data and (b) application of long-term river flow series to estimate source yield and develop drought plans.

Figure 3.1: Hindcast annual minimum groundwater levels for Washpit Farm (Jones *et al*., 2006a)

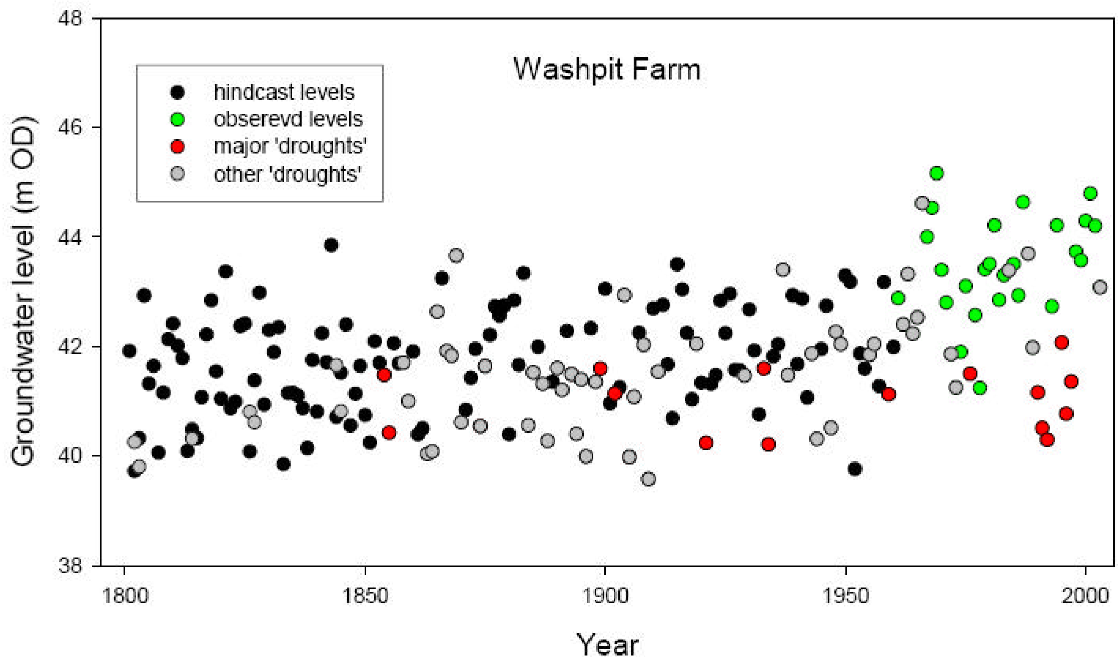
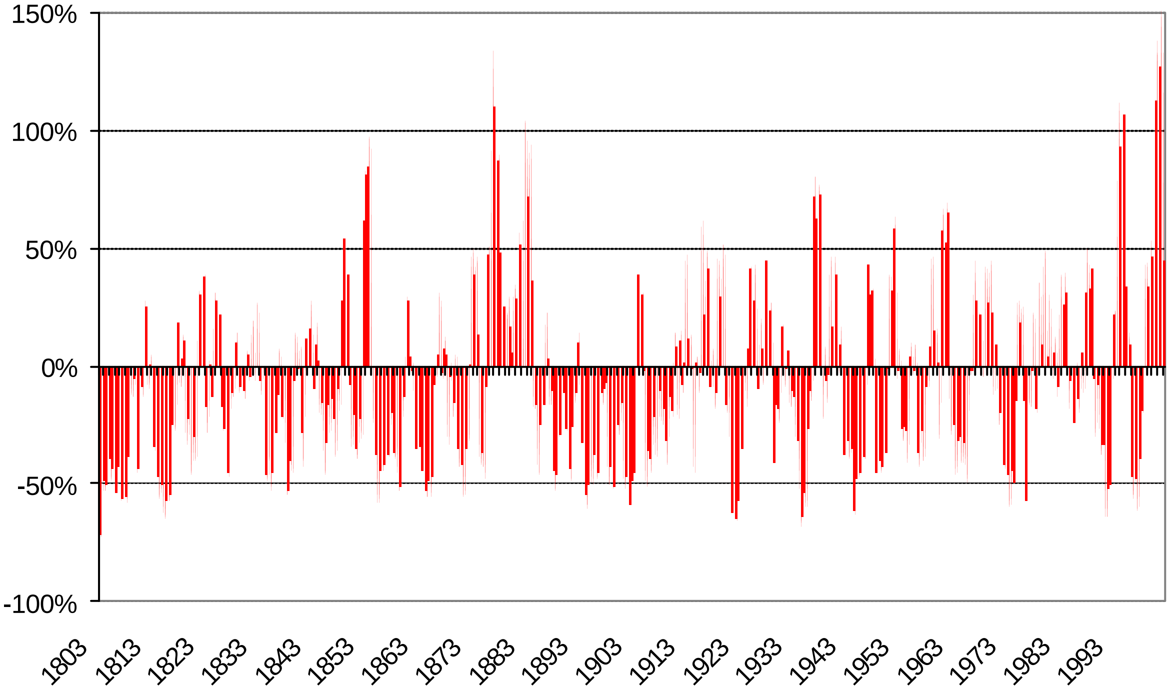


Figure 3.2: (a) Eighteen-month flow deficits with respect to the 1961-90 average for the Ely Ouse at Denver Sluice (synthetic flow series); (b) six-month flow deficits with respect to the 1961-90 average for the River Eden at Temple Sowerby (synthetic flow series)



(b)

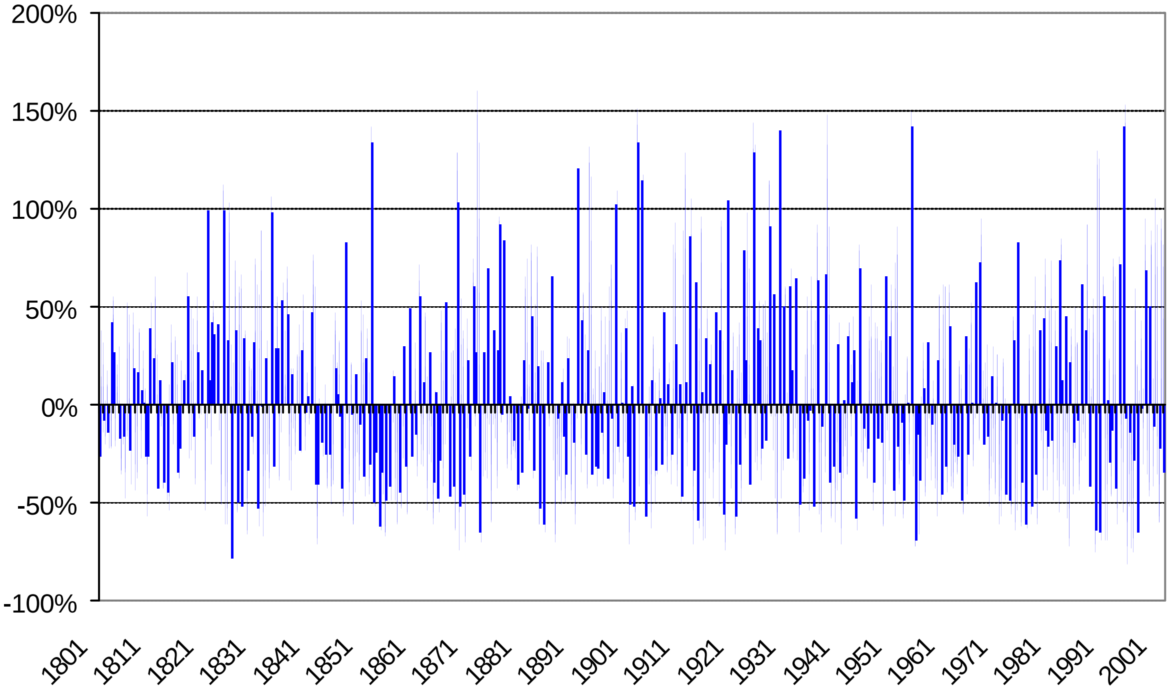
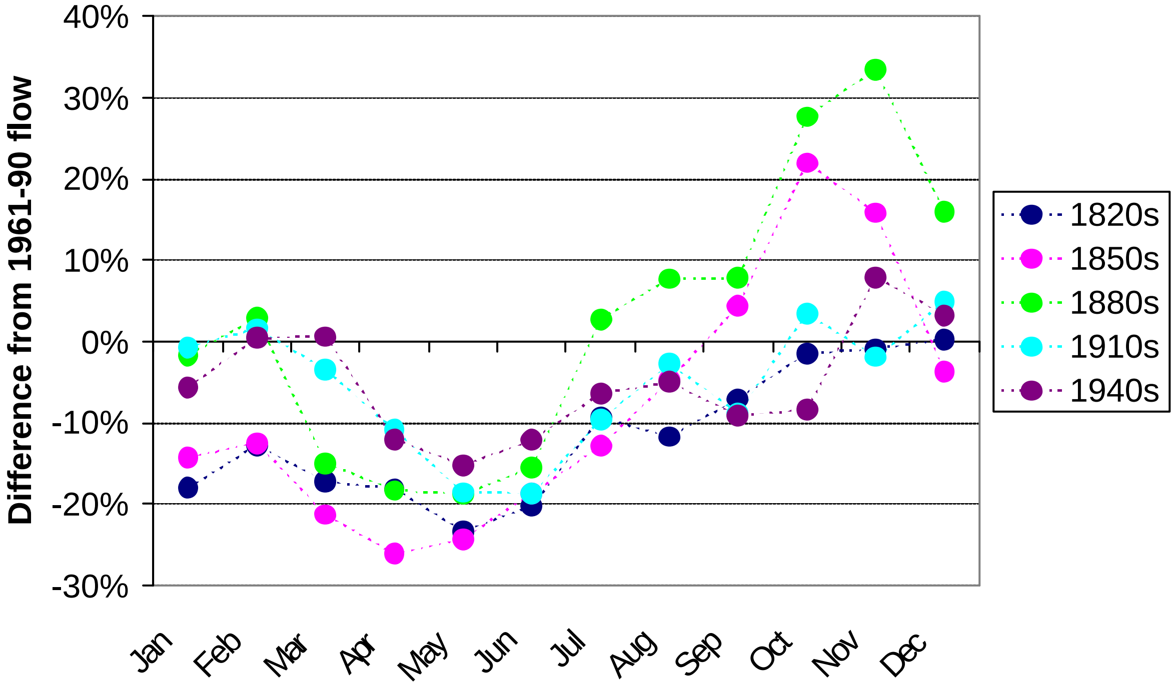


Figure 3.3: Characteristics of historical periods compared to the 1961-90 period for the Ouse at Denver Sluice: (a) monthly differences in flow; (b) differences in average flow. (For each plot the data describes 30-year blocks centred on the listed decade)

(a)



(b)

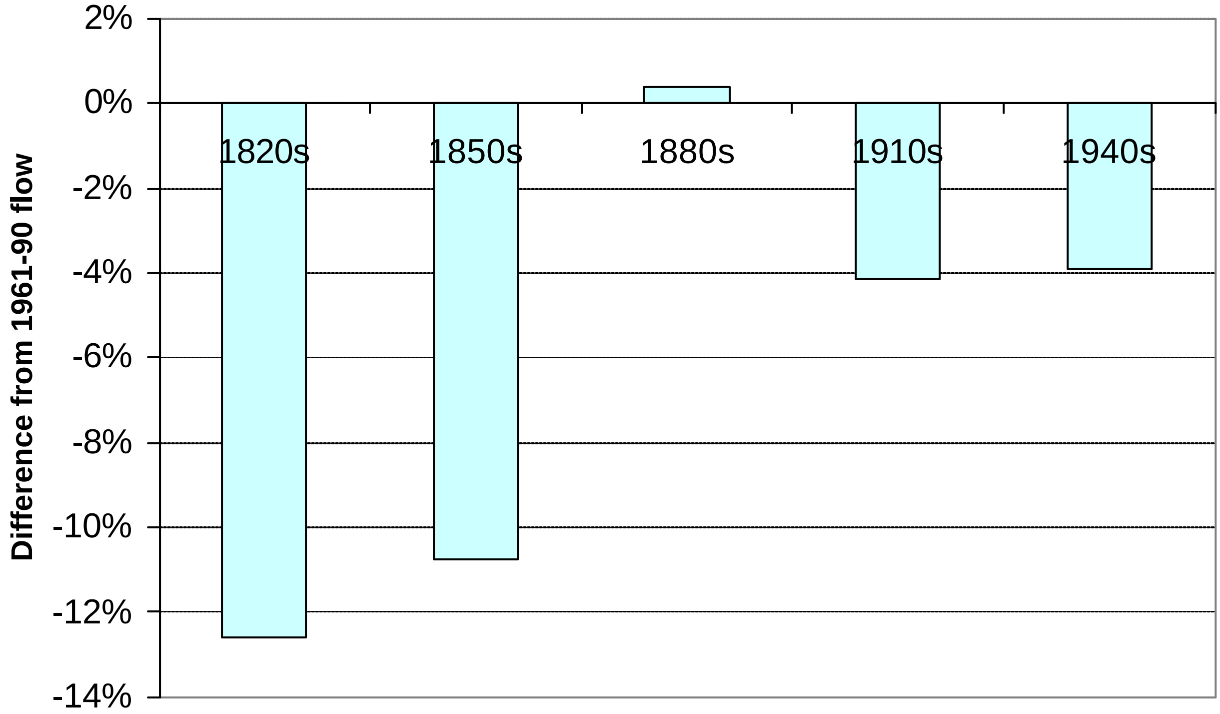
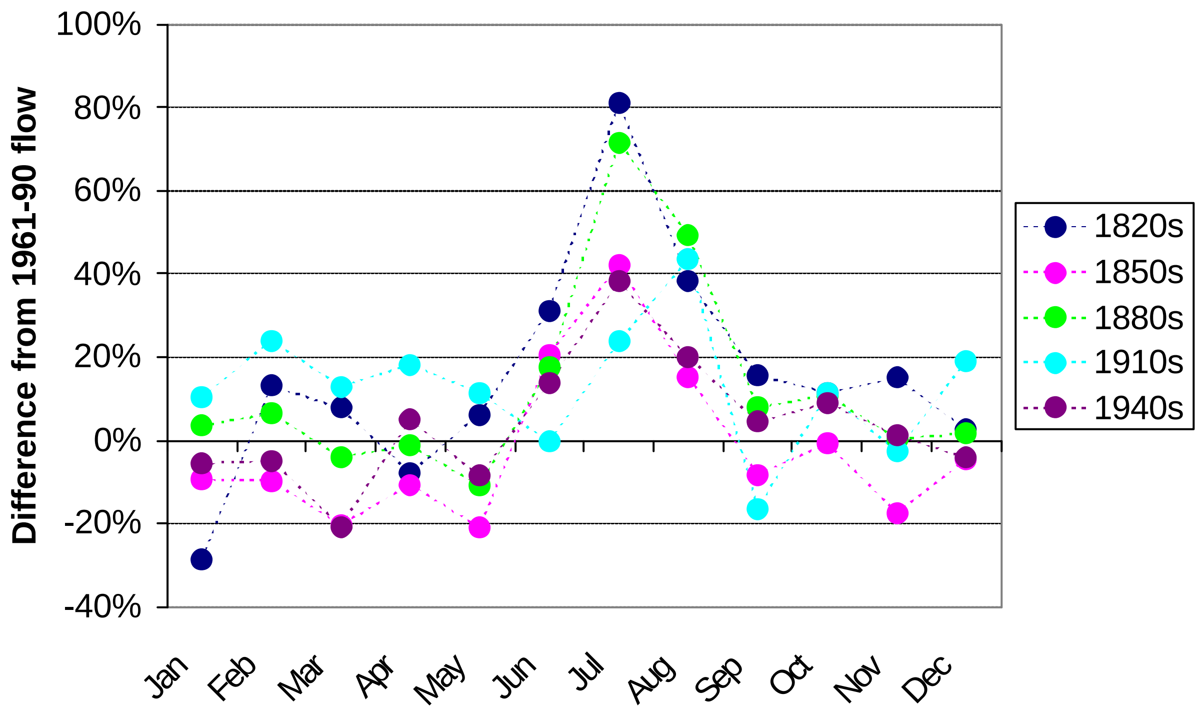
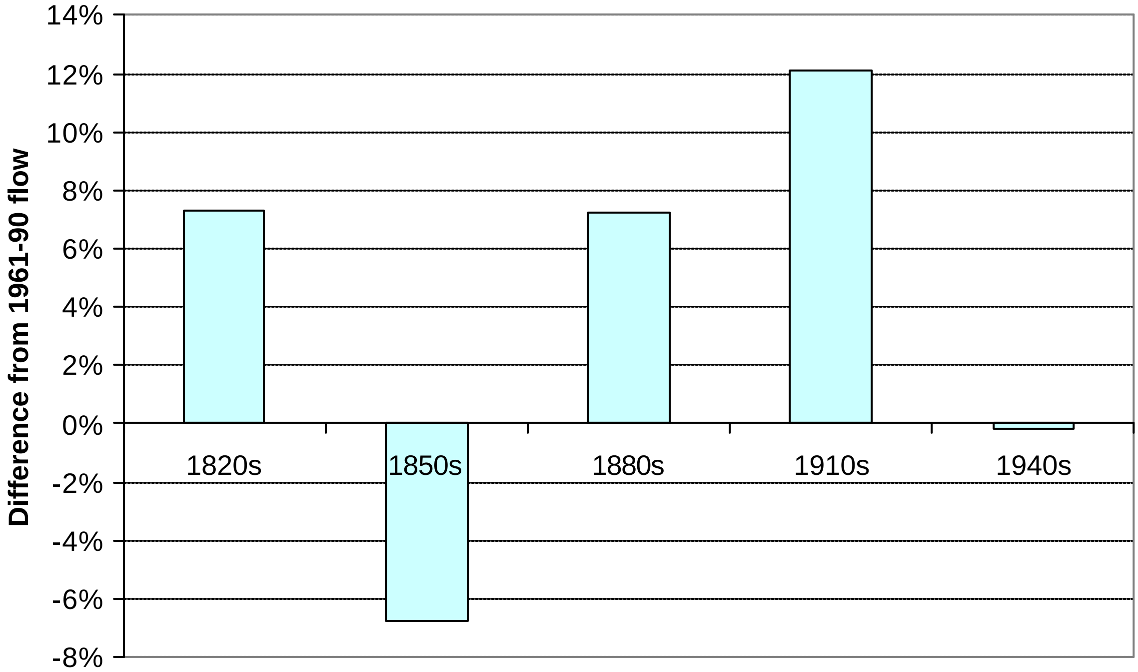


Figure 3.4: Characteristics of historical periods compared to the 1961-90 period for the River Eden at Temple Sowerby: (a) monthly differences in flow; (b) differences in average flow. (For each plot the data describes 30-year blocks centred on the listed decade)





4 East of England case study

4.1 Background

This case study was based on an area in Eastern England covering parts of Cambridgeshire, Northamptonshire and Bedfordshire and the town of Milton Keynes. This area forms Anglian Water's Ruthamford water resources zone that includes the river catchments of the Great Ouse, Welland and Nene. Water is abstracted from these rivers and stored in a number of reservoirs including Grafham, Rutland, Pitsford, Ravensthorpe and Hollowell. These sources form the basis of this case study.

Anglian Water's supply area is located in the driest part of England, with a regional annual average rainfall of just 600 mm, significantly lower than the Thames catchment with 688 mm and catchments within the Southern Region with 776 mm of annual rainfall (Marsh and Lees, 2003). This low annual rainfall means that the water balance is vulnerable to warm and dry years with high evaporation and/or low rainfall. The case study catchments are groundwater-influenced and have a slow response to changes in effective rainfall. Therefore, the rivers are vulnerable to prolonged periods of rainfall drought lasting for several seasons or years.

Anglian Water aims to maintain a good level of service (LoS) to water customers that avoids the need for restriction or emergency supplies in most drought situations. For water resource modelling purposes, the following LoS are considered:

Demand restriction:	Frequency not more than:
Hosepipe bans	1 in 10 years
Restrictions on non-essential use	1 in 40 years
Emergency supplies (standpipes)	1 in 100 years

Investment in the water supply system since privatisation in 1989, including the development of a more integrated system, operational improvements and the development of new sources, means that the water company is less vulnerable to a drought than in the past. The last hosepipe ban was during the 1990/91 drought and the company managed the drought of 1995 without the need for restrictions. New development in the region in some 'hot-spots' (Figure 4.1) places pressure on the supply-demand balance during droughts, and further investments and drought planning are required to maintain supplies and protect the environment.

The Anglian Water Services Drought Plan (AWS, 2003) provides background on previous droughts and how the company manages drought conditions through demand and supply-side measures including the use of publicity campaigns, demand restrictions and local emergency water supplies. The company considered climate change in its last water resources plan based on the UKCIP02 scenarios (Hulme *et al*., 2002), data provided by UKWIR (UKWIR, 2003). The net impact on reservoirs was a loss of yield of around 10 per cent by the 2020s (AWS, 2003).

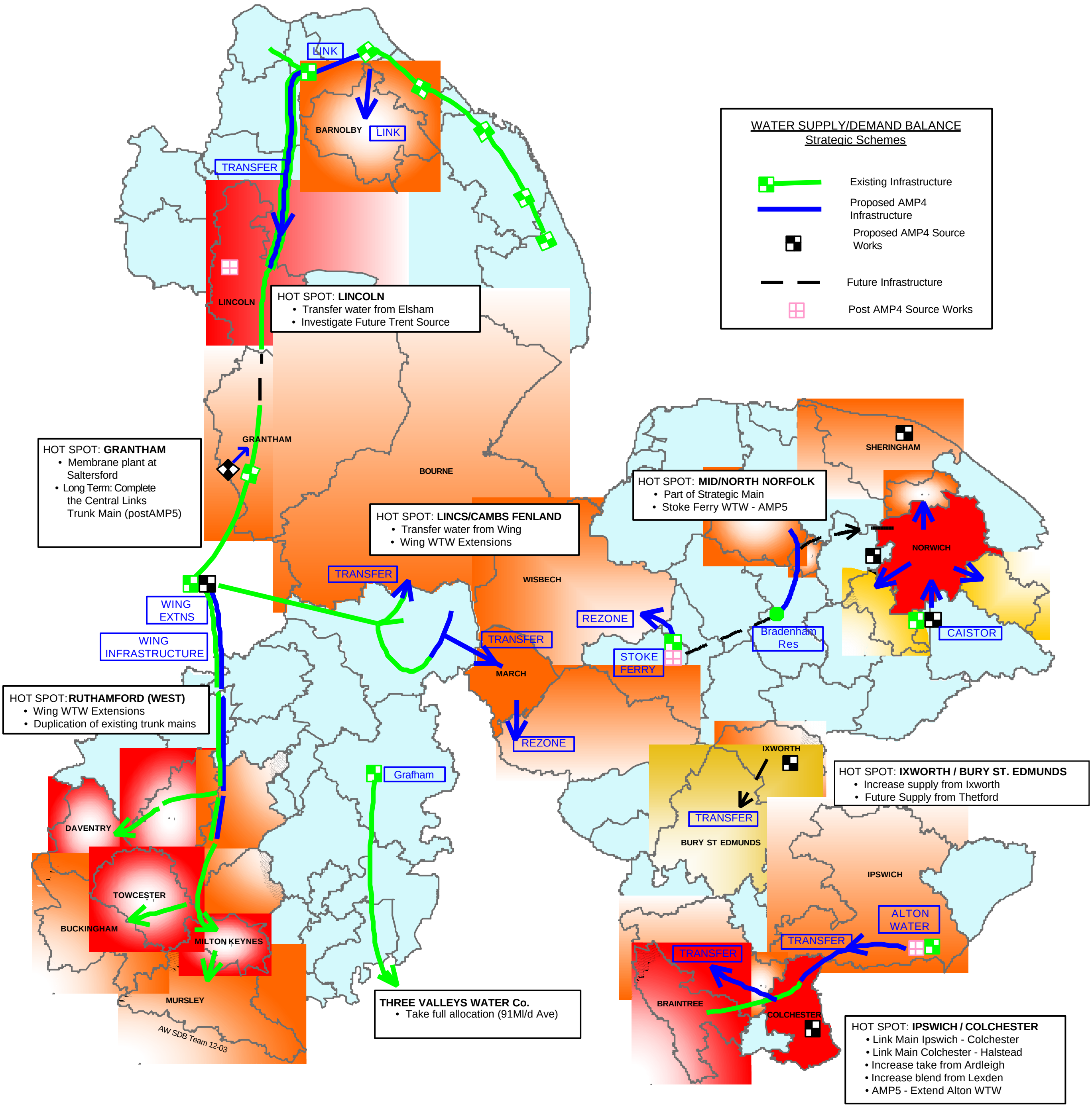


Figure 4,1: Map showing Strategic Water Supply Schemes in Anglian Water's supply area (Source: Anglian Water Services Water Resources Plan Digest, 2003). http://www.anglianwater.co.uk/assets/WRP04final.pdf)

4.2 Methods

The climate change impact assessment involved applying ‘perturbed’ river flow time series (Section 3) to a spreadsheet reservoir model. This was used to estimate the impact of climate change on the deployable outputs of each resource and identify any changes to system ‘behaviour’ in response to past and future droughts that were not previously considered in water resources or drought planning. The spreadsheet model was developed to model each source in a similar way to Anglian Water’s OSAY model (Section 4.3) and is described in Appendix 2. The model was applied in detail to Grafham, Pitsford, and Ravensthorpe and Hollowell and for selected runs for Rutland Water.

