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for Climate Change Research

Sustainable water resources: A framework for assessing adaptation options in the rural sector

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Project T2/33

FINAL REPORT

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The report is available from the Tyndall website: www.tyndall.ac.uk/

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Sustainable water resources:
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Tyndall Centre Technical Report No. 44
November 2005

This is the final report from Tyndall research project T2.33 (Sustainable water resources: A framework for assessing adaptation options in the rural sector).

The following researchers worked on this project:

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Abstract

This project developed a framework to assess how the irrigated agriculture and turf grass leisure sectors in England could adapt to climate change impacts on water resources.

Two catchments (the Nar and Wensum) in East Anglia provided case studies for hydrological, crop yield and land-use modelling; farmer interviews were held across East Anglia, and the golf sector study covered England and Wales. Future climate scenarios were developed from the UKCIP02 dataset, using the high and low emission scenarios for the 2020s and 2050s.

For all these scenarios, hydrological modelling showed, even by the 2020s, groundwater recharge is reduced, ground water levels are lower, and both summer and winter river flows fall despite higher winter rainfall. These changes imply major reductions in water available for abstraction and its reliability. It would be impossible to meet the current environmental river flow objectives even without abstraction.

Crop yield and land use modelling suggested that farmers will still grow high value irrigated crops such as potatoes and field-scale vegetables. If water resources are limited, they will reduce irrigation of other crops and invest in farm reservoirs, using winter abstraction. However, the extra costs will reduce farm net margins, and make farm businesses more vulnerable. Farmer interviews confirmed that cropping changes and reservoirs are the preferred adaptations. A prototype knowledge elicitation tool was developed to improve understanding of farmer behaviour.

A survey of golf course irrigation in England and Wales revealed courses are about equally split between using mains water and direct abstraction. If water is limited, many could adapt by restricting irrigation to greens and tees; others could use reservoirs, re-use and water harvesting. However, client/member pressure is for fully irrigated surfaces.

Overall, the study revealed that adaptations options do exist, albeit with costs. Better information on the climate impacts and careful regulation would reduce the risks of users adopting individual adaptations that are not optimal overall and/or inappropriate.

Keywords: Irrigation, water, agriculture, golf, adaptation.

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ACRONYMS, ABBREVIATIONS and SYMBOLS

ABM	Agent based model
CAMS	The Environment Agency’s Catchment Abstraction Management Strategies
CO_2	Carbon dioxide
Defra	UK Government’s Department for Environment, Food and Rural Affairs
EA	Environment Agency
ETo	Reference evapotranspiration
ERFO	Environment River Flow Objective, within CAMS
GIS	Geographical Information System
ha	hectare
HOF	hands-off flow, a condition on some licences stopping abstraction.
KnETs	Knowledge elicitation tool
LARS	Weather generator used for yield modelling
MAFF	(previously) UK Government’s Ministry of Agriculture, Food and Farming
MIP	Mixed integer programming
Ml	Megalitre; equal 10^6 litres, 10^3 m^3 and 1 tcm (thousand cubic metres)
NALD	The Environment Agency’s National Abstraction License Database
OSR	Oilseed rape
PSMD	Potential soil moisture deficit
Q95	Flow which is equalled or exceeded 95% of the time
RAM	The Resource Allocation Methodology, within CAMS
SMD	Soil moisture deficit
UKCIP	UK Climate Impacts Programme
UKCIP02	UKCIP climate change dataset published in 2002 (Hulme *et al.*, 2002)
2020	UKCIP02 2020 scenario, for the 30 years centred around 2025
2050L	UKCIP02 2050 low emission scenario, for the 30 years centred around 2055
2050H	UKCIP02 2050 high emission scenario, for the 30 years centred around 2055

Section 1: Overview of project work and outcomes

Abstract

This project developed a framework to assess how the irrigated agriculture and turf grass leisure sectors in England could adapt to climate change impacts on water resources.

Two catchments (the Nar and Wensum) in East Anglia provided case studies for hydrological, crop yield and land-use modelling; farmer interviews were held across East Anglia, and the golf sector study covered England and Wales. Future climate scenarios were developed from the UKCIP02 dataset, using the high and low emission scenarios for the 2020s and 2050s.

For all these scenarios, hydrological modelling showed, even by the 2020s, groundwater recharge is reduced, ground water levels are lower, and both summer and winter river flows fall despite higher winter rainfall. These changes imply major reductions in water available for abstraction and its reliability. It would be impossible to meet the current environmental river flow objectives even without abstraction.

Crop yield and land use modelling suggested that farmers will still grow high value irrigated crops such as potatoes and field-scale vegetables. If water resources are limited, they will reduce irrigation of other crops and invest in farm reservoirs, using winter abstraction. However, the extra costs will reduce farm net margins, and make farm businesses more vulnerable. Farmer interviews confirmed that cropping changes and reservoirs are the preferred adaptations. A prototype knowledge elicitation tool was developed to improve understanding of farmer behaviour.

A survey of golf course irrigation in England and Wales revealed courses are about equally split between using mains water and direct abstraction. If water is limited, many could adapt by restricting irrigation to greens and tees, without licences; others could use reservoirs, re-use and water harvesting. However, client/member pressure is for fully irrigated surfaces.

Overall, the study revealed that adaptations options do exist, albeit with costs. Better information on the impacts and careful regulation would reduce the risks of users adopting individual adaptations that are not optimal overall and/or inappropriate.

Objectives

UK farmers apply supplemental irrigation to many high value crops, particularly potatoes, and water demand is growing at 2 to 3% every year. Irrigation in the outdoor leisure industry, particularly for golf, is believed to be growing even faster. However, water resources in many catchments are already over-committed and in some over-abstracted. Even without climate change, current trends are unsustainable. Climate change is expected to result in higher water needs, and reduced water availability, particularly in the summer months when irrigation use is highest.

This project set out to study future scenarios and likely responses and adaptations within these two sectors.

Work undertaken

Future climate scenarios were based on the UKCIP02 dataset, using the 2020s High, 2050s Low and 2050s High emissions scenarios. Two catchments (the Nar and Wensum) in East Anglia were used as case studies, though the farmer interviews and golf sector survey extended more widely.

Hydrological and hydro-geological models were used to assess impacts on water resources. River flows were simulated using two hydrological models, calibrated against baseline flows. The primary output indicator was the flow duration curve, describing the variability in river flows from day-to-day. The Environment Agency's Resource Assessment Methodology (RAM) was then to assess permissible abstraction.

The impacts on crop yield were analysed using a semi-empirical crop model with statistically generated daily weather data, for 200 scenario years, 13 crops and 3 soil types within the 2 catchments. The crops were winter wheat, winter barley, spring barley, sunflowers, winter oilseed rape, potatoes (non-irrigated and 3 irrigation levels) and sugar beet (non-irrigated and 3 irrigation levels). The yields were then adjusted to allow for the fertilisation effects of increased atmospheric CO_2 concentrations.

A land management model was then used to explore impacts and adaptations at the catchment level. In this model, management decisions are taken at farm (rather than catchment) level; farmers make decisions based on historic data, interactions can occur between farms and some adaptations such as reservoirs are multi-year commitments. At farm-level, the model maximises farm net margin by optimising crop, animal, labour, machinery, storage, animal housing and irrigation mix. In total 132 farms were modelled. The model runs continuously for the whole study period; outcomes of previous years (e.g. profitability of a particular crop) affect current year decision making. For each scenario, the model was run 100 times, allowing the effects of uncertainty and stochastic variability to be included.

Results from the land management model were themselves fed back into the groundwater model to ascertain the impacts on groundwater levels and water availability.

Semi-structured farmer interviews were used to assess how individual farmers have adapted to water scarcity in the past, and how they might adapt to climate change in the future. Their views on water resources, understanding of climate change impacts, and potential adaptation options were explored. A Knowledge Elicitation Tool (KnETs) was developed and trialled as an innovative method of increasing understanding of adaptation and as a basis for the development of an agent-based model (ABM) for further understanding farmer behaviours.