Each reservoir model was run independently using the following input data series:

1. Anglian Water’s naturalised river flows from 1920 to 2002, based on outputs of the Stanford Watershed Model (SWM).
2. Reconstructed river flows, based on the methods described in Section 3, for the period 1920 to 2002, to provide a direct comparison with the existing data.
3. Reconstructed river flows, based on the methods described in Section 3, for the period 1801 to 2002, to demonstrate the impacts of hindcasting the series to include the major droughts in the early nineteenth century.
4. Reconstructed and ‘perturbed’ river flows providing 200-year flow records for the 2020s, 2050s and 2080s, based on application of predictions from the three RCMs to the hydrological model as described in Section 3.

The spreadsheet model was run in ‘no restrictions’ mode, based on unfettered water demand. Some additional OSAY runs were set up for LoS runs, based on the criteria described in Section 4.1.

The impacts of adopting a different modelling approach were estimated by comparing (1) and (2) and the impact of extending the time series by comparing (2) and (3). The impacts of climate change on yield were estimated by comparing the results of (3) and (4). Finally, the results were reviewed to examine how the ‘behaviour’ of the reservoirs changed in response to different drought conditions.

4.3 The OSAY model

The OSAY model calculates the water balance of the reservoir based on river flows, licence conditions, pump capacities, reservoir characteristics and target level of service. This kind of model is often described as a behavioural model. For ‘no restrictions’ runs, it works by running the water balance, subject to the above constraints, and increasing the demand for the water until the reservoir is empty or reaches a defined level to estimate the average deployable output (ADO) for the ‘worst historical drought’ (WHD). This estimate is very sensitive to the length of record.

For ‘levels of service’ runs it searches for a demand that can be met when demand restrictions are put in place. The LoS ADO will be higher than the ‘no restrictions’ ADO because using restrictions will reduce the drawdown of the reservoir and prevent it from failing during the drought period. The details of the OSAY model are described in Clarke *et al*., (1980) and Page (1997) and the specific assumptions made in this analysis are summarised in Appendix 3.

An example of the inputs required is shown in Figure 4.2 and example outputs in Figure 4.3. The reservoir drawdowns in Figure 4.3 show the predictions for Grafham Reservoir from the reconstructed historical time series and the HadRM3H scenario. In both cases the prolonged impact of drought in the early 1800s is evident. The coloured bars indicate the use of drought restrictions and in both runs the model outputs show that year-on-year restrictions (for six years), from hosepipe bans to standpipes, would be required for such a long duration drought. These results illustrate a common theme in the HadRM3H results - the overall deployable output declines or remains unchanged but the length of restrictions decreases because the higher winter flows in the scenarios tend to terminate drought conditions sooner than the historical sequences.

Figure 4.2: An example of the data inputs required for the reservoir yield analysis using the OSAY software

SURFACE WATER YIELD ANALYSIS
Date 13/11/2009 Time: 20:38
Page 1

Grafham Yield Calculation
EA Severe Droughts Project - CRU HADLEY 2050 LEVELS OF SERVICE (Scen 3)

Reliability criterion:	LEVELS OF SERVICE	Scaling factor for demand	1.01
Timestep:	DAILY	Scaling factor for demand restrictions	1
Calculation type.	SENSITIVITY	Amount control curves raised (MCM)	-8
Control Data File:	C:\...\GRA50HA3.CTL	Daily Simulation:	SELECTED
		Outage:	NOT SELECTED

CONTROL DATA

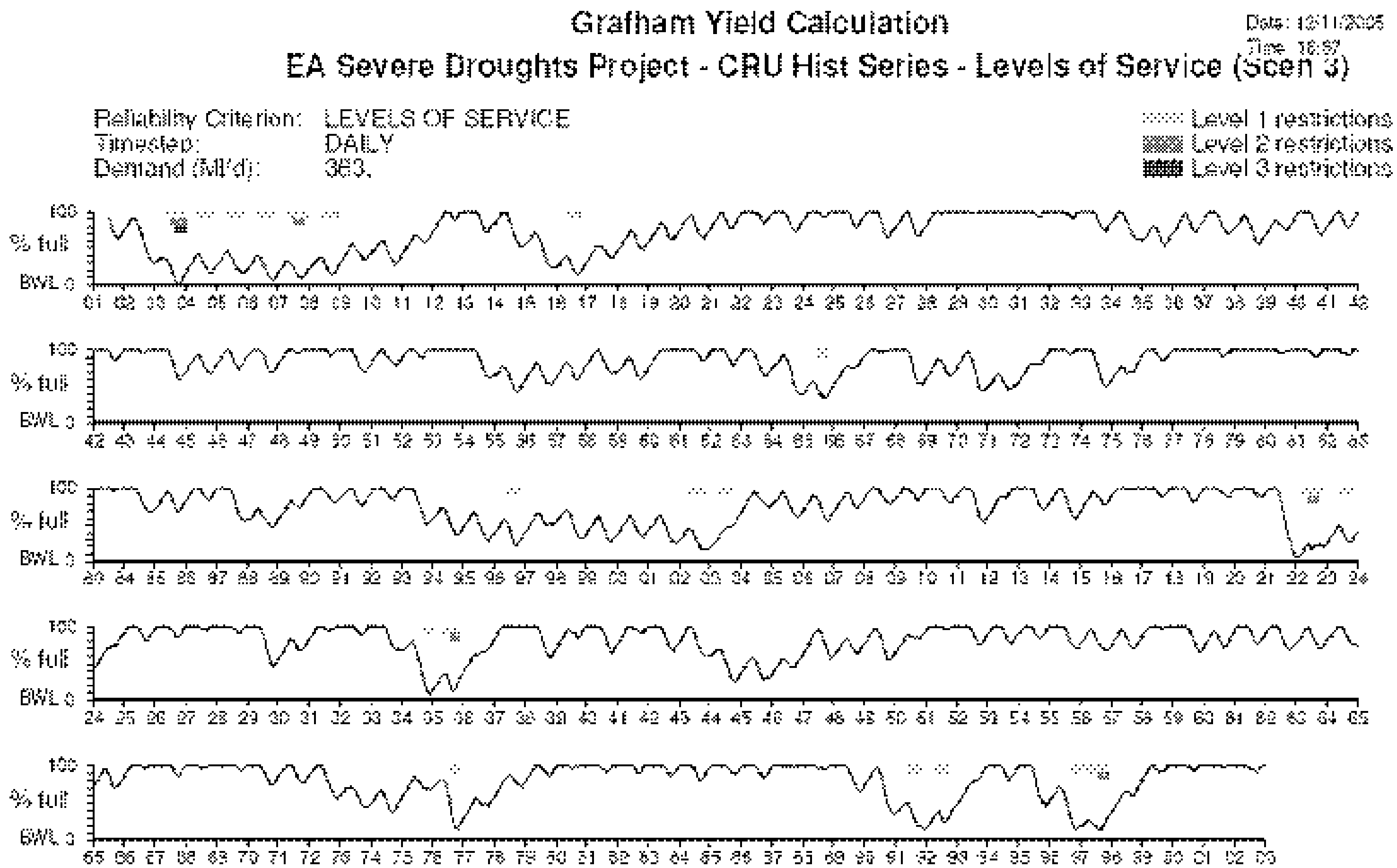
TITLES: Grafham Yield Calculation / EA Severe Droughts Project - CRU HADLEY 2050 LEVELS OF SERVICE (Scen 3)

Reservoir capacity (MCM)	53.96	Number of augmentation levels	1
Reservoir dead storage (MCM)	2.65	Number of restriction levels	3
Emergency storage (MCM)	0	Target return periods	1: 10; 2: 40; 3: 100
Starting storage (MCM)	50	Minimum duration of each restriction (months)	3
'Risk' drought severity (Return Period or 'WRD')	WRD	Max number of months to count as one event	12
Maximum drought length (months)	24	Scaling factor for 'worst months' no pumping	0
Data Prep File	C:\...\GRAF50HA.DAT	Scaling factor for 'plan' inflows	1
Monthly Flow File	C:\...\GRAF50HA.MFL	X Margin required before restriction lifted	
Daily Flow File	C:\...\GRAF50HA.DFL	X Monthly target levels required	

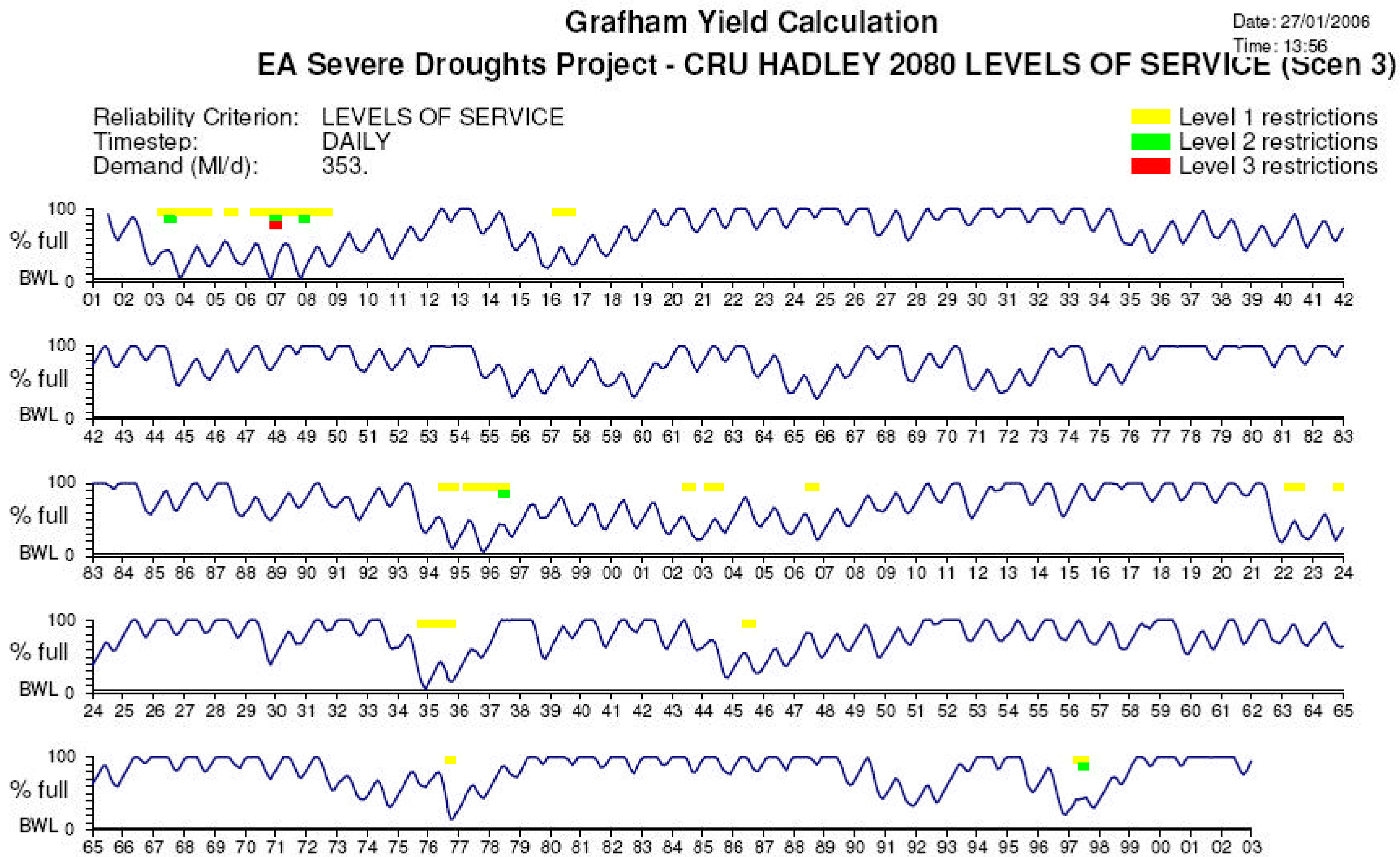
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DEMAND FACTORS	1.00	1.00	.97	.97	1.00	1.06	1.11	1.07	.95	.92	.95	1.00
DEMAND REDUCTION FOR EACH LEVEL OF RESTRICTION												
Level 1	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05
Level 2	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10
Level 3	.34	.34	.36	.42	.48	.52	.52	.48	.46	.42	.36	.34
TARGET LEVELS (%)	100	100	100	100	100	100	100	100	100	100	100	100

Figure 4.3: Example of outputs showing variations in reservoir water storage for a 203-year simulation based on (a) synthetic historical flow series and (b) modelled river flows using Hadley Centre RCM changes in precipitation and evapotranspiration. Note that the 'demand' is the demand that could be met and is therefore equivalent to source yield.

(a)



(b)


Grafham Yield Calculation
Date: 27/01/2006
Time: 13:56
EA Severe Droughts Project - CRU HADLEY 2080 LEVELS OF SERVICE (Scen 3)
Reliability Criterion: LEVELS OF SERVICE
Timestep: DAILY
Demand (Ml/d): 353.
Level 1 restrictions
Level 2 restrictions
Level 3 restrictions
100
% full
BWL 0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42
42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83
83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65
65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03

In the following sections, the average changes in monthly precipitation, PET, flows and reservoir yields are summarised in a series of figures. The precipitation and PET plots compare the selected RCMs with similar data based on the UKCIP02 scenarios. Detailed results are shown in Appendix 4.

4.4 Changes in precipitation and PET for the Ouse

Figures 4.4 and 4.5 show changes in monthly precipitation and PET for different climate change scenarios for the 2020s. Changes in precipitation for the Ouse based on ARPEGE and HIRHAM follow a similar pattern but changes in summer are less extreme than the UKCIP02 scenarios. The HadRM3H data are different from the UKCIP02 medium high scenario that is based on the same model and emissions scenario. This is because the data cover marginally different catchment areas, is subject to different forms of spatial interpolation and finally, PET was estimated using a Penman Monteith formula for the UKCIP02 scenarios whereas the Thornwaite formula was used for the HadRM3H model.

The subtle changes in seasonality between the three RCMs are important because these translate to larger differences in seasonal flow characteristics as discussed in Appendix 1. Changes in PET for the three RCMs are less than the UKCIP02 scenarios but changes in winter relate to very small increases in mm/day.

Finally, changes in AET are particularly important in lowland catchments in the East of England where the effective rainfall (P minus AET) is low. Increases in AET can have a large impact on flows and this was evident in the Ouse flow modelling, where the ARPEGE model produced the lowest flows despite being the wettest model, due to increases in AET from March to August that reduced effective rainfall more than in the HadRM3H and HIRHAM models (Appendix 1).

Figure 4.4: Comparison of monthly precipitation change factors for the 2020s, three RCMs for the Ouse at Denver Sluice and UKCIP02 data for the Ouse CAMS based on the UKCIP02 scenarios

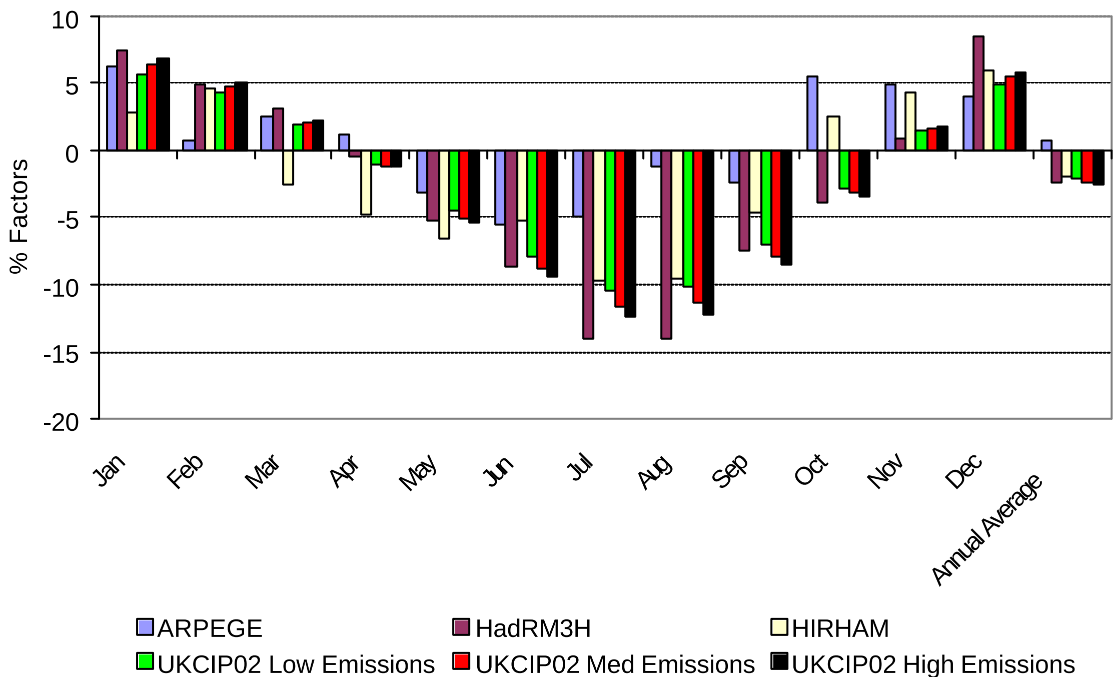
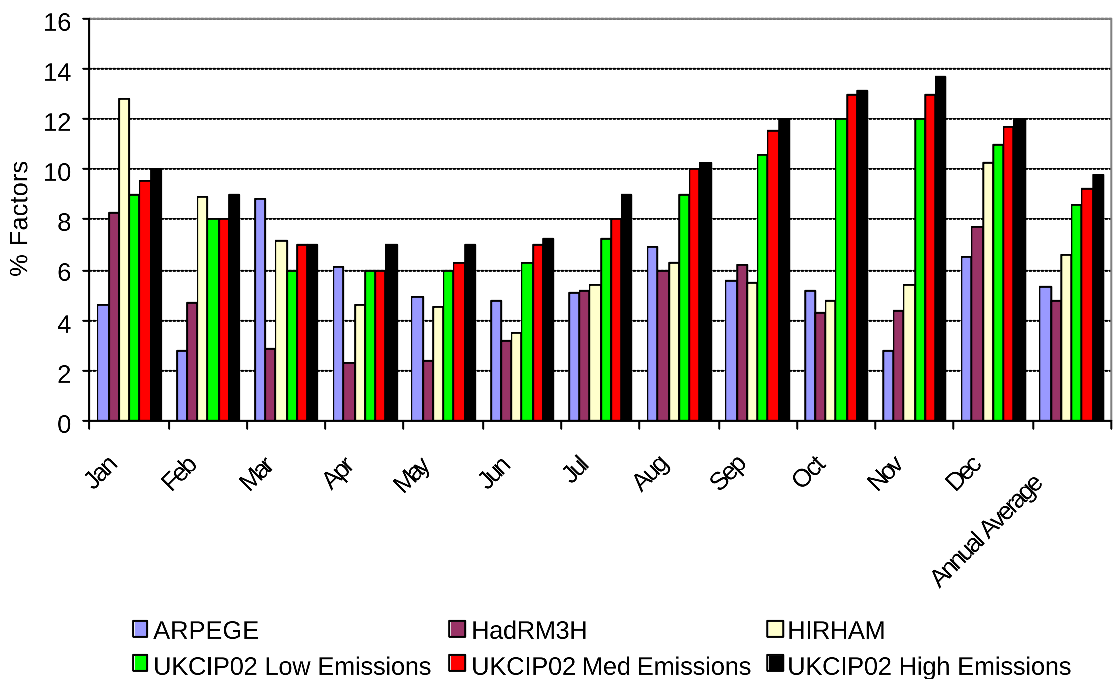


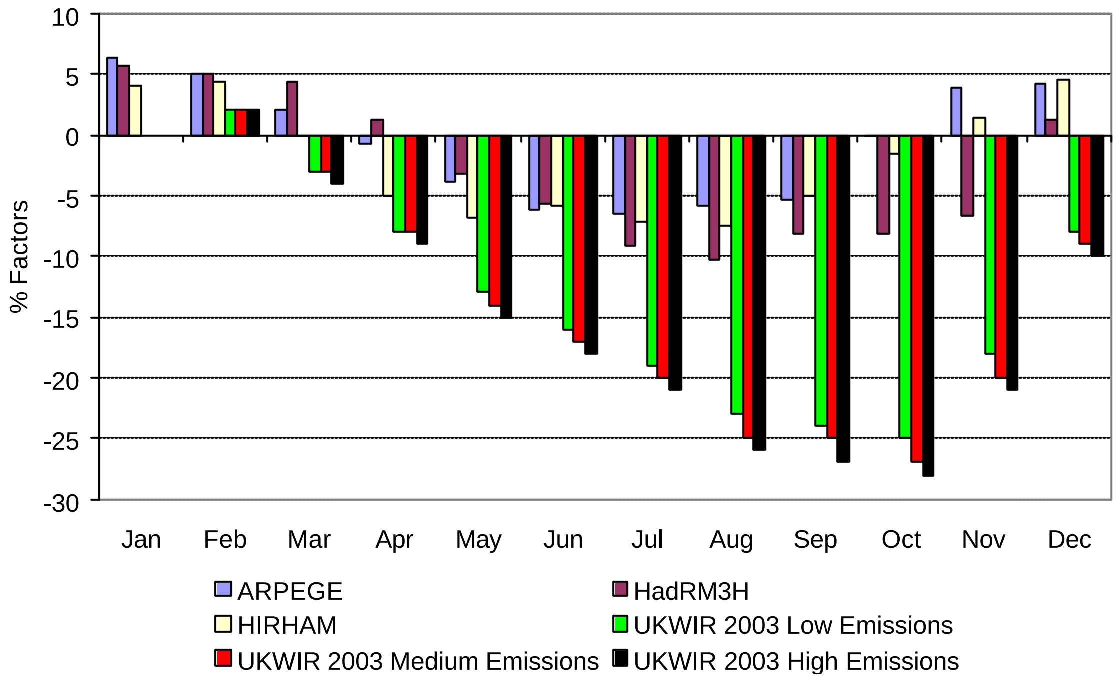
Figure 4.5: Comparison of monthly PET change factors for the 2020s, three RCMs for the Ouse at Denver Sluice and UKCIP02 data for the Ouse CAMS



4.5 Changes in river flows for the Ouse

Figure 4.6 compares the changes in average monthly flow based on the models developed in this project to the standard Anglian Region run-off factors (UKWIR, 2003). The latter factors were based on the average results of several PDM rainfall run-off models within Anglian Region (UKWIR, 2003). The outputs of this study indicate higher winter flows and smaller reductions in summer flows compared to the UKWIR river flow factors.

Figure 4.6: Comparison of monthly flow change factors for the 2020s, three RCMs for the Ouse at Denver Sluice and UKWIR 2003 Anglian Region run-off factors



4.6 Changes in yield

Changes in deployable output (or yield constrained by licence and pump capacities) for the different scenarios are shown in Figure 4.7 to 4.13 and in Appendix 3. The first three figures show the impacts of climate change on the DO for Grafham, Pitsford and the Ravensthorpe and Hollowell models respectively. For the 2020s, the impacts are generally within plus and minus two per cent, indicating that any reductions in summer flow are balanced by increases in winter. However, minus two percent is a significant impact for Grafham, equating to a reduction in yield of seven million litres per day (Ml/d).

Figure 4.7: Grafham percentage yield changes from CRU 1801-2002 series to CRU 1801-2002 RCM series

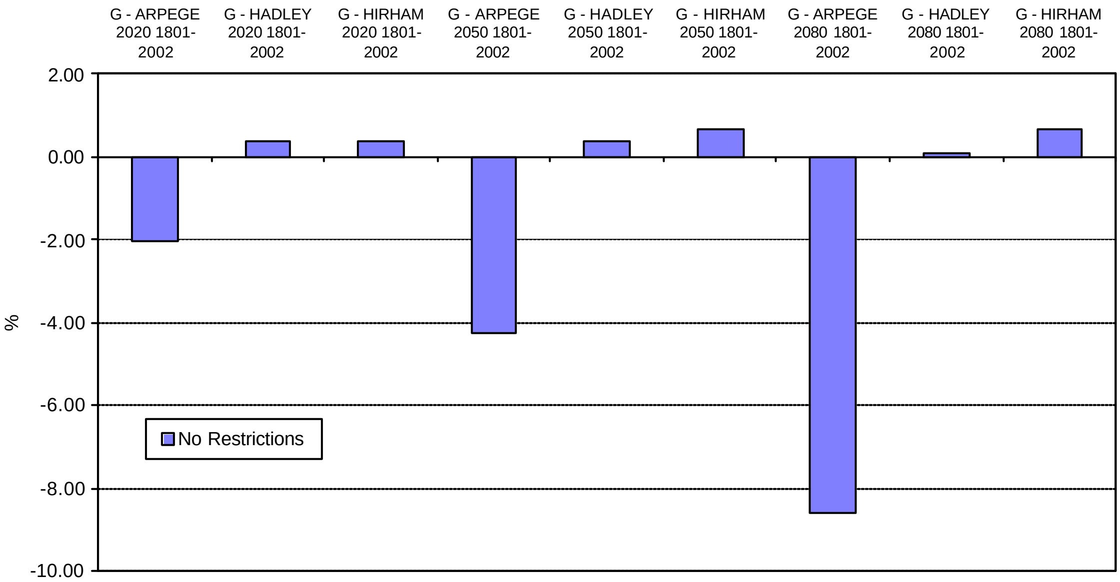


Figure 4.8: Pitsford percentage yield changes from CRU 1801-2002 series to CRU 1801-2002 GCM series

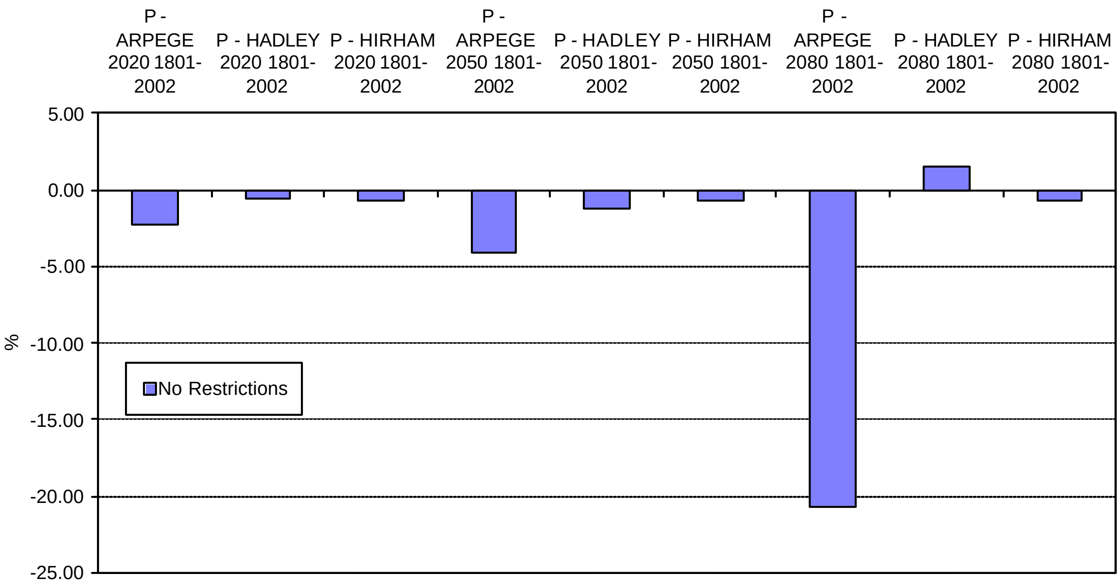


Figure 4.9: Ravensthorpe and Hollowell percentage yield changes from CRU 1801-2002 series to CRU 1801-2002 GCM series

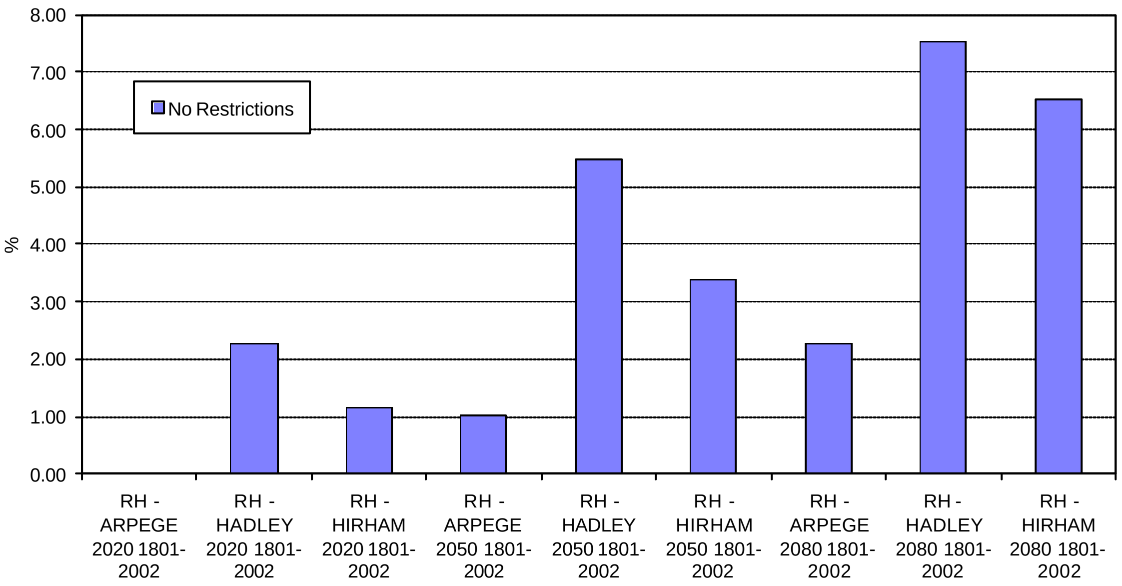


Figure 4.10: Overview of impacts on reservoir yields for the 2020s climate change scenarios in millions of litres per day (Ml/d)

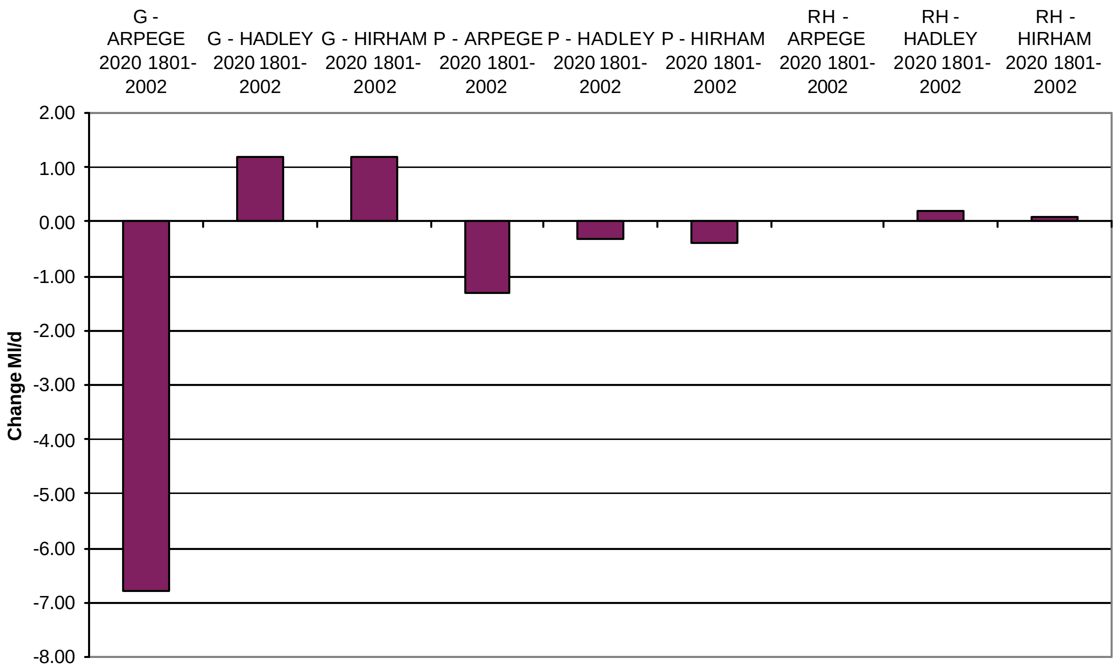
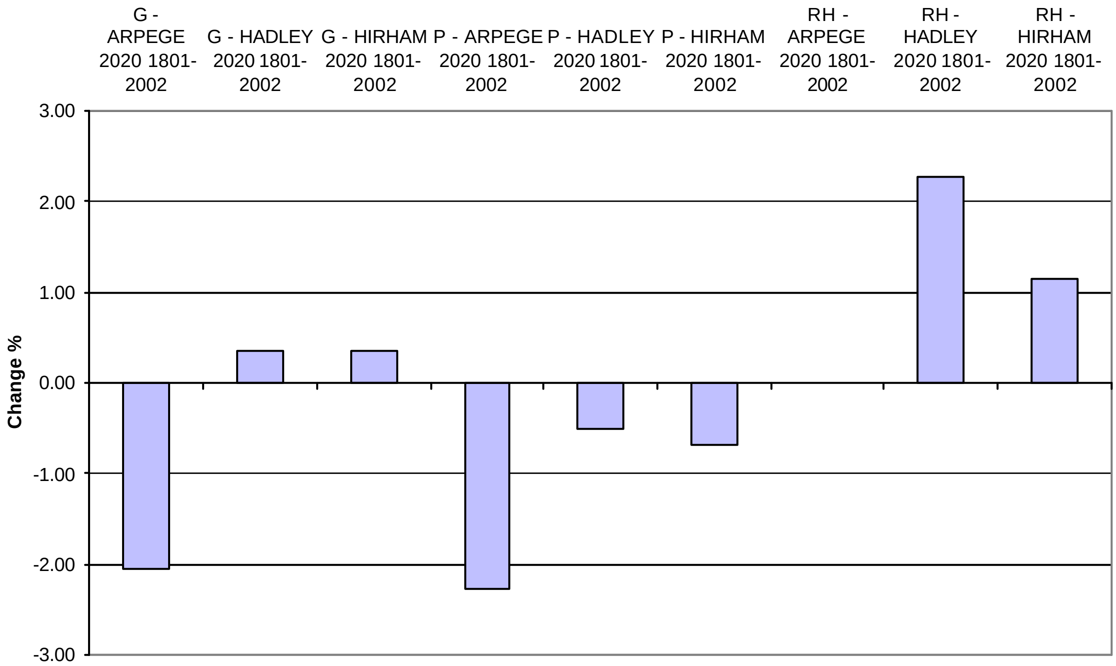


Figure 4.11: Overview of impacts on reservoir yields for the 2020s climate change scenarios – per cent change



As shown in Figure 4.10, the net impact by the 2020s on the entire reservoir group ranges from a reduction in yield of eight Ml/d to an increase in one Ml/d depending on the RCM scenario. This study has not estimated the social or economic consequences of these changes, but if a further resource was required to provide eight Ml/d by 2025 the costs could be of the order of £8 million to £16 million. Due to the uncertainty in the results, this level of investment based on one emissions and climate scenario (ARPEGE model and A2 emissions) would be unwise.

Current water industry planning approaches include the use of the concept of 'headroom' to consider a range of uncertainties related to future supply and demand forecasts. With the headroom method, reductions in yield due to climate change would be considered as a statistical distribution of losses in yield with the ARPEGE model included as the maximum and 'no change' considered as the minimum. For water resource planning and drought management, a full appraisal of options is required that considers a wide range of drought risk management measures and the uncertainties related to climate change.

4.7 Hydrological uncertainties

The results of the different runs also provide information on the uncertainty related to the use of different data sources and hydrological models on estimates of yield. Figure 4.12 shows the apparent increases in yield based on the reconstructed 1920-2002 river flows rather than Anglian Water's time series based on their own modelled river flows. These differences are greater than those in the climate change runs, indicating that for this case study hydrological uncertainty is greater than climate change uncertainty.

Hydrological uncertainty includes the choice of methods, hydrological model to convert changes in rainfall and evaporation into run-off and the uncertainty in the parameters of the chosen model. The length of record selected for analysis will affect estimates of yield in the same way that the length of record influences peak flows in flood risk studies. Different models and alternative sets of parameters may be able to satisfactorily reproduce past river flows but will respond differently to changes in climate and predict different changes in flows and source yields. As this case study shows, these uncertainties can be large and therefore should be considered in detailed studies that assess the impacts of climate change on river flows for water resource planning.

Figure 4.13 illustrates the effect of extending the analysis back to 1801 to include major droughts in the nineteenth century. For all reservoirs this reduces yields for the 'no restrictions' run as expected, due to the inclusion of 1803 and 1808 droughts.

Figure 4.12: Per cent yield changes from AWS 1920-2002 series to CRU 1920-2002 series – illustrating the effect of hydrological modelling uncertainty

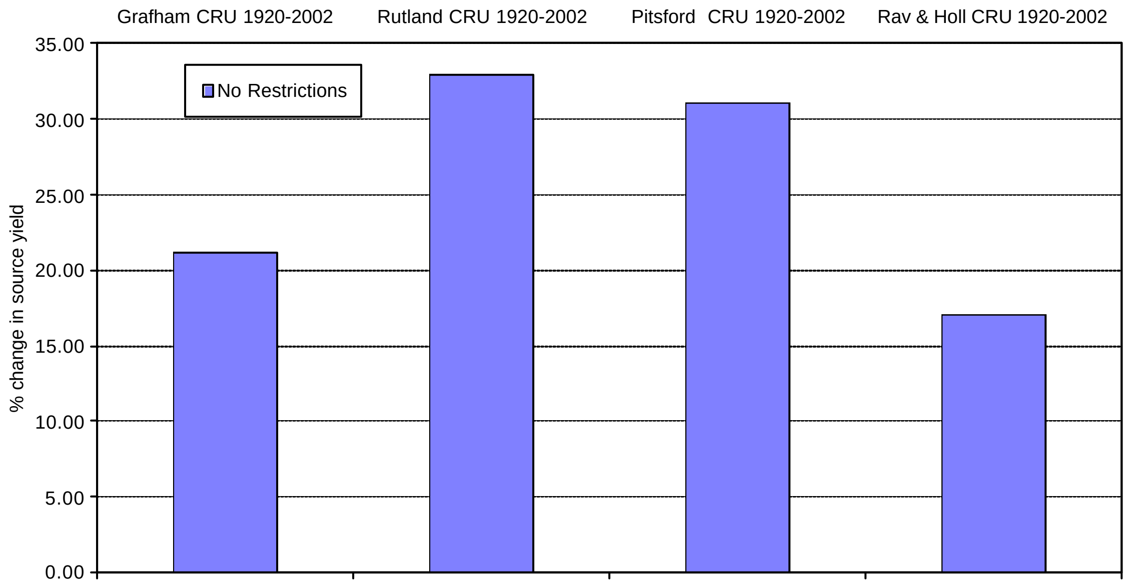
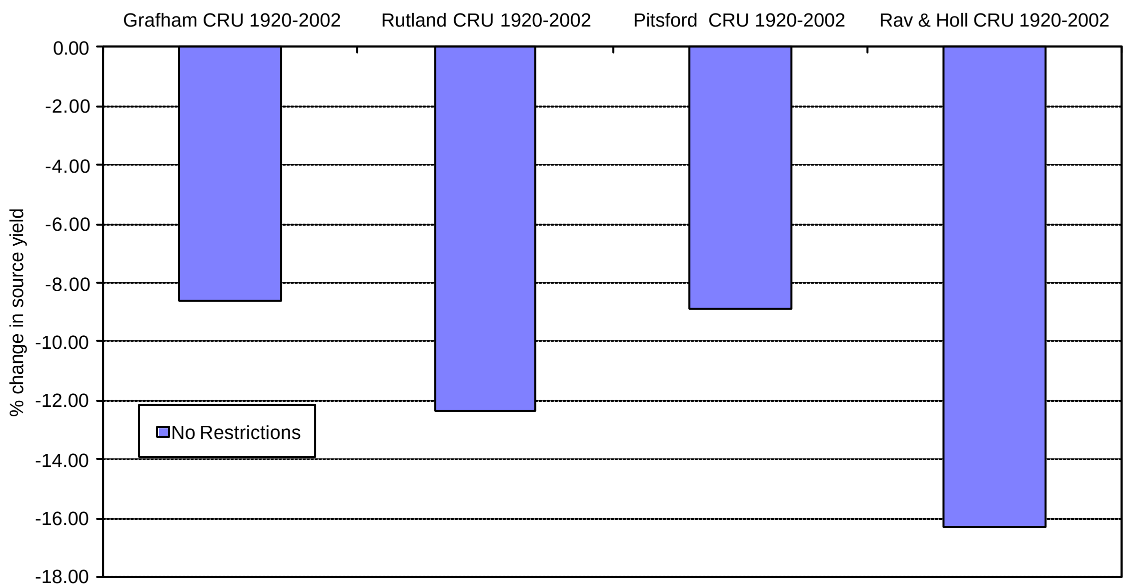


Figure 4.13: Per cent yield changes from CRU 1920-2002 series to CRU 1801-2002 series – illustrating the effect of extending records backwards or 'hindcasting' to include more severe historic droughts



4.8 Summary of case study results

Overall, the impact assessment for the Ruthamford system highlights a number of climate change uncertainties. The comparison of different climate change scenarios reveals differences between each RCM and between this sample of RCMs and the UKCIP02 scenarios currently used for water resources planning (UKWIR, 2003). Differences in rainfall and PET over several seasons affect both average monthly river flows and the minimum flows related to historical droughts (for example, see the seasonal flow time series in Appendix 1).

The net impact of climate change on the reservoir group yield, projected by three RCMs and for the 2020s, varies from minus eight Ml/d to plus one Ml/d. The impact on individual sources is approximately +/- two percent of yield but this equates to a significant yield change at Grafham.

Given that the selected RCMs had wetter winters than the UKCIP02 scenarios, it is not surprising that this impact is less than the average 10 per cent reduction in reservoir yield derived by applying the UKCIP02 scenarios to all of Anglian Water Services reservoirs.

In the longer term, the modelling results suggest large reductions in yield for Grafham and Pitsford for the ARPEGE RCM. However, models suggest an increase in yield for the Ravensthorpe and Hollowell system, due to specific reservoir characteristics such as licence conditions and pump volumes.

The analysis does not compare the ‘skill’ of individual RCMs or the hydrological models, so no conclusions can be drawn on the relative weights that should be given to the different outputs. Nevertheless the range of uncertainty is wide and should be considered in long-term water plans.

There are large differences in reservoir yields depending on the data and hydrological modelling approach used. This is demonstrated by the differences in yield obtained when using the reconstructed flows for 1920-2002 compared to Anglian Water’s own river flow time series that is a mixture of observed data, hindcast to 1920 using a conceptual rainfall run-off model. For this case study, hydrological uncertainty is larger than the uncertainty related to using different RCMs for the 2020s.

Each reservoir model responds differently to the climate change scenarios due to their characteristics and licence constraints. Grafham has significant reductions in yield increasing from the 2020s to 2080s for the ARPEGE scenarios. Rutland and Pitsford may have reductions or increases in yield depending on the choice of RCM. These differences are due to reservoir characteristics, including licence constraints, river intake and reservoir storage capacity. Policy or operational changes to licensing rules could be an option for increasing yields, making the most of the increased winter run-off without damaging the environment. This requires further investigation by completing a sensitivity analysis of the reservoir models.

The net impact by the 2020s is a reduction in yield for one climate change scenario, but no significant changes for the other two climate scenarios.

5 North West region case study

5.1 Background

This case study was based on Ennerdale Water and Crummock Water in West Cumbria that supply water to the towns of Whitehaven and Workington and the surrounding areas (Figure 5.1). Ennerdale Water drains to the River Ehen. Crummock Water drains to the River Cocker and then into the Derwent at Cockermouth. The characteristics of the lake catchments and the River Eden, which was used to develop a long-term synthetic flow record, are summarised in Table 5.1. These smaller lake catchments have much ‘flashier’ hydrological responses than the lowland reservoir examples in the East of England and the River Eden. This has a bearing on the drought plans for the West Cumbria resource zone (see below) and the results of the water resources modelling (Section 5.6).

Table 5.1: Characteristics of the case study lake catchments and the River Eden

Station number	Station	Catchment area km^2	Baseflow index	Mean annual run-off mm
074003	Ehen @ Bleach Green	44.2	0.35	853
0175016	Cocker @ Scalehill	64.0	0.40	530
076005	Eden @ Temple Sowerby	616.4	0.38	738
076002	Eden @ Warwick Bridge	1366.7	0.50	785

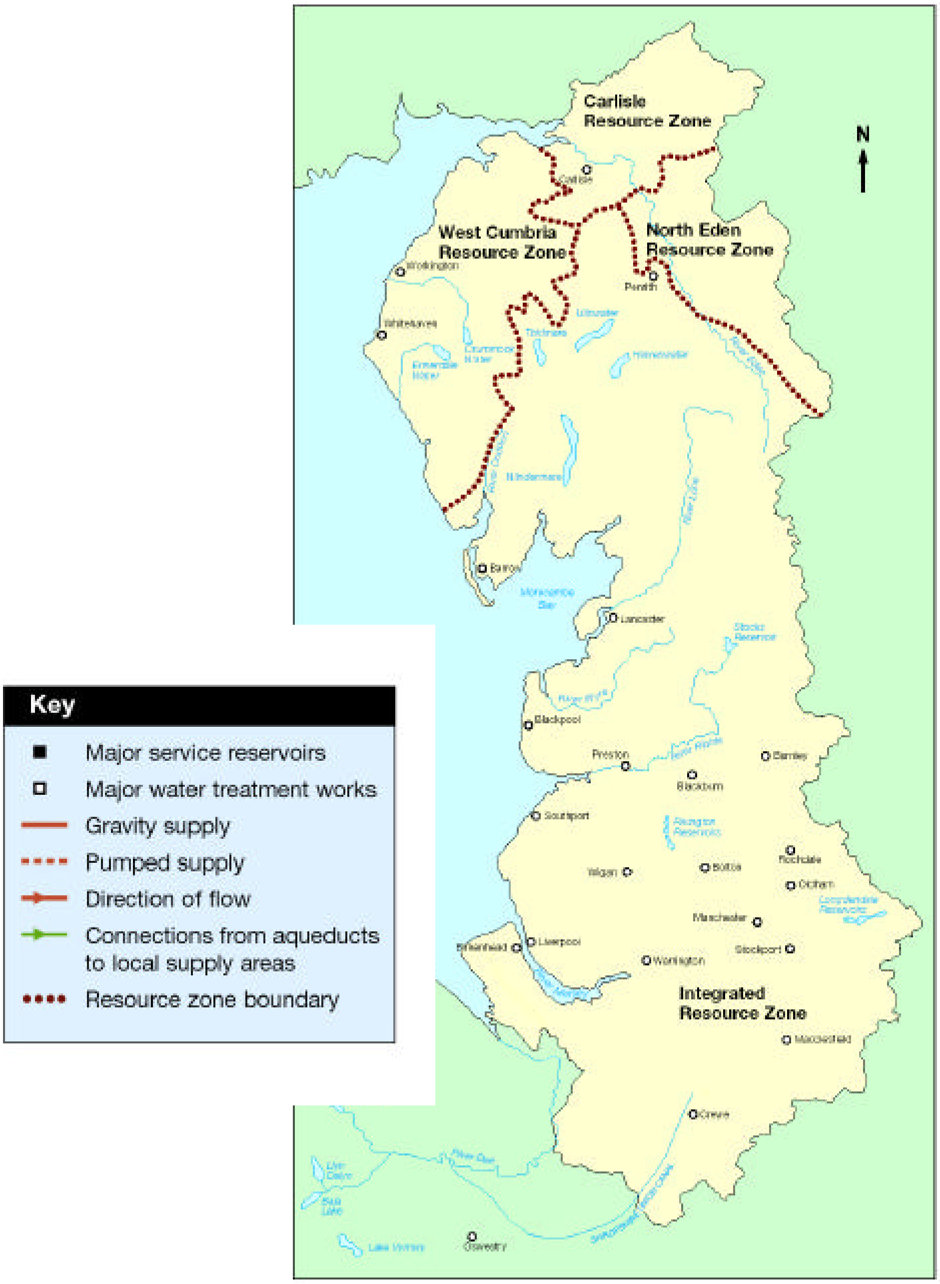
The rivers Eden, Ehen and Derwent are Special Areas for Conservation (SACs) and Ennerdale Water and Crummock Water are important environmental, landscape and amenity features, as well as critical sources for public water supplies.