Golf irrigation is the major outdoor leisure water user, and expected to be significantly impacted by climate change. A postal survey of golf courses across England and Wales was undertaken to provide base data on water use and irrigation practices, and to explore the available and preferred adaptation options. The impacts of climate change on soil moisture and turf irrigation needs were modelled. The national survey was supported by in-depth interviews and water use studies on selected courses.

Results

The modelling showed that for all the scenarios considered groundwater recharge is substantially reduced, summer river flows fall considerably, and winter river flows also fall despite higher winter rainfall. These changes imply major reductions in the water available for abstraction and its reliability, and limitations to the extent to which winter reservoirs can resolve shortages. The results suggested it may be impossible to maintain the current environmental river flow objectives even if all abstraction ceased. It is important for abstractors to know how the government will split the flow reduction between public water supply abstraction, other direct abstraction and the environment.

The crop yield modelling suggested that, in general, it is only under the 2050s High emissions scenario that climate change begins to have an impact on a wide range of crops. An uncertainty here is the size of any fertilisation gain at field scale from higher atmospheric CO_2 levels. The land use modelling suggested that farmers will continue to grow high value irrigated crops such as potatoes. If water resources are limited, they will reduce irrigation of lower value crops, and then invest in farm reservoirs allowing more winter abstraction. However, the extra costs would have a large impact on farm net margins, and make the farm businesses more financially vulnerable. Where existing abstraction licenses are already highly used, changes are adopted sooner. Water trading as an adaptation could have a large impact, especially if permitted where there are unused licences.

The farmer interviews confirmed that they were already concerned about water shortages and aware of climate change, although they are mainly focussed on shorter-term issues. Most do not really believe the present forecasts, and see climate change as a gradual process that they will adapt to when (if) it occurs. Cropping changes and winter reservoirs are their preferred adaptations to water scarcity; they see little scope for further improving water management.

The golf sector survey revealed that courses are equally split between mains water and direct abstraction, and many use a combination of sources for security. Many courses could adapt by restricting irrigation to greens and tees. Combined with small reservoir storage and/or increased mains water use, their abstractions may be small enough to abstract without licences. However, client/member pressure is for irrigation is intense, to emulate international course standards. This suggests winter reservoirs, re-use and/or water harvesting may be preferred. In a free water trading market, golf courses are likely to out-bid farmers growing low-value crops.

Overall, the study revealed that adaptation options do exist, albeit with costs. Appropriate regulation and better guidance and information on the impacts of climate change in both the short and long term, including changes in extremes, would reduce the risks of individual adaptations that are not beneficial overall, or mal-adaptations such as excessive reservoir construction.

The research has highlighted the need for the regulators to address the issue of how reducing water resources will be allocated between existing abstractors and the environment under a changing climate. Climate change needs to be built into the information available from the Environment Agency's Catchment Abstraction Management Strategies (CAMS). The regulators need to critically re-appraise the present focus on raising efficiency, and introduce a licence trading system that does allow water to move to the highest value user. The promotion of reservoirs needs to be undertaken with care, in view of possible lower winter flows in some catchments.

Relevance to Tyndall Centre research strategy and overall objectives.

The project fitted predominantly within the "Adapting to Climate Change" theme (Theme 3), particularly Q1 ("Who adapts, to what, and why…?") and Q2. ("What influences …ability to adapt...?"). It confirms that water users in both the irrigated agriculture and outdoor leisure industries will have to adapt, and that there are adaptation routes available, albeit at increased cost. It suggests that adaptation is being driven more by pressures from legislation and water regulation rather than by climate change *per se*. Results also indicate (Q3. "Are there critical thresholds..?") that because of the different water availability status in each catchment, there will be no single critical threshold unless induced through abstraction regulation.

Potential for further work

The study provides a useful baseline on adaptation to water scarcity in these industries for future studies. The study has had and will have impacts on associated research into future water availability, and water demand, regulation and management in both sectors. Some further research is recommended:

- To confirm these results under different climate models and future UKCIP datasets;
- To extend the results to other water-stressed catchments;
- To continue development of the knowledge elicitation tool;
- To undertake case studies of adaptation on selected sites, including environmental impacts;
- To develop a water trading model to investigate the impacts of abstraction licence trading and shares reservoirs;
- To ascertain the impacts of higher atmospheric CO_2 levels on potatoes/vegetables at field level.