Climate change was considered in United Utilities’ latest water resources plan (United Utilities, 2004) based on the latest methods (UKWIR, 2003) and following Environment Agency water resources planning guidance (Environment Agency, 2003). For West Cumbria, the company’s impact assessment suggested a reduction in yield of six to seven per cent by the 2020s from the impacts of climate change (United Utilities, 2004).

United Utilities aims to operate a relatively high level of service and, for the purpose of water resource modelling, the frequencies of restrictions stated by the company are:

Demand Restriction:	Frequency not more than:
Hosepipe bans	1 in 20 years
Restrictions on non-essential use	1 in 35 years
Emergency supplies (standpipes)	Never

Figure 5.1: United Utilities regional supply network and water resource zones



In a drought situation equivalent to the worst drought on record, lakes within the case study area would be drawn down but large volumes of water would remain in each water body due to hydraulic and licence constraints. The water company was affected by the 1995 drought, prompting further investment to improve the security of water supplies. If future droughts prove more extreme there will be consequences for water supplies as well as the environment, and the water company has developed a detailed drought plan to manage these situations, involving different phases of drought management measures as set out in Table 5.2.

Table 5.2: United Utilities drought management measures

	Operational Actions	Customer Communication Actions	Regulatory Actions
Normal Operation	Continuous water resource monitoring. Operation of water sources according to control and operating rules	Maintain normal customer communications to promote water conservation, UU free leak repair service and *LeakLine*	Ongoing monthly water resources meetings with the EA
Trigger 1 **Prepare Drought Action Plan and Communications Plan**	Rezone water sources to supplement water supplies and conserve reservoir storage in the worst affected parts of the region	Prepare Drought Communications Plan Step-up media communications (e.g. increase issue of press releases)	Prepare Drought Action Plan with EA Set up UU/EA Drought Liaison Group English Nature liaison
Trigger 2 **Commence Drought Actions**	Bring reserve water sources into supply Target leakage detection and repairs in areas where the greatest demand savings could be achieved	Further enhance customer communications (e.g. UU Roadshows and issue of Saver Flush devices) to provide regular updates on the water resources situation and reinforce water conservation advice	Consider options for drought powers (e.g. hosepipe ban, prescribed uses order, drought permits) and discuss with EA and EN Discussions with EA, EN and DEFRA to agree environmental monitoring and mitigation actions
Trigger 3 **Intensify Drought Actions**	Bring all available licensed water sources into supply	Further enhance customer communications (e.g. adverts in newspapers) to explain seriousness of the supply situation and the actions being taken to safeguard essential water supplies + seek co-operation in minimising non-essential uses of water	UU-EA Director-level liaison established Prepare and apply for drought powers e.g. hosepipe ban, prescribed uses order, drought permits
Trigger 4 **Drought Powers in Place**	Consider use of non-commissioned sources	Further enhance customer communications (e.g. television and radio adverts) to explain the reasons behind the drought powers and need to comply with water use restrictions	Drought powers in place e.g. hosepipe ban, prescribed uses order, drought permits

5.2 Methods

The climate change impact assessment was based on applying 'perturbed' river flow time series (Section 3) to a spreadsheet model that calculates lake or reservoir water balance in the same way as the water company's reservoir model – MOSPA. The model runs were developed to estimate the impact of climate change on the yield of each resource and identify any changes to system 'behaviour' in response to past and future droughts that were not previously considered in water resources or drought planning.

Each reservoir model was run independently using a similar framework to the previous case study. The following inflow series were considered:

1) United Utilities own flow time series for Ennerdale and Crummock that are based on instrumental record from the 1950s to 2002 for the two reservoirs.
2) Reconstructed time series for the1950s to 2002 period for comparison to the 1800 to 2002 period.
3) Reconstructed inflow time series, based on the methods described in Section 3, for the full 1800 to 2002 period, to demonstrate the impacts of hindcasting the series to include the major droughts in the early and mid-nineteenth century.
4) Reconstructed and 'perturbed' time series providing 200-year flow records for 2020s, 2050s and 2080s based on application of outputs from the three RCMs to the hydrological model as described in Section 3.

Unlike the East of England case study, it was not necessary to run the models with a shorter reconstructed time series (2) because the worst droughts were generally within the latter half of the twentieth century and therefore extending the time series backwards had no impact on yield. The impacts of adopting a different modelling approach and extending the time series back to 1800 were evaluated by comparing (1) and (3). The impacts of climate change on yield were estimated by comparing outputs of (3) and (4). Some additional runs were completed based on the nineteenth century only, to determine increased yields if the 'record-breaking' droughts of the late twentieth century were ignored.

Each model was run in 'no restrictions' mode based on unfettered demand that provided an estimate of the impacts of climate change on yield. The spreadsheet models used identical spill equations for the lakes to those in MOSPA and the results, in terms of yield estimates and system behaviour, are comparable (see Appendix 2).

5.3 The MOSPA model

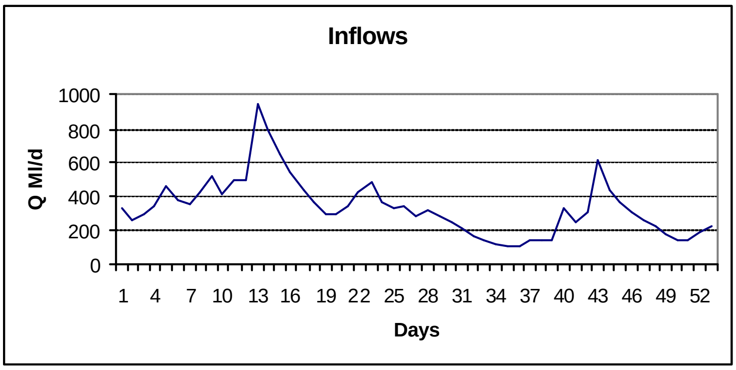
The MOSPA model calculates the water balance of the reservoir based on river flows, licence conditions, environmental flow requirements, demand and the target levels of service. The model works in one of two modes: the first is a 'yield search' that finds the maximum daily demand that can be met over the whole historical record subject to the licence and hydrological constraints. The second is a 'simulation mode' that operates the reservoir in order to meet a demand by changing operational management, including the levels of service. This is slightly different to the OSAY model that allows the setting of levels of service targets to estimate yields. The details of the MOSPA model are described in Wyatt (1996).

An example of the inputs required are shown in Figure 5.2 and example outputs in Figure 5.3. The reservoir drawdowns in Figure 5.3 show the outputs for Ennerdale. The periods marked with a green bar are when the reservoir level is below the first trigger to initiate drought planning actions (Figure 5.2). In both plots, the ‘flashy’ nature of the reservoir is evident and once outputs (demand, spills, compensation flows, evaporation losses) exceed inputs (inflows, rainfall), the reservoir can be drawn down rapidly. Equally, it can be refilled quickly following heavy rainfall or snowmelt. The historical run shows the reservoir levels during the 1984 and 1995 droughts. The future scenario has greater drawdown and lower levels but, as shown in Figure 5.3c, it also has larger volume spills in winter months because the lake cannot store the additional winter run-off.

Figure 5.2: Example data input requirements for the MOSPA model

Model parameters

Parameter		Value
Max volume Ml	:	4867
Dead storage Ml	:	2125
Net volume Ml	:	2742
Start volume f	:	0.5
a (Spill parameter)	:	11100
b (Spill parameter)	:	171.7
Target demand Ml/d	:	43.5
Compensation flow Ml/d	:	27.27
Month	:	Demand factor
1	:	0.967
2	:	0.985
3	:	0.967
4	:	1.01
5	:	1.025
6	:	1.07
7	:	1.07
8	:	1.065
9	:	1.02
10	:	0.945
11	:	0.945
12	:	0.945



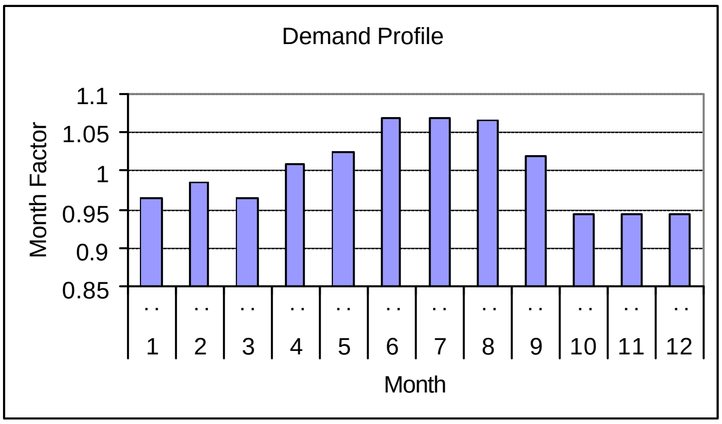
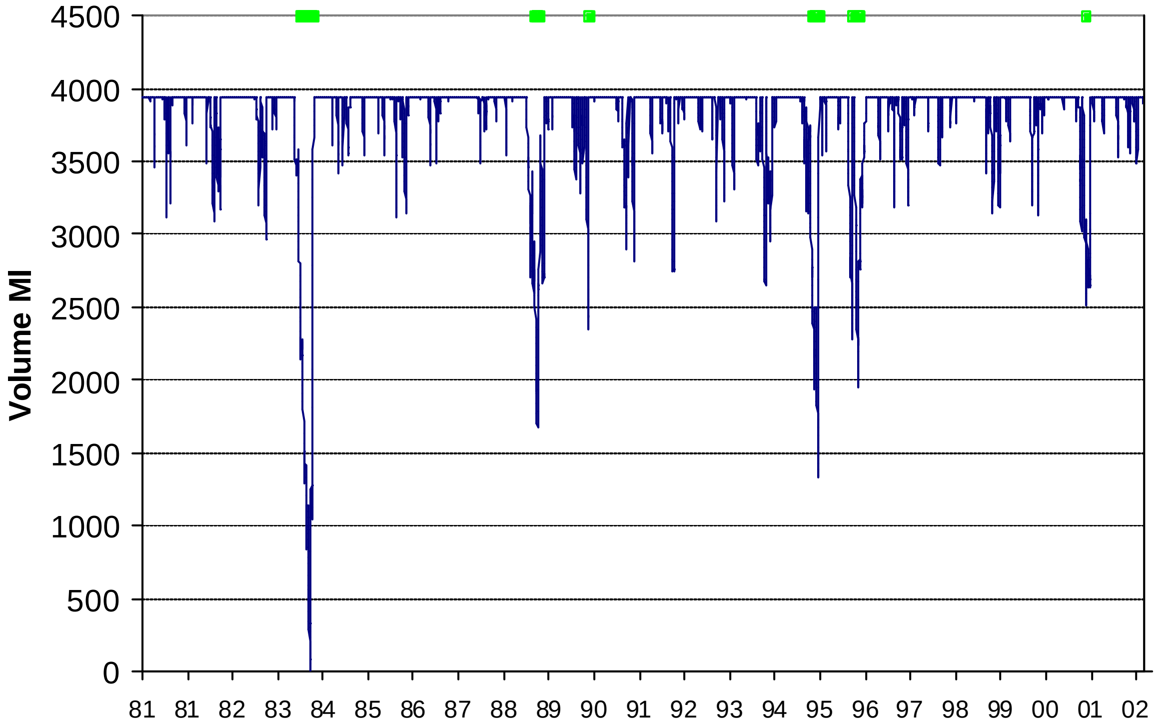
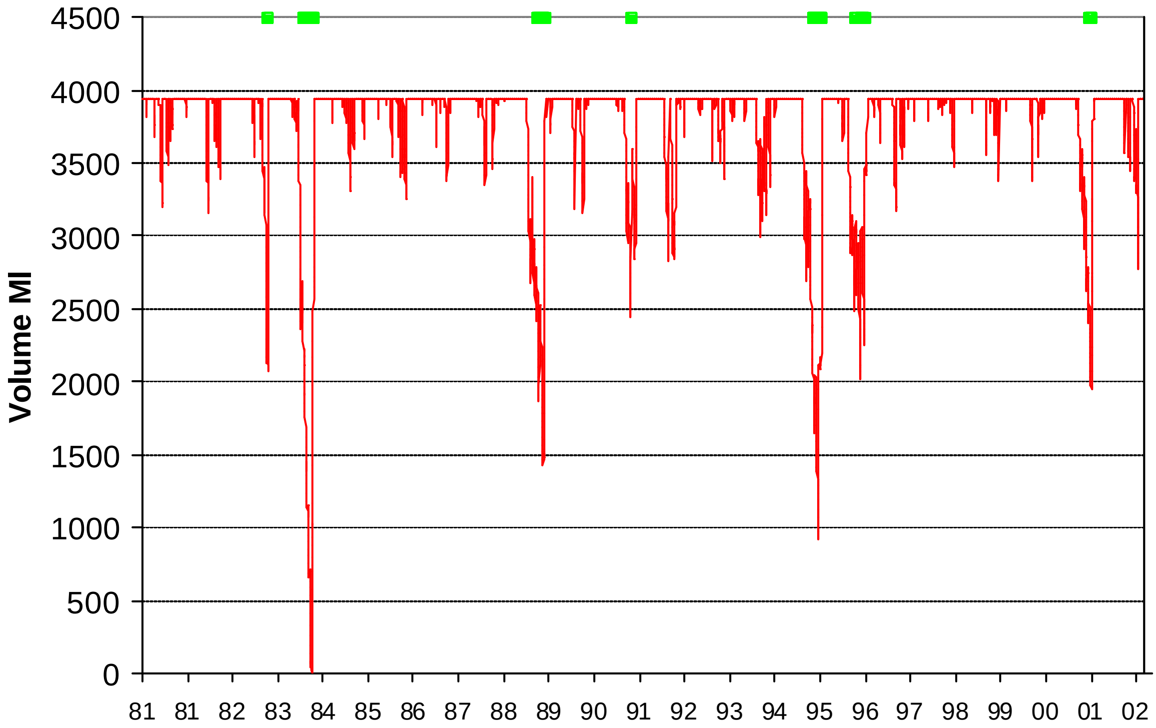


Figure 5.3: Example of reservoir behaviour for Ennerdale for (a) historical scenario (yield 55.2 Ml/d); (b) Had2080s scenario; (c) impact on downstream flows

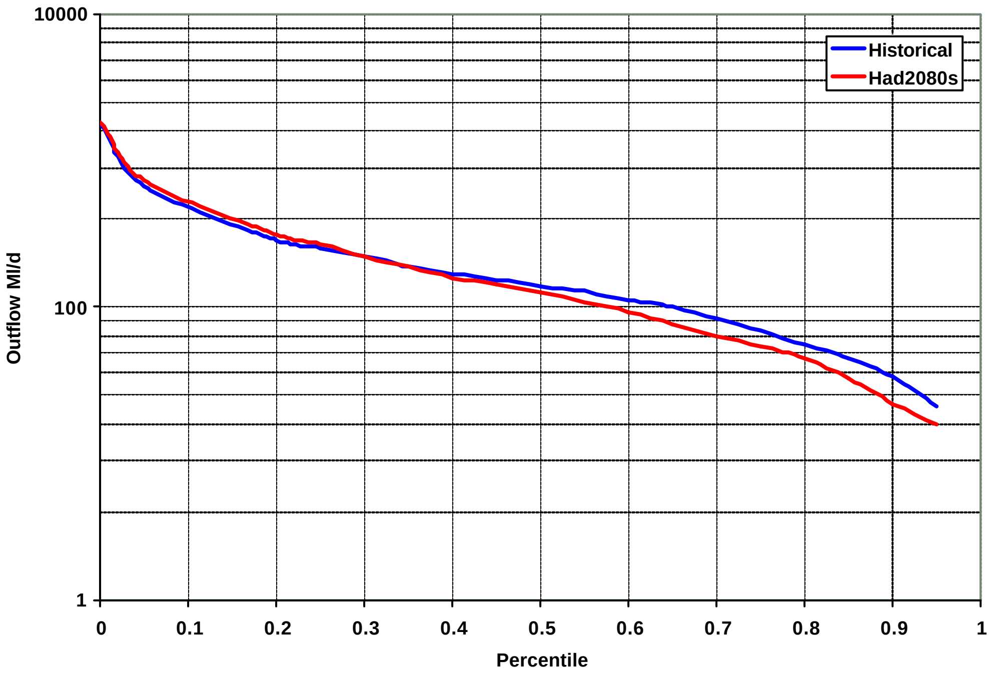
(a)



(b)



(c)



5.4 Changes in precipitation and PET for the River Eden

Figures 5.4 and 5.5 show changes in mean monthly precipitation and PET based on different RCM outputs and the UKCIP02 2020s climate change scenarios. Figure 5.4 shows that the UKCIP02 scenarios are drier than the models used in this research project, with a reduction in mean annual precipitation compared to an increase based on the RCMs. Figure 5.5 shows a similar pattern for PET between the UKCIP02 scenarios and the three RCMs, but the evaporation losses are marginally higher in the UKCIP02 scenarios.

Figure 5.4: Comparison of monthly precipitation factors for the 2020s, three RCMs for the River Eden and UKCIP02 data for the Eden CAMS

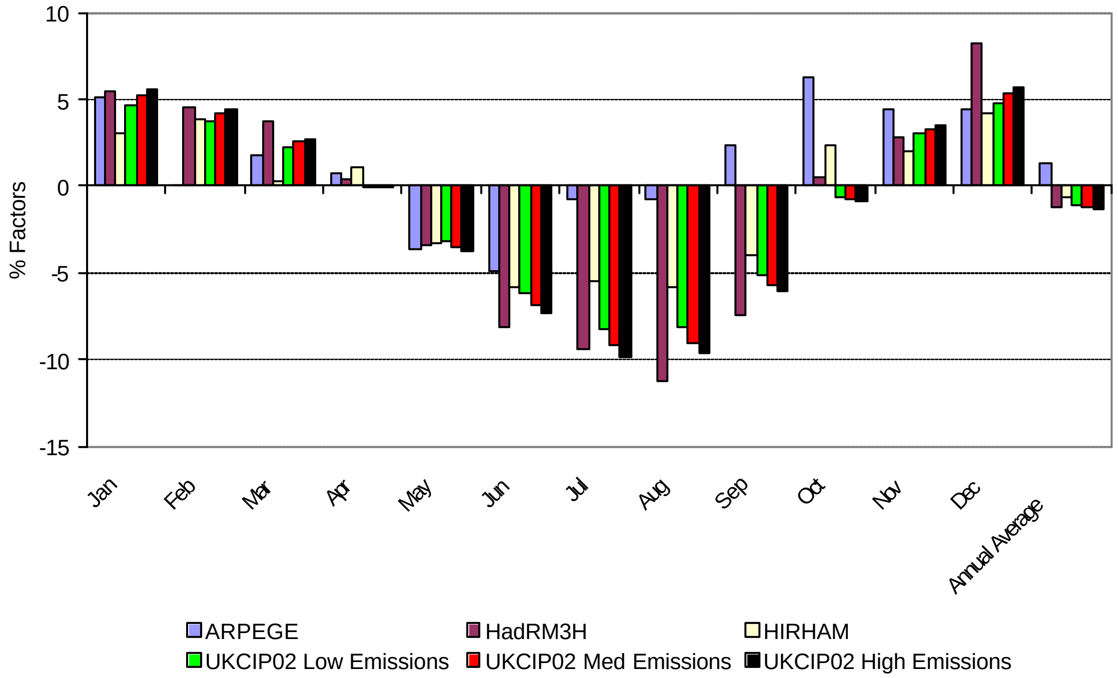
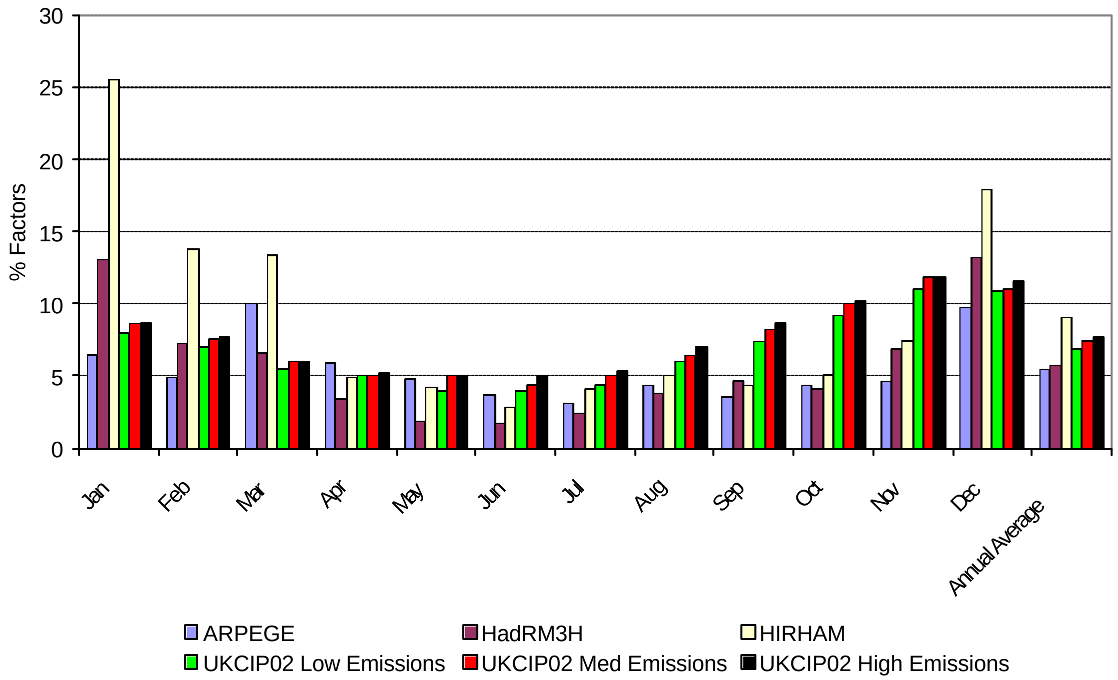


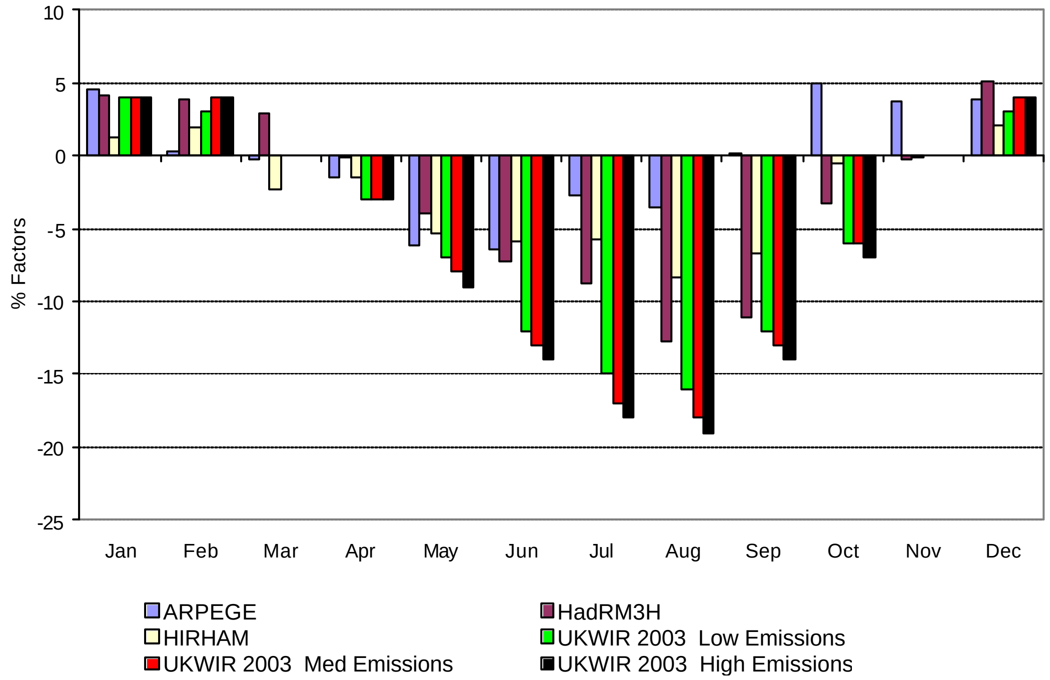
Figure 5.5: Comparison of monthly PET factors for the 2020s, three RCMs for the River Eden and UKCIP02 data for the Eden CAMS



5.5 Changes in river flows for the River Eden

The modelled changes for the River Eden, based on three RCMs and the empirical hydrological model summarised in Section 3, are not as great as the reductions in flow estimated in UKWIR (2003). The HadRM3H, ARPEGE and HIRHAM model runs all indicate reductions in average monthly run-off for May, June, July and August and increases in run-off during the autumn and winter months, October to March (Figure 5.6).

Figure 5.6: Comparison of monthly run-off factors for the 2020s, three RCMs for the River Eden and UKCIP02 data for the River Eden from UKWIR (2003)



5.6 Changes in yield for Ennerdale and Crummock

The impacts of changes in river flows on reservoir yields and minimum storage volumes are shown in Figures 5.7 to 5.11. The yield for Ennerdale is reduced significantly, by 13 to 18 per cent in the 2020s and by up to 40 per cent in the 2080s. The impacts of climate change on yield depend upon how the future climate change scenarios modify flows for the worst drought on record. For the Eden reconstructed flows this was 1984, so system behaviour for this one event is the key factor affecting yields, rather than changes in average monthly conditions.

Figure 5.7: Reductions in yield for Ennerdale 'no restrictions' runs

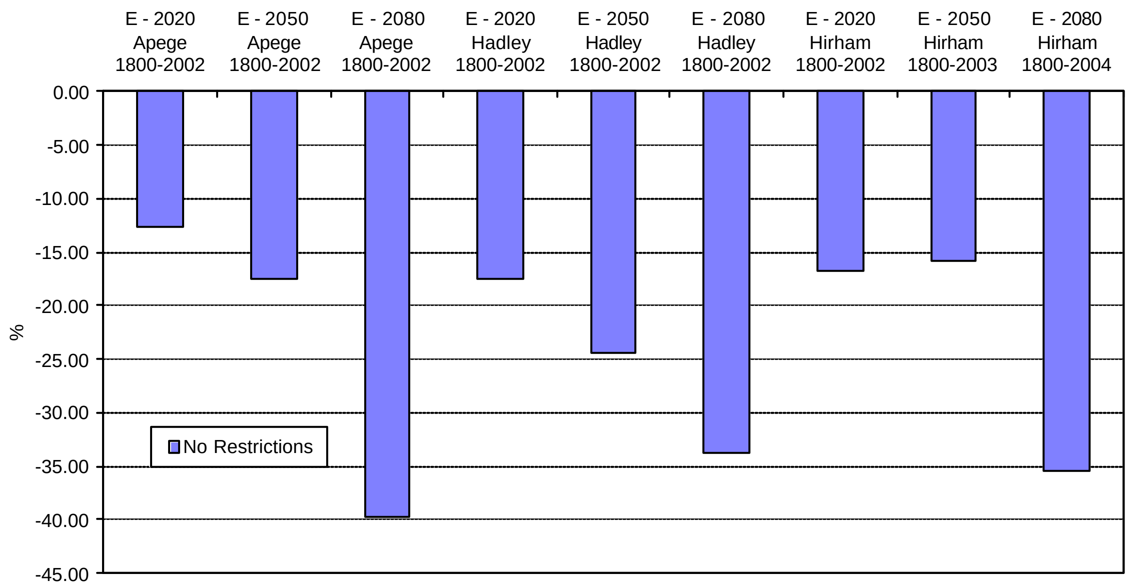
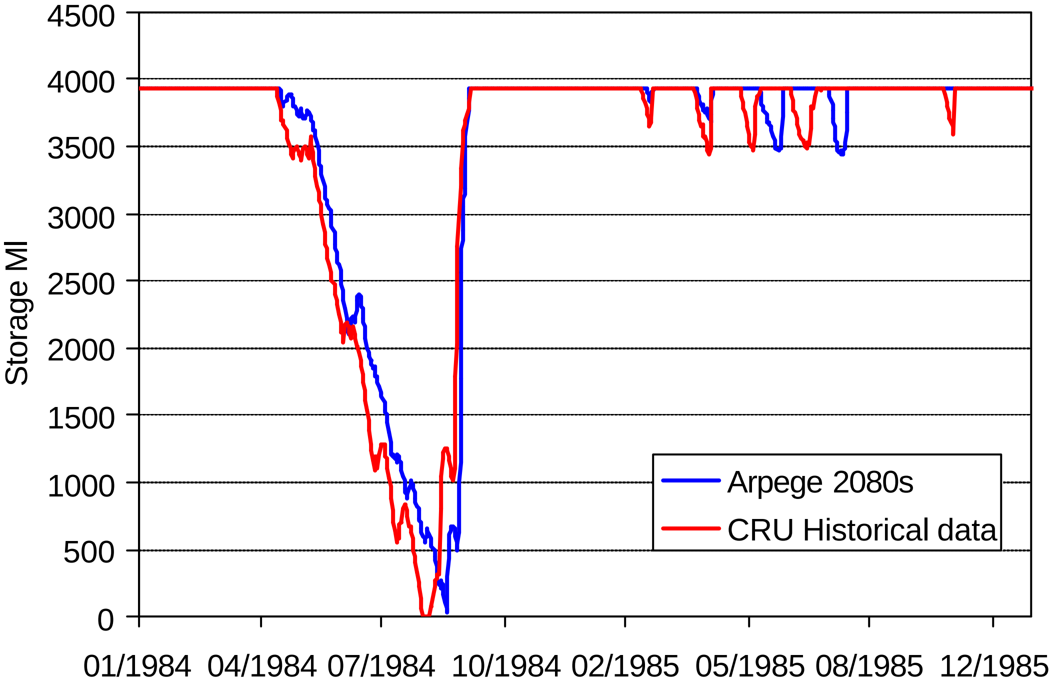
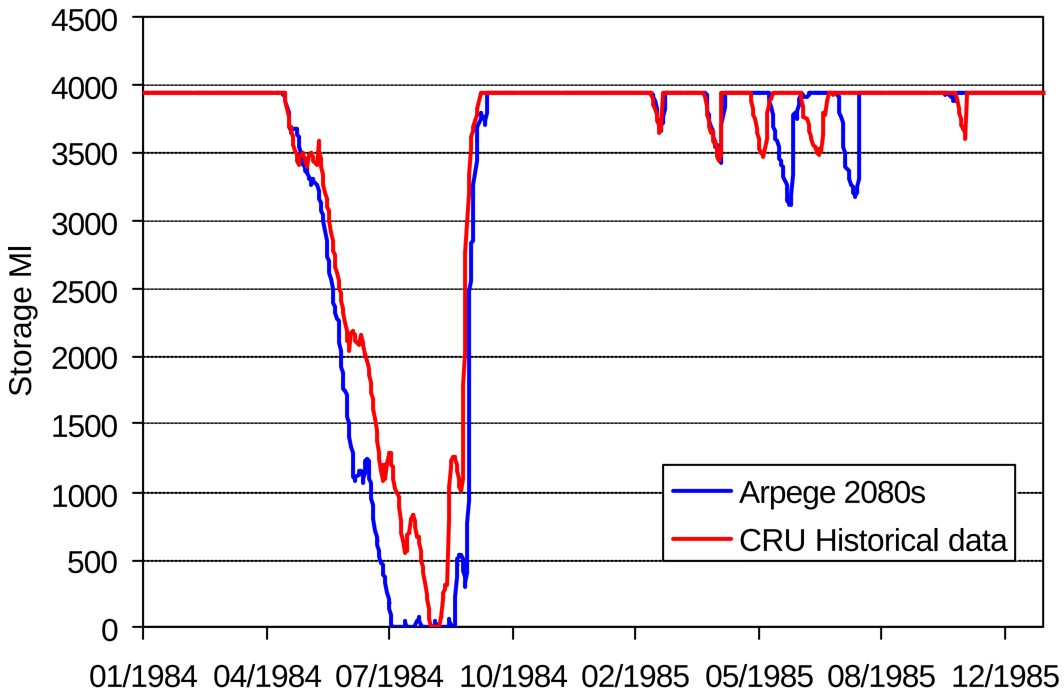


Figure 5.8: Ennerdale drawdown behaviour for worst historic drought (according to CRU record) for ARPEGE 2080s run and historical run with (a) a revised yield estimate of 39.5 Ml/d and (b) the same target yield of 55.23 Ml/d for the future and historical run.

(a)



(b)

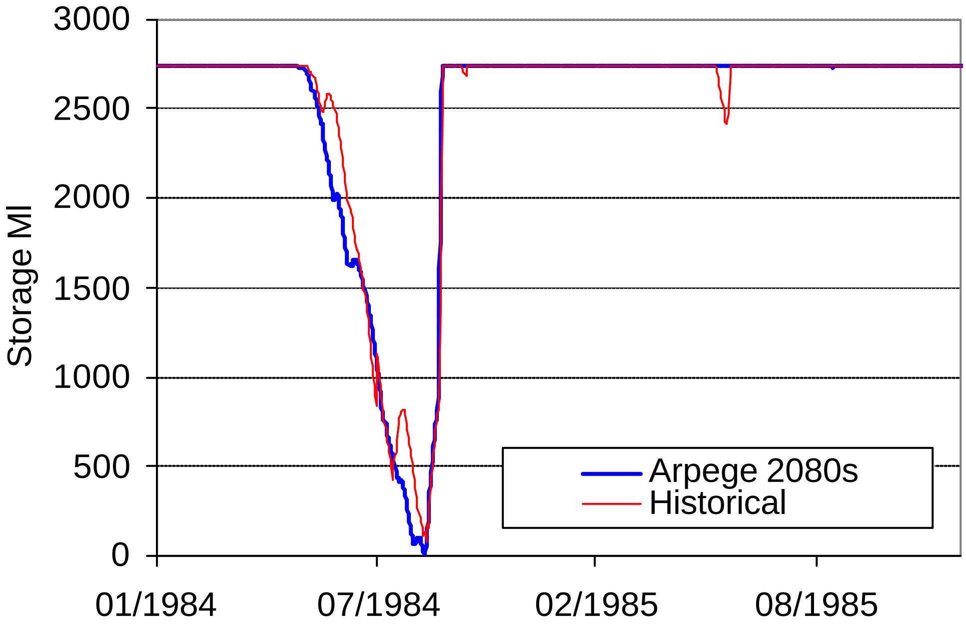


With reservoir yields reduced, the drawdown of Ennerdale Water is marginally later under the ARPEGE scenarios (Figure 5.8a). If the resource was used to meet the demand equal to the current yield, the resource would be drawn down more quickly and the source would fail for a longer period during the WHD year (Figure 5.8b). Lower lake levels would also persist for longer periods. Note that actual abstraction rates from Ennerdale are significantly lower than the yield of the source.

Despite the changes in seasonal river flow, Crummock is not affected by climate change scenarios because its yield is constrained by the abstraction licence. Additional model runs were completed with the licence conditions removed for the historic and ARPEGE 2080s scenario and comparison of these runs showed that the hydrological yield would be reduced by 40 per cent under this scenario (Figure 5.9). In both cases there can be significant reductions in storage that will have landscape and amenity impacts. Figure 5.10 shows that the lake would be less than half full for four per cent of the time when it currently never reduces to this volume.

The results for both lakes for the 2020s are shown in Figure 5.11. Overall, the water resource modelling suggests an eight to ten percent reduction for the 2020s. This is comparable to the six to seven percent assumed in the company's water resources plan given subtle differences between the methodologies applied. The full economic consequences of these changes were not calculated as part of this study. The maximum reduction in yield for the 2020s is approximately eight Ml/d and if a new resource was required to replace this loss, it would cost in the order of £8 million to £16 million. The intangible costs related to environmental impacts may be much greater in this example. All the climate models indicate significant impacts on these resources and further consideration of the implications of climate change and implementation of the Water Framework Directive (WFD) is required.

Figure 5.9: Patterns of drawdown for Crummock if licence constraints are removed: (a) comparison of drawdown for '1984' drought with reduced demand; (b) comparison based on no change in average demand.



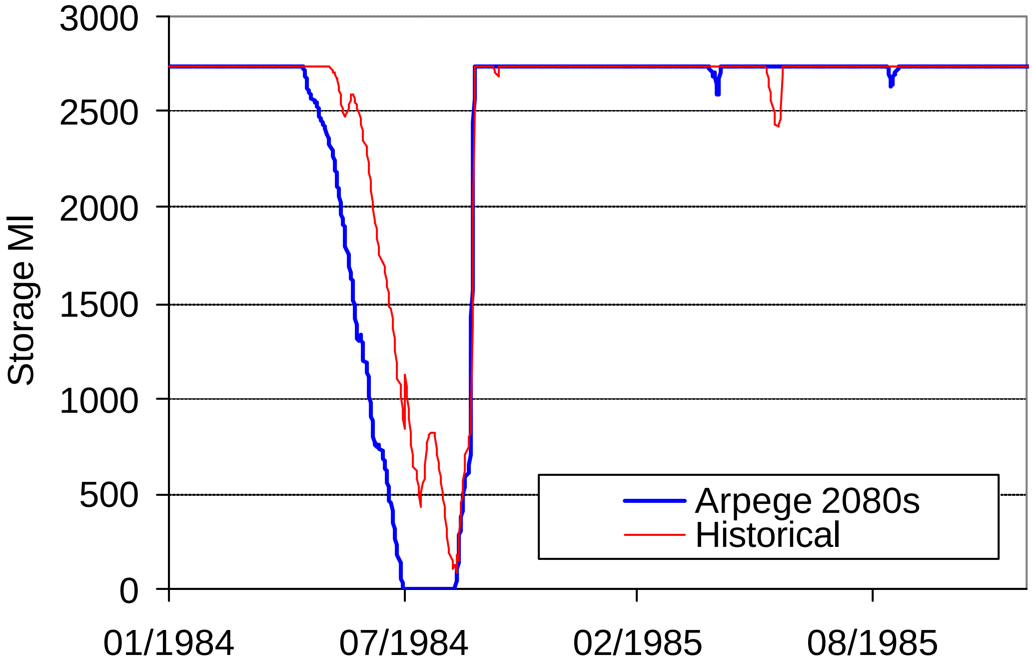


Figure 5.10: Percentile plot of net storage for Crummock – historical CRU time series compared to ARPEGE 2080s (for run equivalent to Figure 5.9b)

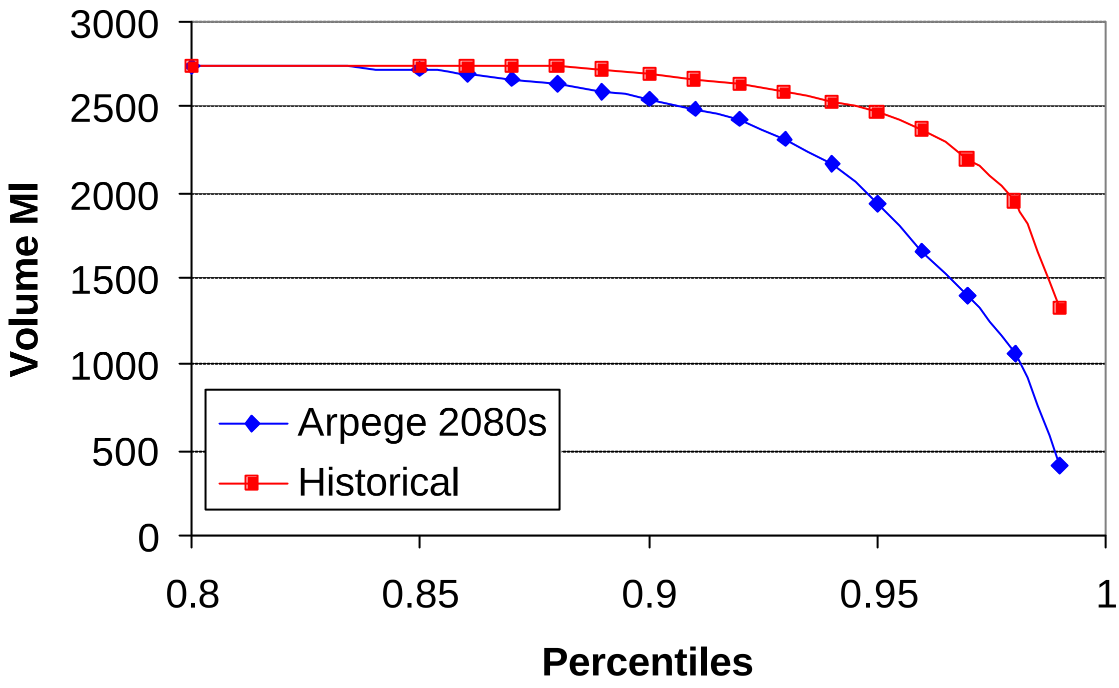
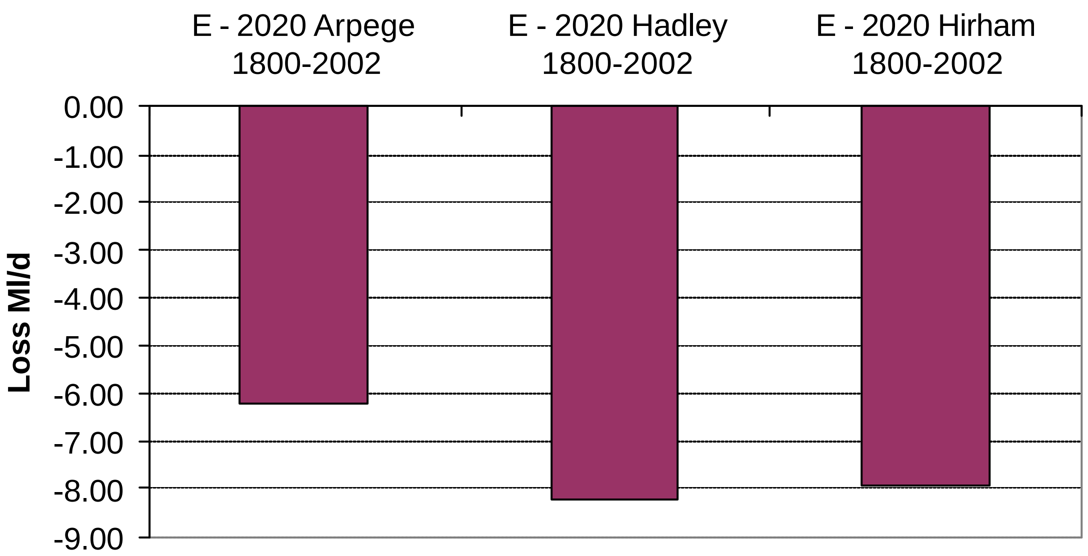
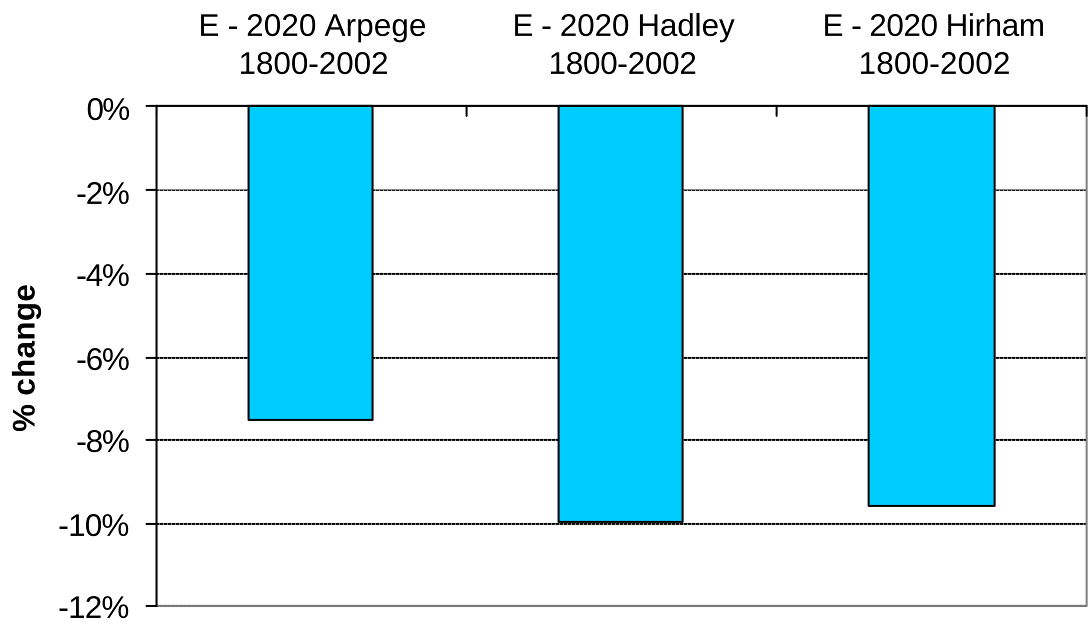


Figure 5.11: Impacts of climate change in the 2020s for Ennerdale Water in (a) Ml/d and (b) loss of yield (%). Note that there is no change in the yield of Crummock because it is constrained by licence conditions, so a figure is not included.

(a)



(b)



5.7 Hydrological uncertainties

The different runs also provide information on the uncertainty related to the use of different data sources and hydrological models on estimates of yield. In this example, extending the flow records back to 1801 had no impact on yields because droughts in the late twentieth century were more severe than those in nineteenth century. The modelling was aimed at finding a yield based on the worst drought on record; this approach means that yields can only be reduced as and when more 'record-breaking' events are included in the analysis. An alternative approach, based on defining the return period of a water resources drought, would be sensitive to lengthening the record and might have the effect of increasing as well as decreasing yields for a given return period.

Yields based on the synthetic flow time series were compared to the water company's current flow records (1955-2004). The yield for Ennerdale based on the instrumental flows was 48.5 Ml/d, which was 6.7 Ml/d less than the yield based on the synthetic flow series, illustrating the uncertainties in yield related to different data and modelling approaches. In addition, the run based on the observed flows identified March 1963 as the worst drought on record; this was regarded as a local event related to low winter snowfall and snowmelt and highlights some of the issues associated with transferring data from a catchment with different hydrological characteristics or drought history, that is, from the River Eden to the River Ehen.

5.8 Summary of case study results

Overall, the impact assessment for West Cumbria water resources indicates a number of points regarding climate change uncertainties. The comparison of different climate change scenarios shows significant differences between each RCM and between this sample of RCMs and the UKCIP02 scenarios that are currently used for water resources planning (UKWIR, 2003).

The net impact of climate change on yield, based on three RCMs, is an eight to ten per cent reduction in yield by the 2020s and reductions in minimum lake storage that may have significant environmental and aesthetic impacts. The climate change impact assessment indicated similar or marginally greater reductions in yields than previous analyses (for example, United Utilities, 2004). For this case study, the results are more consistent and clear-cut than the East of England case study. There was a reduction in yield and minimum storage for all three RCMs.

In terms of hydrological uncertainty, the comparison of observed flows for the Rivers Ehen and Cocker to the synthetic flow series based on the Eden showed that some characteristics of local data were not captured in the synthetic flow series. This highlights two important hydrological issues:

- the requirement for water companies and the Environment Agency to maintain or develop a good understanding of local catchments, including monitoring of water supply catchments and models that reproduce key local characteristics;
- common problems of hydrological analysis, such as dealing with ungauged catchments or applying regional relationships to specific catchments with different characteristics.

Some of these hydrological issues are discussed in the context of climate change adaptation in Section 6. In terms of reservoir yields, climate change impacts were marginally greater than hydrological uncertainties for the 2020s and much greater for the 2050s and 2080s.

On reservoir characteristics, the two reservoir models respond differently to changes in flow due to characteristics such as licence constraints, lake volume to catchment area ratio and so on. Changes in reservoir yield are site specific, hence the need for impact assessments for each source and/or water resource zone.

In a company-wide impact assessment on yield, lakes such as Crummock that are constrained by licence could be screened out at an early stage in order to focus modelling resources on those that are more vulnerable to climate change. However, the modelling highlighted potential environmental impacts that may be overlooked in such a hierarchical risk assessment.

Overall, the net impact in the 2020s is a reduction in yield for Ennerdale and hence West Cumbria as a whole. A fall in summer to early autumn lake levels may have ecological, landscape and amenity impacts. The implementation of the WFD may affect the acceptability of increased drawdowns if it can be shown that this limits the ecological potential of the lakes. There will be increased reservoir bypass and/or spills in the winter months due to increase in winter run-off. Flood risk in general and the risk of erosion will increase.

The impacts increase through to the 2080s. For example the impacts on yield for Ennerdale were minus 13 to 18 percent for the 2020s, minus 16 to 24 percent for the 2050s and minus 34 to 40 percent for the 2080s.

6 Better drought risk management

Overall, this study has provided insights into the effect of natural climate variation and climate change on rainfall, potential evaporation, river flows, groundwater levels and reservoir yields. The findings are relevant for both water resources planning and drought planning, activities that are carried out by water companies and the Environment Agency. Table 7.1 lists fifteen options for adapting to climate change and improving water resources and drought planning. Most of these relate to hydrology and climate change impact assessments, such as:

- developing long-term records, back to the 19th century where data are available;
- improving water resource models;
- developing better risk assessment methods;
- considering multiple GCMs or RCMs for climate change impact assessments;
- providing guidelines on the development of hydrological models for water resource studies;
- developing methods to test the sensitivity of water resources to natural variability;
- considering climate change uncertainties in options appraisal;
- testing drought and water resource plans against a range of future scenarios.

The fifteen options include research on ways of adapting that do not rely on long-term water resources planning, such as:

- reviewing levels of service, and changing the frequency, nature or effectiveness of drought restrictions;
- investigating the best use of additional winter run-off; changing licensing or increasing storage volumes;
- including some drought powers within abstraction licences; making licensing more flexible to deal with greater seasonal and annual variations in climate.

Further measures such as reducing demands, flexible water tariffs, water trading, and drought forecasting could be added to the list but the case studies did not provide results that could be used to comment on these options.

It is clear that better drought risk management will involve changes to national policy, regional and strategic water and land use planning and local actions to reduce demands, as well as refinements to water resources and drought planning. Some of these issues are addressed within the current Department for Environment, Food and Rural Affairs (Defra) Cross-Regional Programme of Climate Change Impacts and Adaptation (see HR Wallingford, 2006).

7 Conclusions

This report provides an overview of previous research and describes two case studies of the impacts of climate change on reservoir yield. The case studies were used to develop a list of adaptation measures to improve water resource policy, monitoring and research (Table 7.1).

For the two case study areas, three regional climate models (HadRM3H, HIRHAM and ARPEGE) were used to develop long-term river flow sequences. These synthetic flows were then applied to reservoir water resources models to determine the impacts of climate change on yields and elucidate the 'behaviour' of these systems under nineteenth century climate conditions and a range of future climate change scenarios for the 2020s, 2050s and 2080s.

For the East of England case study, the river flow reconstruction showed that the hydrological drought of 1803 was more severe than the droughts in 1933/4 and 1943/4 that are used for drought and water resources planning. For the River Ouse, the synthetic flow record indicates much lower flows in the first half of the nineteenth century, particularly in spring and early summer. For the North West, contemporary droughts such as 1984 and 1995 were the most severe in the 200-year synthetic flow record.

For both case studies, the RCM synthetic flow series for the 2020s has the typical pattern of wetter winters and drier summers associated with climate change. However, small differences between the RCM flow series had an impact on yield, with the ARPEGE results generally producing lower yields.

For both case studies, climate change reduces the yield of reservoir sources for the 2020s scenarios. The average impact was a 10 per cent reduction in yield for the North West case study, but the picture was more complex for the East of England where the direction as well as the magnitude of impacts varied for different RCMs and different reservoirs. Only Grafham has a clear reduction in yield and this was only for the ARPEGE RCM. Conversely, Ravensthorpe and Hollowell showed an increase in yield for all RCMs. These lowland systems benefit from the increased winter flow, whereas for the upland reservoirs in the North West the increase in winter run-off simply leads to an increased spill volume.

Comparison of the different models runs, based on river flow series derived in different ways and of different record lengths, allowed hydrological uncertainties to be compared to climate change uncertainties. For the East of England, hydrological uncertainties were larger than climate change uncertainties and the methods used to develop the flow record had the greatest impact on estimates of yield. For the North West, hydrological modelling did not fully capture some of the local characteristics and drought history of the small lake catchments.

As well as changes in yield, a range of other changes were identified by the water resources models including changes in the length of time that reservoir levels were below specific triggers, lower annual minimum reservoir levels and increases in spill volumes for the West Cumbria lakes. These changes may have ecological, landscape and amenity impacts. The implementation of the WFD may affect the acceptability of increased drawdowns if this proves to limit the ecological potential of the lakes.

Inevitably, there is a trade-off between levels of service and yield. Reductions in demand will buffer the impacts of climate change and careful consideration of different water resource management options will determine the best responses to climate change. These might include comparisons between ‘predict and provide’ approaches and policy changes involving changing levels of service or drought or abstraction management.

With regards to drought communication, the current system in England and Wales is well developed. The Water Act (2003) made drought plans statutory and the Environment Agency has developed clear guidance (Environment Agency, 2005). However, this communication could be improved by making stronger links between water resources, drought, environmental impact and regional and strategic, individual and community measures to reduce demand. For example, national classification of droughts, better forecasting and water efficiency information on utility bills may help to reduce demand and the environmental impacts of drought.

Table 7.1: Fifteen options to adapt to climate change

No	Adaptation option	Themes	Response type	Comments
C1	Consider multiple GCMs or RCMs for climate change impact assessment	Climate change	Policy and process (research)	The impacts of climate change in the 2020s for the case studies include a reduction in yield and lowering of minimum water levels for specific reservoir and lake sources. However different climate models show different results regarding the direction of changes (increase/decrease in yield) as well as the magnitude of changes. For the East of England case study, the results of the HIRHAM RCM indicate an increase in yield for Rutland and Pitsford Reservoirs which is counter to the common assumption that climate change will reduce source yields. In addition, the sample of three RCMs used in this study appears to be wetter than the UKCIP02 scenarios that are currently used for water resources planning in England and Wales. Consequently the research indicates that for these two case studies, the impacts on summer river flow could be less than those currently assumed by the water industry (UKWIR, 2003). The relative ‘skill’ of the selected RCMs at reproducing the UK or local climate was not tested in this project. However if each RCM scenario is considered as valid as the UKCIP02 scenarios the impacts of climate change would be lower than in previous water resources plans. Different climate models should be considered in water resources planning using practical methods proportionate to the risk. This issue was previously flagged in UKCIP and Environment Agency guidance but there were no appropriate tools available to water companies to help them consider these uncertainties. This is being addressed by ongoing UKWIR research (UKWIR, 2005)

No	Adaptation option	Themes	Response type	Comments
C2	Test drought plans and water resource plans against a range of future scenarios	Climate change	Process	The case studies show a range of potential climate change impacts depending on choice of RCM and reservoir characteristics. Testing drought and water resource plans against different scenarios can help to identify options resilient to climate change and/or natural variability. The case studies show that using levels of service and drought plans can help to meet demand (NW case study) during drought and dampen the potential impact of climate change on yield (Anglian case study). Although not implemented in this study, sensitivity testing based on different types of drought and climate change may identify management measures that can reduce drought impacts, such as drought awareness campaigns or more stringent drought restrictions. It would therefore seem appropriate to test plans against future drought scenarios as well as historical single season and multiple season droughts.
C3	Develop and implement methods for dealing with hydrological uncertainties	Hydrology	Process (research)	The case studies show that hydrological uncertainties can have a large effect on yield estimates, drought and water resource plans and therefore future investment. For drought planning it is important to have a good understanding, based on historical evidence or hydrological models, of the response of catchments to periods of rainfall drought. In drought forecasting, any hydrological uncertainty should be considered alongside the uncertainties in medium to long-term weather forecasts to provide probabilistic estimates of river flow. Where major water resource schemes are planned, hydrological uncertainties should be explored, translated into risk in terms of a supply-demand deficit or economic cost and documented.
C4	Develop hydrological models that reproduce observed drought conditions	Hydrology	Process	The NW case study highlights the difference between regional drought conditions in the Eden catchment that were not reflected in the instrumental record of the smaller lake catchments. This raises a number of issues on the development of hydrological models, the use of donor catchments to hindcast records in ungauged catchments and the inclusion of regional run-off factors to account for climate change.

No	Adaptation option	Themes	Response type	Comments
				If models are developed for water resource studies, they need to accurately reproduce critical drought conditions, such as Q95, low summer flow and cumulative flow deficits. There is a need for guidance on hydrological modelling and how to reconstruct records in ungauged water supply catchments. Finally, the use of regional climate change factors may not be appropriate if local catchment characteristics are the most important control of hydrological response. Ongoing research supported by the Environment Agency and UKWIR is currently looking at the regionalisation of low flows under climate change
C5	Develop long-term records, back to 19th century where data are available	Hydrology	Process	The research has clearly demonstrated that long-term records can help to place the 20th century climate in context and provide information on how climate and run-off may vary even without climate change. Following the Water Summit in 1997, water companies were asked to reassess the yields of all water sources, typically hindcasting flow records back to the 1920s. The Anglian case study shows that the worst drought on record was 1803 and there was a series of drought conditions in the early nineteenth century that would present a real challenge for existing systems. Therefore, one method for dealing with natural variability would be for planners to develop longer term records to improve their confidence in the probability of drought conditions.
C6	Maintain/develop a good understanding of local hydrological conditions of source catchments	Hydrology	Process	(See C4) Many reservoirs and lakes are still poorly monitored and there is a need to ensure that water company and Environment Agency staff maintain a good understanding of local hydrological conditions and monitor inflows, levels and outflows of lakes and reservoirs.
C7	Provide guidelines on the development of hydrological models for water resource studies	Hydrology	Process	(See C3) The case studies have demonstrated that the use of different data sets and hydrological modelling approaches can have a major impact on yield estimates and therefore on drought planning. There is a requirement for clear technical guidance on hydrological modelling as well as climate change impact assessments.

No	Adaptation option	Themes	Response type	Comments
C8	Develop methods for testing sensitivity of water resources to natural variability	Hydrology	Research	Perturbing historical sequences can change the worst drought on record and the response to drought in terms of demand restrictions. No two droughts will be the same and therefore methods of perturbing past droughts or stochastically generating climate or river flow data may provide useful methods for testing the resilience of water resources systems to a wider range of conditions.
C9	Development of (and access to) long-term, high quality hydrological records	Hydrology	Research	The case studies demonstrate the benefits of considering a longer historical time series in terms of improving planners' understanding of natural variability, the probability of drought conditions and estimates of source yield. Reconstruction of long-term data sets requires research and access to climate data at reasonable cost. At present there is limited data available to water companies and the Environment Agency and a concerted effort to collect, digitise and quality control archive records would increase the uptake of these methods.
C10	Review levels of service - role in climate change adaptation	Water resources	Policy (research)	Levels of service play a role in reducing demand and maintaining supply during drought conditions. Making restrictions easier to apply or allowing companies greater flexibility on the frequency of restrictions could potentially play a role in adaptation and be an alternative to engineered supply-side measures. However, any changes to levels of service may be unpopular with the water industry and the public, and further research is needed such as consultations with water consumer councils, surveys and behavioural studies.
C11	Develop improved water resource system models	Water resources	Process	The impacts of climate change cannot be generalised for reservoir and lake sources because impacts depend on source and water resource zone characteristics. Water resource models are an appropriate tool for assessing impacts on sources and zones, particularly where yields are hydrologically constrained (see C12). Water companies are at different stages of development in water resource models – some companies do not use water resource models and others have complex integrated modelling systems. Companies need to develop

No	Adaptation option	Themes	Response type	Comments
				appropriate models, with a requirement for guidance, standards and training in how they should be used for planning.
C12	Develop better risk assessment methods	Water resources	Policy & process (research)	Risk assessment could include estimates of the probability of drought and its consequences. Yield estimates should be based on the worst drought on record rather than a drought of a specific return period, such as one in 50 years or two per cent drought, though this has a number of limitations and makes comparisons across the UK difficult. In addition, the design conditions for water resources planning combine supply and demand scenarios without considering their combined probability. There are appropriate measures for supply, like the Security of Supply Index (SOSI), but there are no standard methods for quantifying the wider environmental consequences of drought. Further work is required in this area to support adaptation to climate change. Without appropriate risk metrics, adaptation options cannot be properly evaluated. The NW case study shows that climate change does not have an impact on all sources because reservoir yields can be constrained by licence or works capacity. A hierarchical method of risk assessment would ensure that these sources are identified as low risk with regard to climate change, so that modelling efforts could focus on the most vulnerable sources.
C13	Consider climate change uncertainties in options appraisal	Water resources	Process	Climate change should be considered in options appraisal as well as reviewing the potential impacts of climate change on current water supply systems. The East of England case study shows that some reservoirs have characteristics that make them less vulnerable to climate change, such as licence conditions and pump capacities that enable them to abstract larger volumes of winter run-off. Similarly, some options for future water resources development may be more or less vulnerable depending on catchment and source characteristics.

No	Adaptation option	Themes	Response type	Comments
C14	Investigate the best use of additional winter run-off – changing licensing or increasing storage?	Water resources	Process (research)	Winter run-off increases in all scenarios and in all of the case studies. There is a potential opportunity to make use of this additional water by changing licence conditions and pumping capacities or increasing storage while maintaining or improving compensation flows and summer abstractions. Behavioural water resource models (C11) are the best means to test if and how existing, modified or new storage schemes can benefit from increased winter run-off without damaging the environment.
C15	Include some drought powers within abstraction licence.	Water resources	Policy	Measures should make it more straightforward and less time consuming for water companies to use drought powers. At present, the requirement for applications and subsequent delays relating to public inquiries could, in some cases, increase the risk of water supply failures.

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United Utilities Water Resources Plan http://www.unitedutilities.com/resources/files/483_WRP%20Public%20Summary%20(Final).pdf

United Utilities Drought Plan

http://www.unitedutilities.com/?OBH=3322

Anglian Water Services – Water Resources Digest

http://www.anglianwater.co.uk/assets/WRP04final.pdf

Appendices

Appendix 1 : Development of future flow sequences
Appendix 2 : Approaches to water resources system modelling
Appendix 3 : Detailed outputs from Anglian Water's resources modelling
Appendix 4 : Detailed results for both case studies

Appendix 1: Development of future flow sequences

All future flow sequences for the principal rivers (the Eden and the Ely Ouse) and the specific input sites for the water resource modelling were derived by perturbing the historic rainfall and temperature data using three different regional climate models (RCMs), under one greenhouse gas emission scenario and for three time slices. The nine generated sequences each span 202 years, and represent the way in which historic variations might be modified by potential future climate change.

Emission scenarios

Only one future emissions scenario has been considered (the project instead focuses on the uncertainty between different global/regional climate models and on the use of early historical observations to capture more fully the natural variations of climate). The scenario used is the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) “A2” scenario. It corresponds to one of the four standard UK Climate Impacts Programme (UKCIP) scenarios (the medium high emissions future, Hulme *et al*. 2002).

The future time periods are representative of the 2020s, 2050s, and 2080s. Following UKCIP, the climate changes for the earlier time periods are scaled versions of A2 scenario results obtained for the 2080s. The scaling factors are given in Table A1-1 (from Table 7 in Hulme *et al.* 2002). The scaling factors are all applied multiplicatively to the temperature and precipitation *changes* (the changes are then applied to the historical observations additively for temperature and multiplicatively for precipitation). If the scaling factor for a future period is 0.5, the implied change from the present-day baseline to this future period is equal to the 2080s scenario reduced to one half. The same scaling is used for each month of the year.

Time slice	Medium high emissions (A2)
2020s	0.27
2050s	0.57
2080s	1.00

Table A1-1: Multiplying factors for conversion from 2080s medium-high scenario to other time slices (Hulme *et al*., 2002, UKCIP02 Report).

Regional climate models

Projections from three RCMs were selected from the PRUDENCE project web site (http://prudence.dmi.dk/). The three RCMs were chosen to span the range of future RCM variability involving three different RCMs as well as three different driving general circulation models (GCiMs). For an in-depth discussion of regional climate modelling (including the abbreviations for the various GCiMs and RCMs) and the PRUDENCE RCM data available, see the web site and also Christensen *et al.* (2006). The three models selected are HadRM3 driven by HadAM3, ARPEGE driven by ARPEGE and HIRHAM driven by ECHAM4. They sample quite well the range of possible RCM futures represented by the full set of RCMs inter-compared within the PRUDENCE project.

Future monthly flows

The development of the historic flow sequences has been described in Jones *et al.* (2006b). The catchment model used requires estimates of monthly areal rainfall totals for the Ely Ouse and the Eden. For the historic flow reconstructions, the catchment model assumed that the areal actual evapotranspiration (AET) was time invariant, varying only through the annual cycle. As future temperature rise in all the RCMs is significantly beyond the range of historic natural variability, a simple water balance or soil moisture model was developed to additionally perturb (increase) AET.

The purpose of the simple soil moisture model was to best simulate the monthly-constant AET values (successfully used in the historic reconstructions, see Jones *et al.* 2006b and references therein) from potential evapotranspiration (PET) values estimated from monthly mean temperatures using the Thornthwaite formula (Thornthwaite, 1948). This formula was used for simplicity as it only requires temperature data. Some of the necessary data to estimate PET using more complex formula (for example, Penman, 1948) were neither readily available historically nor from the RCMs.

The soil moisture model is a simple three box model with infiltration between the top two boxes. The model has three parameters, the maximum water content of the top two boxes and the infiltration rate. The third (lower) box is infinite in size. The input to the model is monthly values of rainfall and PET. Evaporation occurs at the potential rate from the upper box and then reduces linearly to a tenth of the potential rate once the second box has been depleted. Infiltration occurs at the full rate from the top box, but it too reduces linearly to zero until the second box is depleted. Once soil moisture is depleted from the top two boxes, AET occurs at one tenth of PET and no infiltration between the top two boxes occurs. The model produces estimates of AET and the parameters were tuned manually to best simulate the previously used constant historic values of AET when the model is driven by historic time series of Thornthwaite PET and precipitation data. As the AET values used for the historic flow reconstructions were nominally based on the 1941-70 period (see references in Jones *et al.* 2006b), the tuning was undertaken to minimise the difference between the Jones *et al.* (2006b) monthly AET values and the average of the simulated AET monthly values for this 30 year period. The parameters of the soil moisture model for the two catchments are given in Table A1-2. These parameters were then assumed to remain the same in the future.

Catchment	Top soil box (mm)	Main soil box (mm)	Maximum infiltration rate (mm/month)
Ely Ouse	25	250	15
Eden	10	150	70

Table A1-2: The three parameter values for the two catchments.

To estimate future values of AET, the soil moisture model was driven by possible future rainfall and PET sequences. The Thornthwaite formula was used to convert the temperature sequences into time series of future PET. The future rainfall and temperature series were generated from the historic sequence (the development of these is described in Jones *et al.* 2006b) perturbed by mean changes diagnosed from the RCM simulations. Figure A1-1 (top row) indicates the mean annual cycles of future PET for each catchment, obtained for the 2080s using the three RCM scenarios. The largest increases in PET are during summer. They are quite similar between all models for all catchments, though PET for the two Eden catchments increases slightly less in the HadRM3H scenario than in the other two scenarios (reflecting a smaller temperature change in that model over the Eden catchment).

The reduced summer precipitation, especially in the HadRM3H and HIRHAM scenarios, leads to increasing drying of soils in summer and early autumn, and this limits the actual evapotranspiration that occurs to much less than the potential. The future ratio of AET to PET falls below 0.5 during some months in all catchments under all three scenarios (Figure A1-1, second row), though it falls below 0.3 in the Ouse catchment under the 2080s HadRM3H scenario, due to very low soil moisture.

The combination of the increased PET (Figure A1-1, top row) and the seasonally-varying changes in the fraction of PET that is converted into AET (Figure A1-2, second row) gives the future AET (Figure A1-1, expressed as a ratio of present-day AET in the third row and as absolute AET values in the bottom row). AET increases in all catchments and for all three RCM scenarios during winter and spring, but the late summer/early autumn decreases in AET under HadRM3H and HIRHAM scenarios are important in ameliorating the effects of reduced summer precipitation in those models. AET decreases by a smaller amount and for a shorter, ‘high-summer’ season under the ARPEGE scenario.

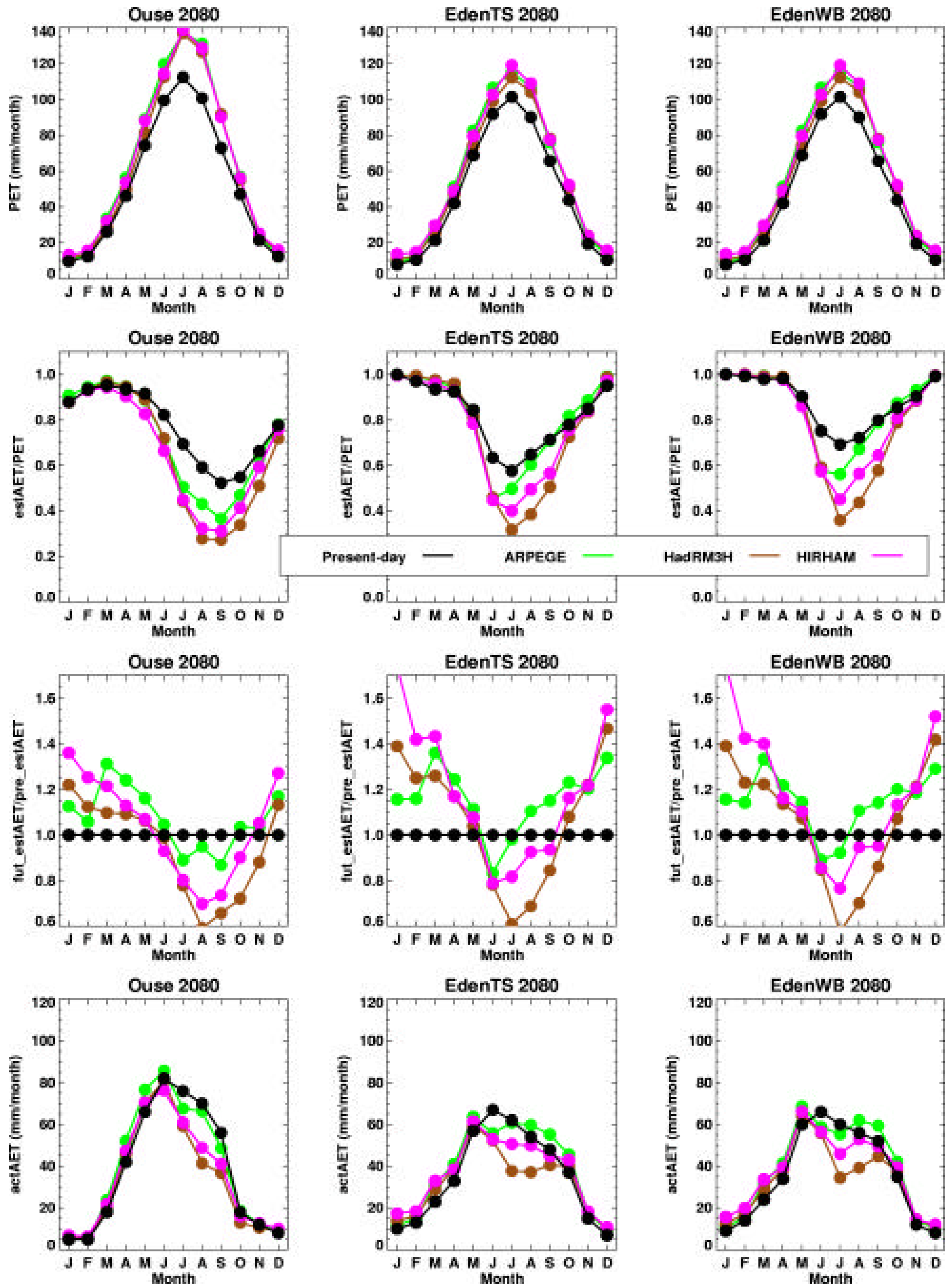

Figure A1-1. Present-day and possible future (2080s) annual cycles of evapotranspiration (mm/month) for the Ouse (left), Eden to Temple Sowerby (middle) and Eden to Warwick Bridge (right). Top row: PET estimated using Thornthwaite formula and historic or future catchment temperature. Second row: ratio of AET to PET, where AET was simulated using the simple soil moisture model driven by historical or future precipitation and PET. Third row: ratio of the future simulated AET to the present-day simulated AET. Bottom row: AET values obtained by multiplying the ratios shown in the third row by the Jones et al. (2006b) historic AET values (black curve). The present-day data are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

Figures A1-2 to A1-4 show the future flow sequences obtained using these estimates of the future mean AET and sequences of precipitation perturbed by possible future precipitation changes.

The top panels of Figure A1-2 show the annual cycle of mean stream flow in the Ouse at Denver Sluice for the present-day and three possible 2080s scenarios, expressed as absolute values in the top left and as fractional changes from the present-day in the top right. All three RCM scenarios simulate an amplified annual cycle of stream flow, though they differ with regard to the phase of the changes (April–September for HIRHAM, May–September for ARPEGE, and May–November for HadRM3H) and the change in mean summer/autumn stream flow, which decreases more strongly under the HadRM3H scenario. For all RCMs and future periods, the Ely Ouse annual-mean flow increases slightly (by about two per cent) because rainfall increases in the winter half of the year. The decreased summer rainfall has a strong effect on summer flows, and is only partly offset by reduced AET and because the Ely Ouse summer flow variability is determined partly by its memory of winter rainfall fluctuations.

The remaining panels of Figure A1-2 show the annual, summer and winter flow series obtained under the three future climate change scenarios. The results indicate some complex behaviour (that is, despite the relatively unsophisticated modelling approaches used in this project, the future flow series are not simply scaled versions of the historical flow series), with different yearly flows being affected by different amounts, principally related to the timing during each year of the main precipitation events (these are affected by climate change differently at different times of the year). In general, the years with the highest annual-mean flows exhibit the strongest annual-mean changes (mostly increased flow), while some (though not all) years with relatively low annual-mean flow are little altered. The summer-mean flows are mostly reduced, though again there are deviations from simple behaviour during individual years (for example, some of the lowest summer flows are decreased most strongly under the ARPEGE scenario, even though the average or high summer flows are affected most by the HadRM3H scenario). The winter-mean flows for the Ouse mostly increase.

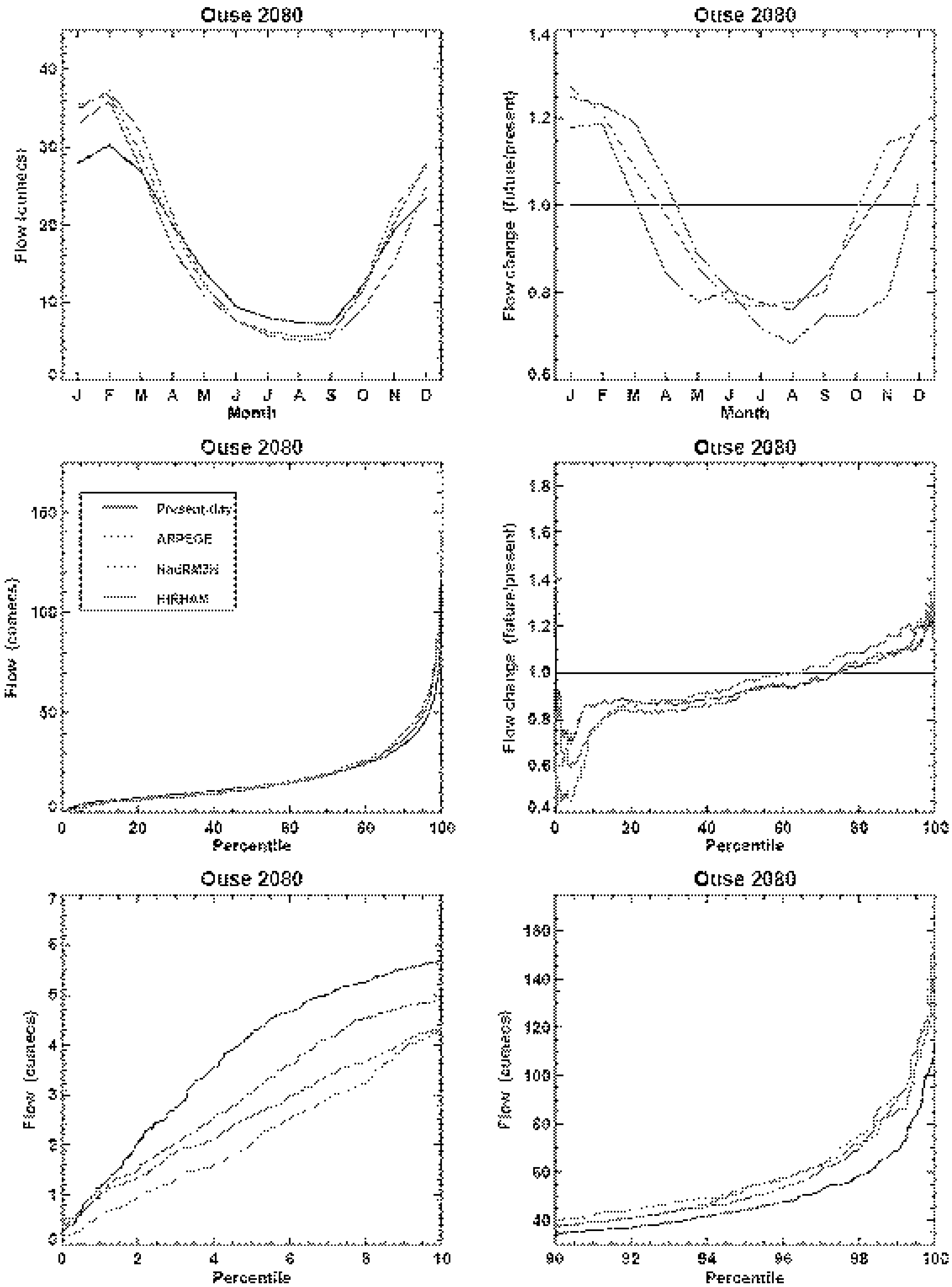

Figure A1-2a. Present-day and future flows for the Ely Ouse at Denver Sluice (cumecs). Top left: mean annual cycle of flows. Top right: mean annual cycle of flows divided by present-day annual cycle. Other rows: changes in percentiles (with 5th percentile as a low flow equal to Q95). The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

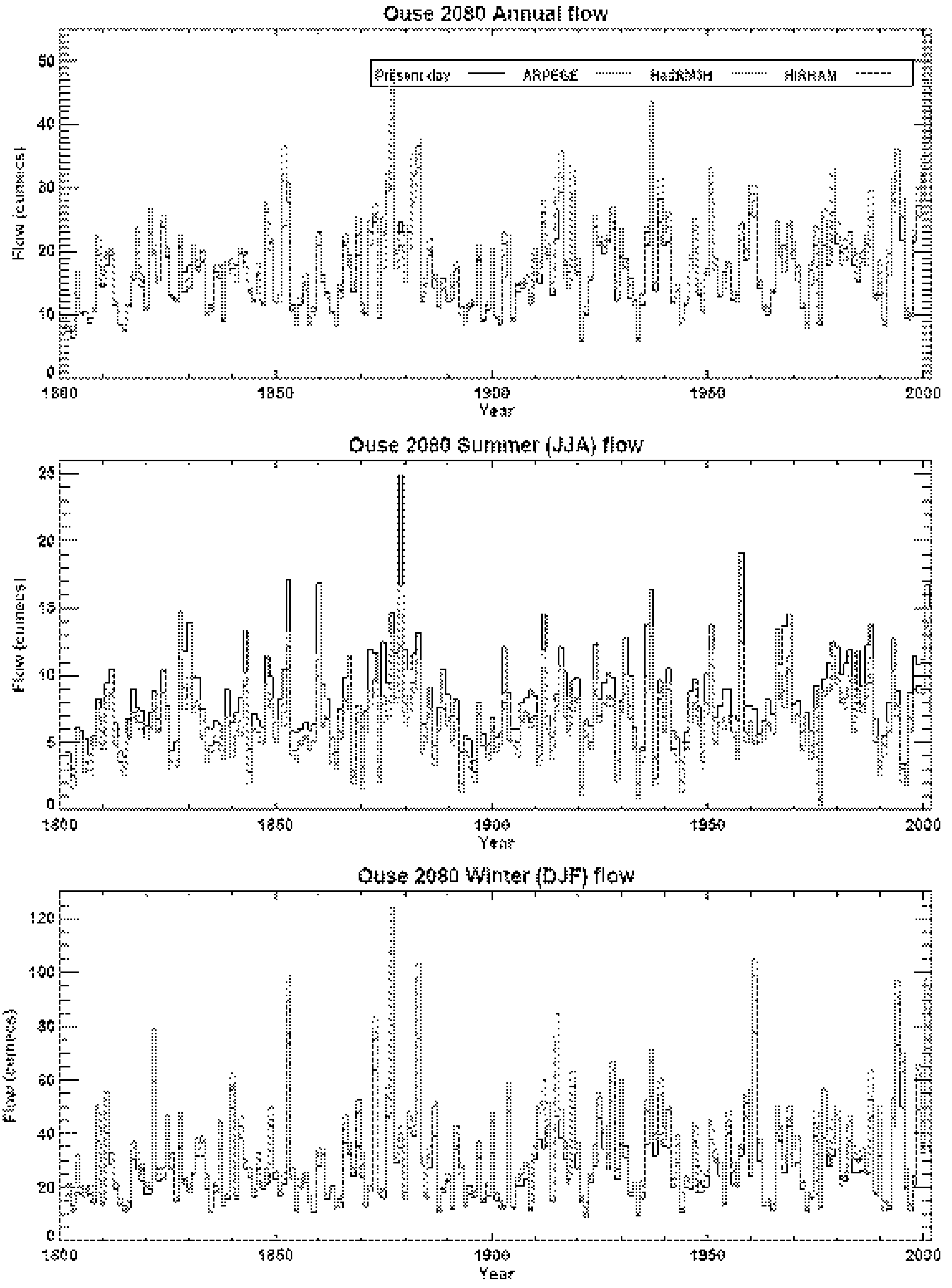

Figure A1-2b. Present-day and future flows for the Ely Ouse at Denver Sluice (cumecs). Top left: mean annual cycle of flows. Time series of annual-mean, summer-mean and winter-mean flows. The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

For the Eden (Figures A1-3 and A1-4), the long-term memory of past rainfall is only three months (compared to 18 for the Ely Ouse), so here, despite the future increase in flows during the winter half of the year, more pronounced flow decreases are simulated during the summer months than was the case for the Ely Ouse, except for the ARPEGE scenario for which the rainfall decreases are more muted over the Eden than over the Ely Ouse. The future scenarios suggest an amplified annual cycle of flow in the Eden. The differences between RCM scenarios manifest themselves most strongly between July and October, with the most pronounced flow decreases under HadRM3H conditions and least pronounced flow decreases under ARPEGE conditions. The long-term average annual-mean flow increases slightly under the ARPEGE future scenario for EdenTS and EdenWB and under HadRM3H for EdenTS, but decreases slightly under HadRM3H for EdenWB and for both catchments under the HIRHAM scenario. The shorter memory of the Eden catchments also results in simpler behaviour of the perturbed flow time series – for example, nearly all the future summer flow values are lower than their equivalent historical value, while the reverse is true for the winter values.

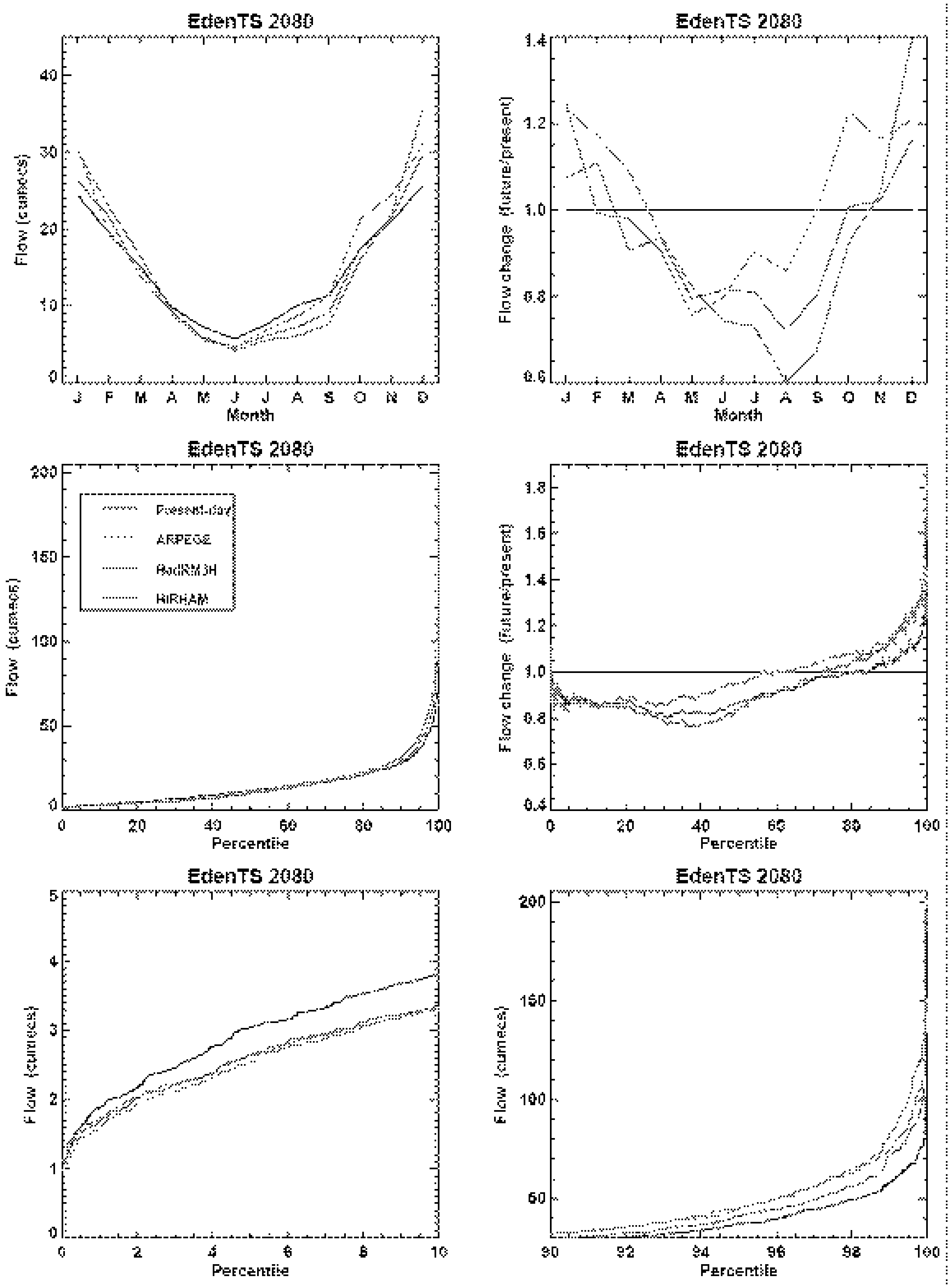

Figure A1-3a. Present-day and future flows for the Eden at Temple Sowerby (cumecs). Top left: mean annual cycle of flows. Top right: mean annual cycle of flows divided by present-day annual cycle. Other rows: flow percentiles (as per previous plot). The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

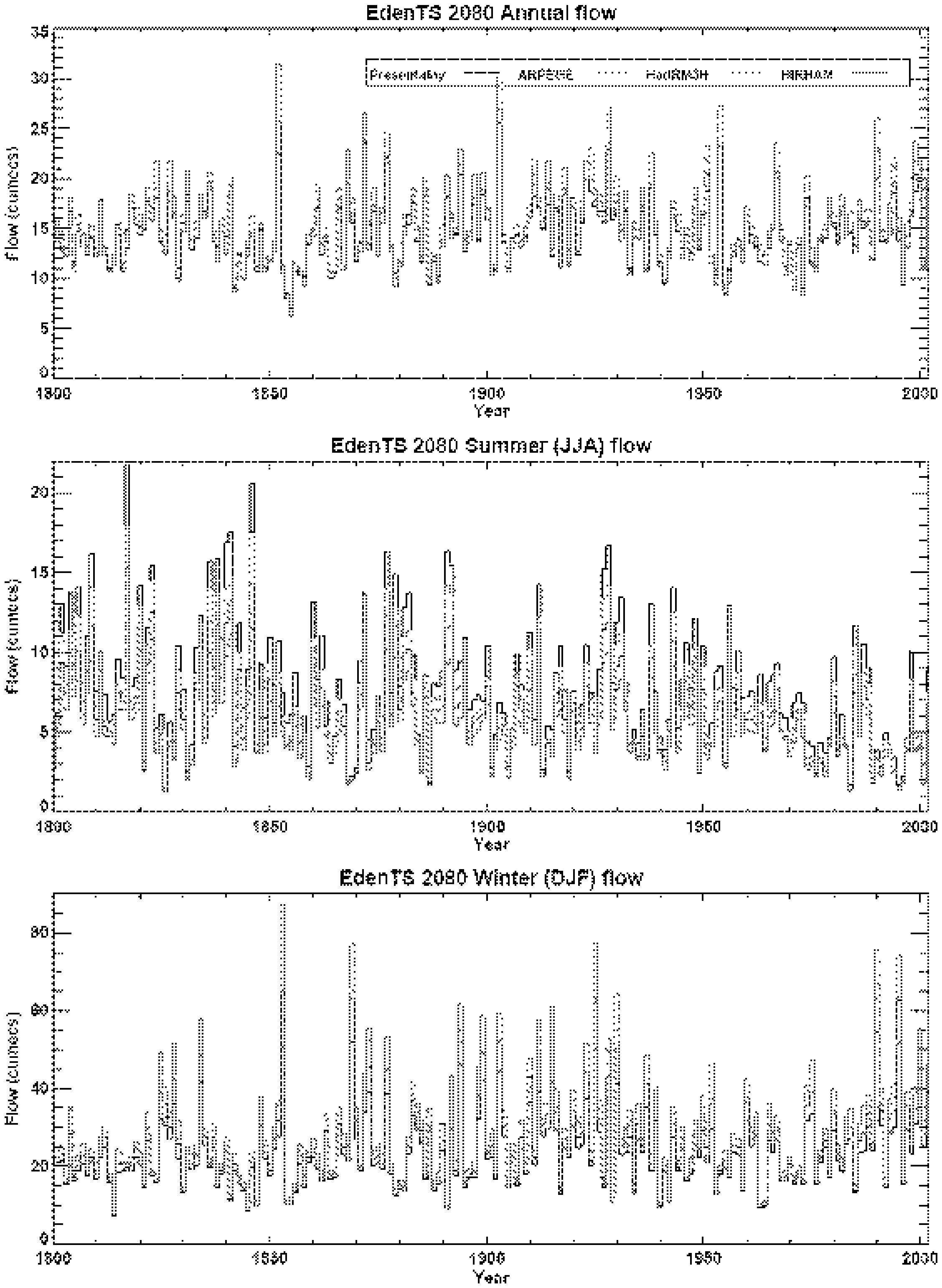

Figure A1-3b. Present-day and future flows for the Eden at Temple Sowerby (cumecs). Top left: mean annual cycle of flows. Time series of annual-mean, summer-mean and winter-mean flows. The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

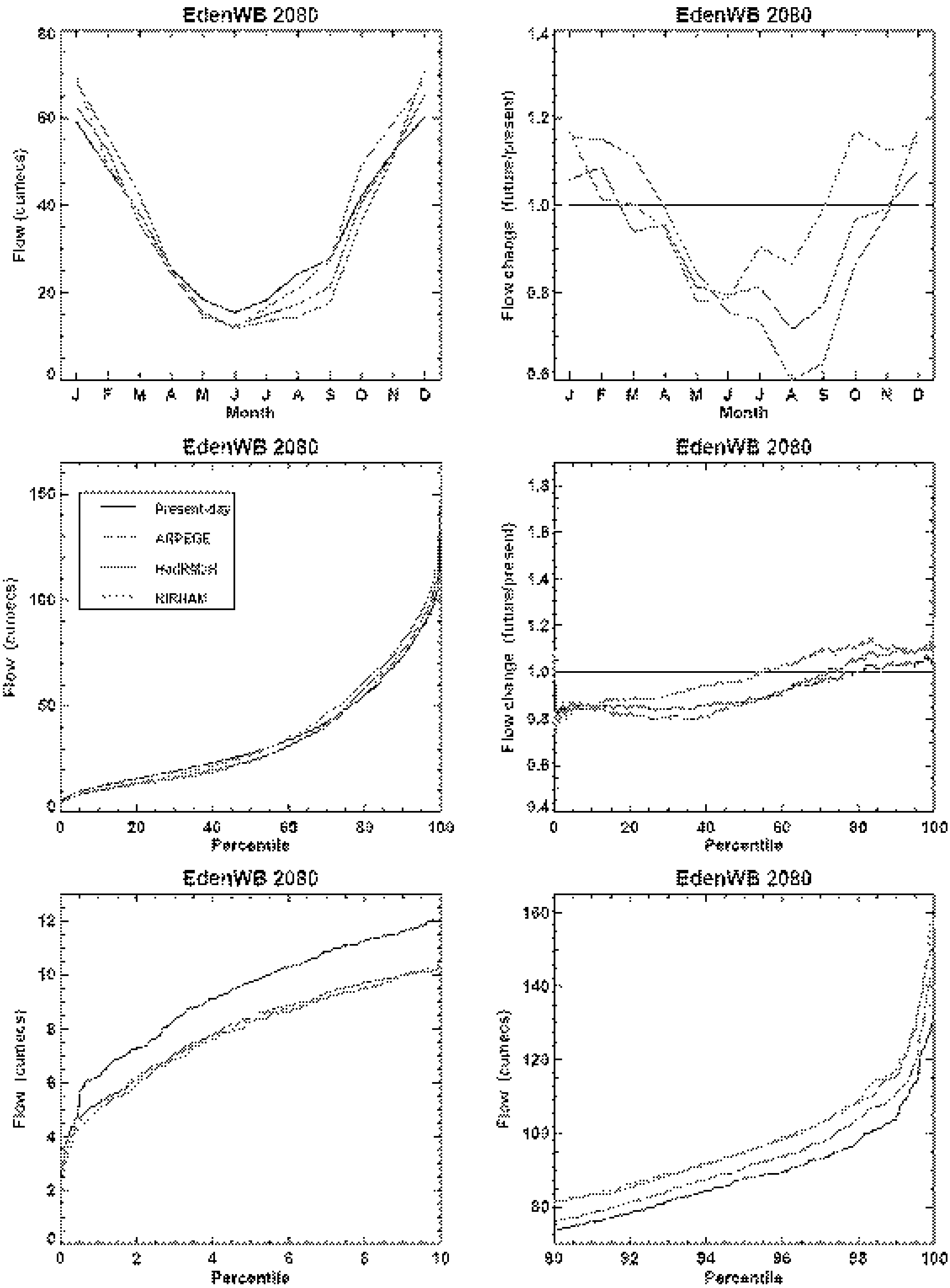

Figure A1-4a. Present-day and future flows for the Eden at Warwick Bridge (cumecs). Top left: mean annual cycle of flows. Top right: mean annual cycle of flows divided by present-day annual cycle. Other rows: flow percentiles (as per previous plot). The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

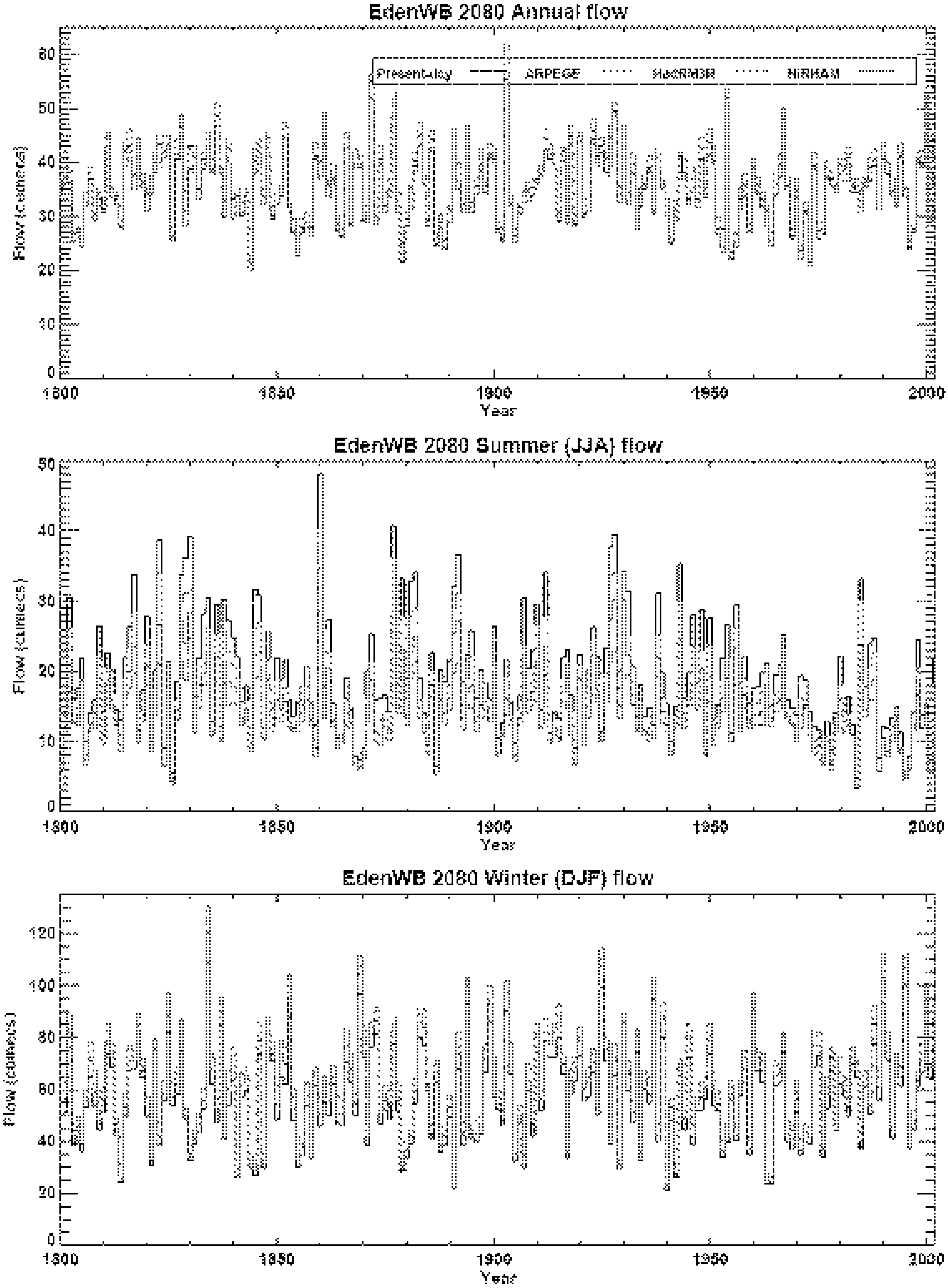

Figure A1-4b. Present-day and future flows for the Eden at Warwick Bridge (cumecs). Top left: mean annual cycle of flows. Time series of annual-mean, summer-mean and winter-mean flows. The present-day flows are black, while the future data are green (ARPEGE), brown (HadRM3H) and pink (HIRHAM).

The future daily flows

Finally, the daily sequences for the required input sites for water resource modelling were developed using the technique described in Jones *et al.* (2006a). This combines a simple regression between the logarithms of flow values and a resampling technique that selects an historic daily sequence from the available daily record. The regression model is used to estimate the monthly-mean flow at the target site from the reconstructed monthly flows of the Ely Ouse or Eden, and then the resampling technique is used to select the historic daily sequence that has the closest monthly average flow to that predicted by the regression model.

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Appendix 2 Approaches to water resources system modelling

Introduction

Water companies estimate the hydrological yields and deployable outputs of individual sources and water resource zones based on the principles set out in the Environment Agency document, *Reassessment of water company yields* (Environment Agency, 1997). The water resource models OSAY and MOSPA, used by Anglian Water and United Utilities respectively, are two examples of code developed to estimate reservoir yield or the conjunctive yield based on the interaction of a number of different water supply sources. The models are most useful for modelling complex systems, involving several sources and interacting constraints on water use. Modelling single sources is relatively straightforward and a simplified Excel model was developed to:

- ensure consistent assumptions were applied to models developed for the East of England and the North West;
- provide greater flexibility for completing climate change impact assessments, for example by allowing repeat simulations and sensitivity testing.

Data sources/Availability

The following time series were required to run the spreadsheet model:

- river flows at the point of abstraction based on: (a) flows currently used by the water company and (b) empirical modelling as described in Part 2 of the research report;
- natural inflow into the storage reservoir or lake (as above).

The time series used for flow were identical to those used in the OSAY and MOSPA modelling.

The following reservoir parameters were required:

- licence conditions;
- maximum pump capacity;
- reservoir volume;
- dead storage;
- emergency storage;
- reservoir surface area-volume relationship (assumed);
- freshets / compensation flow
- start volume;
- target demand;
- demand profile;
- outlet control (for lakes);
- spill equation;

These data were based on parameters used in the OSAY and MOSPA modelling.

Methodology

The spreadsheet model estimated reservoir volume as follows:

$$V_t = V_{t-1} + A + Q_{in} - Q_{spill} - Q_{out} - D$$

Vt	Volume for day t
Vt-1	Volume for previous day
A	Pumped abstraction from river source (limited by pump capacity and licence)
Qin	Natural inflow
Qout	Compensation flow
D	Demand
Qspill	Spill volume determined as an excess natural inflow for pumped storage reservoirs or based on a spill equation for a natural lake

The river flow data (Qin and for estimation of A) were 'de-naturalised' using available information on abstractions and effluent returns to estimate an average annual net return or abstraction. This was multiplied by a set of monthly artificial influence factors. This was a simpler approach than that used in the data preparation programmes for OSAY that consider different profiles for types of abstractions and effluent returns.

The amount of abstraction 'A' was limited by pump capacities or specified minimum residual flows at the abstraction point. For the Anglian models, abstraction was typically limited by pump volumes.

Surface water evaporation, direct rainfall and run-off from reservoir banks were ignored. This was the case in the detailed OSAY and MOSPA modelling used to support this project and is an assumption that is often used in estimating yields, as these components are small and assumed to roughly cancel each other out.

Average demand was multiplied by a monthly demand profile to increase demand in the summer months and reduce demand in the winter.

In order to estimate the yield of the system, all constraints were considered and the average demand was 'ramped up' (by increments of 0.1 Ml/d) incrementally until the system 'failed' (that is, demand was not met for between one and seven days within the same year).

The simple spreadsheet model was developed to calculate a mass balance of a single reservoir with natural inflows and pumped abstractions from one river. Rutland Water (Anglian Water) is more complex and involves transfers from the River Nene to the River Welland and linkages with the operation of other reservoirs in the Ruthamford system. Therefore the Rutland system was simplified with flows from both rivers and other key parameters lumped together and the use of an effective 'hands-off flow' that was calibrated so that the simplified model produced the same yield as OSAY and reproduced the reservoir behaviour (see figures below).

A spreadsheet and example spill equations were provided for Ennerdale and Crummock by United Utilities (Makin, pers. comm.). The spill equations used in MOSPA are based on a method for ‘discretising’ daily inflow into two hourly blocks and applying a power function of the form:

$$Y = a X^{b}$$

where Y is the spill volume in Ml/d, X is the excess water volume (Ml) and a and b are parameters based on fitting the equation empirically using observed reservoir levels and flows. The b parameter is typically close to 1.5 so the formula is similar to a simplified broad-crested weir equation. This approach provides good spill estimates using a daily time-step and therefore avoids the need for hydraulic modelling of the lake outflow.

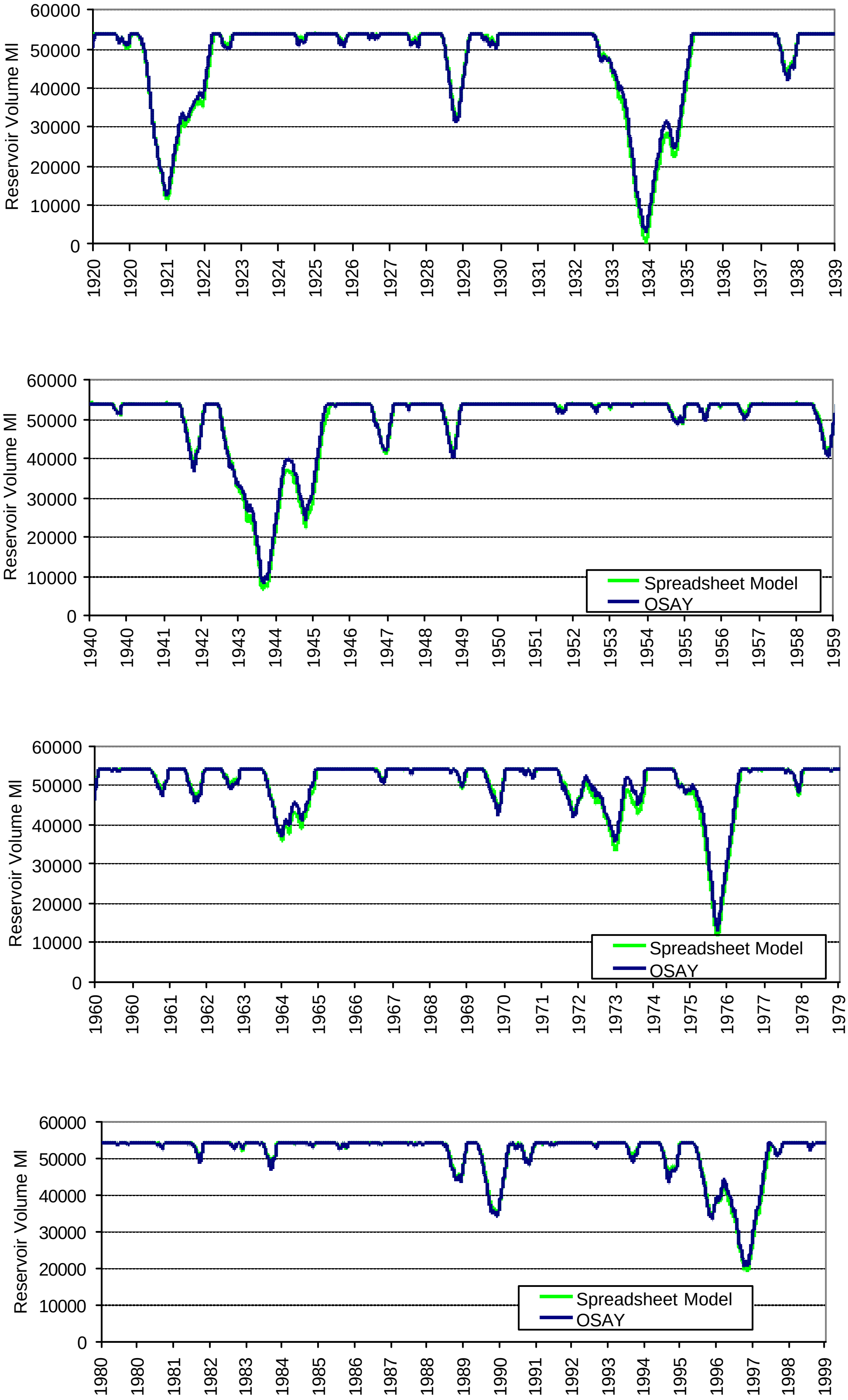

Figure A2-1: Comparison of spreadsheet model to OSAY outputs for Grafham reservoir (OSAY yield 285 Ml/d, spreadsheet model yield 290 Ml/d)

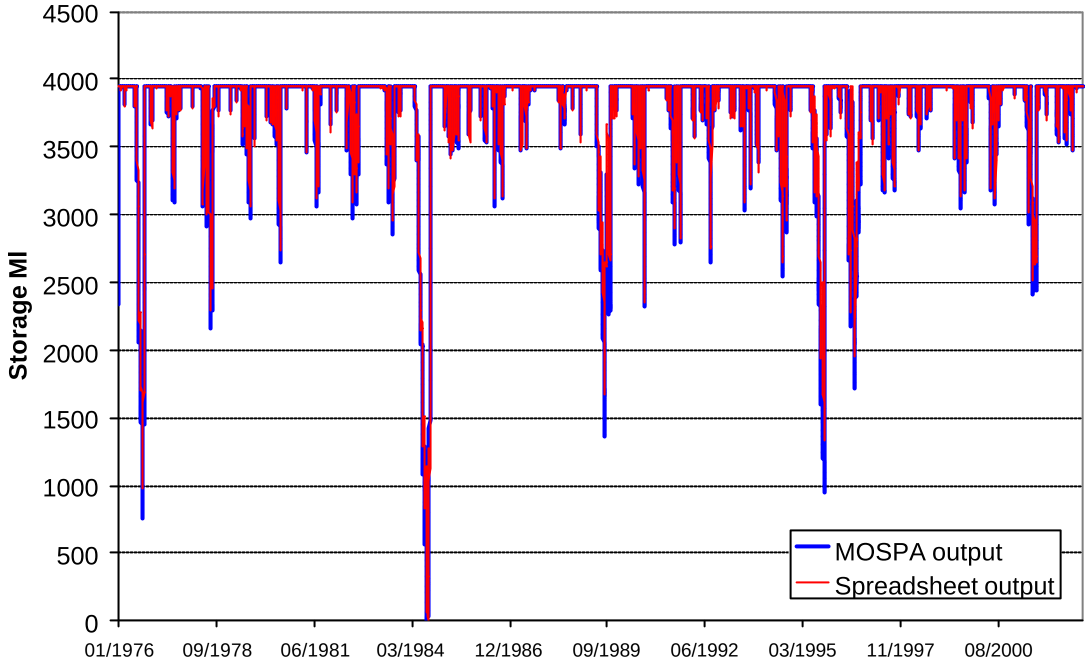

Figure A2-2: Comparison of spreadsheet model to MOSPA outputs for Ennerdale. (Yield is 55.23 Ml/d for both models)

Appendix 3: Detailed outputs from Anglian Water's resources modelling

Method and assumptions in the modelling of the yield of AWS reservoirs

1. OSAY 'no restrictions' (NR) analysis

1.1 Method

Yield assessment with the OSAY model is a two-step process.

The first step is to run the Data Preparation Program (DPP). This reads all daily river flows, denaturalizes these to catchment conditions for a specific year (1996 in the current work) and calculates maximum potential reservoir inflows, taking into account such constraints as abstraction licence conditions and pump capacities. In addition the data files contain potential maximum inflows enhanced by reduced MRFs. These are only used for the LoS yield analysis and are ignored during the NR analysis.

The second step is to run the OSAY model for determining reservoir yield. This involves simulating daily reservoir storage over the historic period using the potential maximum inflows output from the DPP. The yield criterion is that the reservoir storage must not drop below the bottom water level during the simulation (Page, 1997). For the current project, the OSAY software was enhanced to allow simulations up to 240 years in length.

1.2 Assumptions

1.2.1 River Flow Series

(a) General (all rivers)

(i) AWS 1920-2003 daily series were produced with the Stanford Watershed Model (Mott Macdonald, 2005).
(ii) CRU 1801-2002 daily analogue series (Environment Agency, 2005) and climate model perturbed series were produced by the Climatic Research Unit.

(b) Grafham

(i) Dummy files of River Great Ouse flow are used for Brownshill (Browndm2.sim and browndum.sim). See below.

1.2.2 Data Preparation

(a) General (all reservoirs)

(i) Naturalised series (Grafham, Rutland and Pitsford analysis) were de-naturalized with the same artificial influences as for the 1997 yield assessment (Mott MacDonald, 1997).
(ii) Minimum residual flows (MRF) at abstraction sites are followed exactly - there is no allowance for operational safety margins.
(iii) Direct reservoir rainfall and evaporation have been excluded.
(iv) Details are given in data preparation program input files (*.dat).

(b) Grafham

(i) Although the data preparation program reads river flow data at Brownshill Staunch on the R Gt Ouse, the data plays no part in the analysis (AWS hold an abstraction licence for Brownshill but the site is not operational).
(ii) The pump capacity at Offord (459 Ml/d) constrains pumping rather than the maximum daily licence (485 Ml/d).
(iii) The Offord 'weekend rule' is ignored (the rule is that for the period June - September, if the sum of the average rate of flow in the R. Ouse and the average rate of abstraction over the seven days preceding 1200 hours on Friday in less than 227 Ml/d, no water shall be pumped during the subsequent Saturday and Sunday). Exclusion has previously been shown to increase yield by around 0.4 per cent (Mott MacDonald, 1997).
v) Intake pump scheduling is excluded.

(c) Rutland

(i) The data preparation program (DPP) includes artificial influences for the Welland catchment (at Tinwell), Nene (at Orton and Duston), Eye Brook reservoir (Welland catchment), Pitsford reservoir (Nene catchment), Ravensthorpe and Hollowell reservoirs (Nene catchment). The DPP includes mini-models of Eye Brook, Pitsford, Ravensthorpe and Hollowell reservoirs as part of the de-naturalisation. The alternative option – reading output from prior yield assessment of Pitsford, Ravensthorpe and Hollowell – is not used.
(ii) The Gwash-Glen transfer (release from Rutland Water to the R Gwash for transfer to support the R Glen) is set to zero.
(iii) Intake pump scheduling is excluded.
(iv) The pump capacities at Wansford (490 Ml/d) and Tinwell (360 Ml/d) constrain pumping rather than the maximum daily licences (763 and 545 Ml/d respectively).

d) Pitsford, Ravensthorpe and Hollowell

(i) The pump capacity at Duston (91 Ml/d) for Pitsford refill constrains pumping rather than the maximum daily licence (182 Ml/d).

1.3 'No restrictions' (NR) yield analysis

(a) General

(i) All analyses use a daily time step.
(ii) Reservoir capacity is defined as gross storage less an allowance for 'freeboard'.
(iii) Dead storage is always set to the lowest intake level.
(iv) Emergency storage is always set to zero.
(v) None of the LoS-related parameter values (Page, 1997) are operative under the NR analyses - that is, none of: risk, maximum drought length, number of augmentation and restriction levels, target return periods, minimum duration of each restriction, maximum number of months to count as one event, scaling factors for worst months no pumping and 'plan' inflows, margin before restrictions lifted, demand reduction factors.
(vi) Monthly target levels are 'required' and always set to 100 per cent so that the natural reservoir catchment inflows are displayed in the output.

2. OSAY levels of service analysis

2.1 Method

The potential reservoir inflows used for the LoS analysis are the same as those prepared with the DPP for the NR yield analysis.

The OSAY method is described in Page (1997) and Clarke et al (1980). It involves the derivation of rules for the introduction of measures taken to conserve water during dry periods, the simulation of these rules over the historic flow record, and the comparison of the resulting frequencies with target levels of service (LoS).

2.2 Assumptions

2.2.1 River flow series

River flow series were the same as used in the DPP for the NR analysis.

2.2.2 Data preparation

The DPP is run only once for each combination of reservoir and river flow, and the output from these runs are used for both NR and LoS analysis. The output includes potential maximum inflows for normal and drought conditions (see 1.1, 'first step'). The difference between these is that the latter are higher due to reductions in MRFs during the periods during which drought orders are in operation.

2.2.3 OSAY yield analysis

a) General
- (i) All analyses use a daily time step.
- (ii) Reservoir capacity is defined as gross storage less an allowance for 'freeboard'.
- (iii) Emergency storage is always set to zero.
- (iv) The 'risk' or drought severity parameter used is set to WHD. This means that the lowest trigger curve is calculated using the inflows for the worst historic drought rather than the inflows calculated for a return period of one in x years.
- (v) Maximum drought length = 24 months. This is used in the derivation of the trigger curves.
- (vi) Number of augmentation levels = 1 (corresponding to LoS 2 and hence trigger curve 2).
- (vii) Number of demand restriction levels = 3 (corresponding to LoS 1-3 and hence trigger curves 1-3).
- (viii) Target LoS periods = 1:10 for LoS 1, 1:40 for LoS 2 and 1:100 for LoS 3.
- (ix) The minimum duration of each restriction event = 3 months.
- (x) The maximum number of months to count as one event = 12.

(xi) The scaling factor for the worst month's no pumping is a factor used for helping to 'match' simulated LoS with target LoS/maximize yield/'match' simulated storage with dead storage. The factor varies and = 0 (Grafham), 0 or 1 (Pitsford), 0 (R&H), 0 or 1 (Rutland).

(xii) The scaling factor for the 'plan' inflows = 1. This parameter affects the spacing of the control curves. One is the default value.

(xiii) A standard margin is allowed before each demand restriction is lifted to prevent a 'hunting' effect.

(xiv) Monthly reservoir target levels are set to 100 per cent for all months in all reservoirs.

(xv) The yield assessment procedure is as follows:

A. Run OSAY in automatic mode at a monthly time step. This derives an initial yield and control curves.
B. Carry out a daily automatic mode run.
C. If the minimum storage is higher than the dead storage and the LoS criteria are not met follow the procedure described below.

(x) Set the "scaling factor for worst month's no pumping" to 0 rather than 1; this means that pumping is available in all months, as is the case for the NR analysis.

(y) Reduce the dead storage until the minimum simulated storage just exceeds 30 days' demand.

(z) If the minimum storage still exceeds 30 days' demand with zero dead and emergency storage, carry out sensitivity runs in which the control lines are lowered and the demand increased.

3. References

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Appendix 4: Detailed results for both case studies

East of England case study

	No restrictions		
Description of run	**Demand**	**% change**	**Ml/d change**
Grafham AWS 1920-2003	*290.0*		
Grafham CRU 1920-2002	368.0	*21*	*Compared to AWS data above*
		-9	Compared to extended series on line below
Grafham CRU 1801-2002	338.8	0	0.0
G - ARPEGE 2020 1801-2002	332.0	-2	-6.8
G - HADLEY 2020 1801-2002	340.0	0	1.2
G - HIRHAM 2020 1801-2002	340.0	0	1.2
G - ARPEGE 2050 1801-2002	325.0	-4	-13.8
G - HADLEY 2050 1801-2002	340.0	0	1.2
G - HIRHAM 2050 1801-2002	341.0	1	2.2
G - ARPEGE 2080 1801-2002	312.0	-9	-26.8
G - HADLEY 2080 1801-2002	339.0	0	0.2
G - HIRHAM 2080 1801-2002	341.0	1	2.2
Rutland AWS 1920-2003	299.0		
Rutland CRU 1920-2002	446.0	33	
		-12	
Rutland CRU 1801-2002	397.0	0	0.0
R - ARPEGE 2020 1801-2002	n.c.	n.c.	n.c.
R - HADLEY 2020 1801-2002	396.0	0	-1.0
R - HIRHAM 2020 1801-2002	n.c.	n.c.	n.c.
R - ARPEGE 2050 1801-2002	n.c.	n.c.	n.c.
R - HADLEY 2050 1801-2002	n.c.	n.c.	n.c.
R - HIRHAM 2050 1801-2002	n.c.	n.c.	n.c.
R - ARPEGE 2080 1801-2002	n.c.	n.c.	n.c.
R - HADLEY 2080 1801-2002	394.0	-1	-3.0
R - HIRHAM 2080 1801-2002	n.c.	n.c.	n.c.
Pitsford AWS 1920-2003	43.8		
Pitsford CRU 1920-2002	63.5	31	
		-9	
Pitsford CRU 1801-2002	58.3	0	0.0
P - ARPEGE 2020 1801-2002	57.0	-2	-1.3
P - HADLEY 2020 1801-2002	58.0	-1	-0.3
P - HIRHAM 2020 1801-2002	57.9	-1	-0.4
P - ARPEGE 2050 1801-2002	56.0	-4	-2.3
P - HADLEY 2050 1801-2002	57.6	-1	-0.7
P - HIRHAM 2050 1801-2002	57.9	-1	-0.4
P - ARPEGE 2080 1801-2002	48.3	-21	-10.0
P - HADLEY 2080 1801-2002	59.2	2	0.9
P - HIRHAM 2080 1801-2002	57.9	-1	-0.4
Ravensthorpe & Hollowell AWS 1920-2003	8.3		
Rav & Holl CRU 1920-2002	10.0	17	
		-16	

Description of run	No restrictions		
	Demand	% change	Ml/d change
Rav & Holl CRU 1801-2002	8.6	0	0.0
RH - ARPEGE 2020 1801-2002	8.6	0	0.0
RH - HADLEY 2020 1801-2002	8.8	2	0.2
RH - HIRHAM 2020 1801-2002	8.7	1	0.1
RH - ARPEGE 2050 1801-2002	8.7	1	0.1
RH - HADLEY 2050 1801-2002	9.1	5	0.5
RH - HIRHAM 2050 1801-2002	8.9	3	0.3
RH - ARPEGE 2080 1801-2002	8.8	2	0.2
RH - HADLEY 2080 1801-2002	9.3	8	0.7
RH - HIRHAM 2080 1801-2002	9.2	7	0.6

North West case study

Description of run	No restrictions		
	Demand	% change	Ml/d Change
Ennerdale United Utilities 1955-2004	48.5		
E - CRU 1801-2002	55.2	14	Increase compared to above
E - 2020 Arpege 1800-2002	49.0	-13	-6.2
E - 2020 Hadley 1800-2002	47.0	-18	-8.2
E - 2020 Hirham 1800-2002	47.3	-17	-7.9
E - 2050 Arpege 1800-2002	47.0	-18	-8.2
E - 2050 Hadley 1800-2002	44.4	-24	-10.8
E - 2050 Hirham 1800-2002	47.7	-16	-7.5
E - 2080 Arpege 1800-2002	39.5	-40	-15.7
E - 2080 Hadley 1800-2002	41.3	-34	-13.9
E - 2080 Hirham 1800-2002	40.8	-35	-14.4
Crummock United Utilities 1955-2004	27.4		Note that yield is constrained by licence
C - 2020 Arpege 1800-2002	27.4		
C - 2020 Hadley 1800-2002	27.4		
C - 2020 Hirham 1800-2002	27.4		
C - 2050 Arpege 1800-2002	27.4		
C - 2050 Hadley 1800-2002	27.4		
C - 2050 Hirham 1800-2002	27.4		
C - 2080 Arpege 1800-2002	27.4		
C - 2080 Hadley 1800-2002	27.4		
C - 2080 Hirham 1800-2002	27.4		
Additional sensitivity test. If licence constraints are removed:-			
C - CRU 1800-2002	43.5		
C - 2080 Arpege 1800-2002	31.2	-39	-12.3

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