Communication highlights

Aspects of the work have already been published in various formats throughout the study, including presentations to members of the agricultural and golf industries and the water regulators.

The final outputs will be presented to farmers and businesses on March 23rd 2006 in an "i10" seminar to be held in the Zuckerman Institute, UEA, Norwich, "Opportunities for agriculture; responding to climate change and regulation".

Refereed journal publications arising from the research to date include:

Bharwani, S. (2006) Understanding Complex Behavior and Decision Making Using Ethnographic Knowledge Elicitation Tools (KnETs**)**. *Social Science Computer Review*, 24, 78-105.

Gibbons, J..M., Ramsden, S.J. and Blake, A (2006) Modelling Uncertainty in Greenhouse Gas Emissions from UK Agriculture at the Farm Level. *Agriculture, Ecosystems and Environment*, 112, 347-355.

Knox JW, Weatherhead EK and Hess TM (accepted subject to revision) Modelling impacts of climate change on soil moisture: implications for irrigation. Climatic Change.

Papers presented at conferences and meetings to date include:

Cornelius Sandhu, Kevin Hiscock, Declan Conway (2004). Sensitivity of groundwater resources in eastern England to climate change; EGU 1st General Assembly, Nice 25 – 30 April 2004.

De Vries TT and Weatherhead EK (2005) Adapting to irrigation water scarcity due to climate change in eastern England. World Water and Environmental Resources Congress, Alaska.

Knox, J.W. (2004) Protecting water resources for golf course irrigation in England and Wales. National Turfgrass Foundation Annual Symposium, Southport, November 2004.

Knox JW (2005). Climate change impacts and adaptation in leisure (golf). Paper to be presented at the Spanish national golf course managers and greenkeepers congress, Pontevedra, Spain, November 2005.

Knox JW and Weatherhead EK (2005). Golf course irrigation: impacts of abstraction licensing, water resources and regulatory change. Four presentations to English Golf Union roadshow meetings, October/November 2005.

Knox JW (2005). Climate change impacts and adaptation in turfgrass production. Paper to be presented at the UK National Turfgrass Association (TGA) annual technical conference, Peterborough, November 2005.

Weatherhead, E.K. and Knox, J.W. (2004). Assessing the impact of climate change on soil moisture and irrigation demand in England and Wales. Royal Meteorological Society meeting, February 2004, London.

Weatherhead EK (2005). Farmer adaptation to water scarcity. Paper presented at UK-China workshop on Impact of Climate Change and Extreme Events in China, Beijing, August 2005.

Weatherhead EK (2005). Climate change impacts on irrigated agriculture in eastern England. Paper presented at CIWEM (East Anglia Branch) Annual Conference, St Neots, October 2005.

Further publications are in preparation.

Section 2; Technical report

1 Introduction

1.1 Background

Current climate projections suggest that summer mean temperatures in Eastern England will rise, rainfall will decline, and potential evapotranspiration will increase. Under such conditions, farmers are expected to want to irrigate more of their crops, and significant increases in demand for water for irrigation have been forecast (Downing *et al*., 2003). In recent years, the demand on rural water resources has faced an additional pressure, from the sports-turf and leisure industry, and in particular the rapid growth in golf course irrigation. Together with the impacts of climate change on the water resources available, these increasing and possibly competing demands for water could substantially change future farm practices and impact on local environments. An assessment of existing coping strategies and potential adaptations will help to inform those responsible for developing sustainable strategies for managing water resources and protecting the environment. This project set out to develop a framework methodology for such an assessment.

1.2 Study area

The hydrological, crop yield and land-use elements of the project were focussed on two catchments in East Anglia, the Nar and the Wensum. The studies of on-farm adaptation were extended to cover East Anglia whilst the golf course study covered courses across England and Wales.

1.3 Objectives

The overall objective was to develop an integrated framework for assessing adaptation options for agriculture and leisure sectors dependent upon direct abstraction of water resources. The framework was developed and tested using two contrasting catchments in East Anglia. The framework aimed to provide a basis for characterising how aspects of climate change might impact on access to and reliability of water supplies and the capacity of each sector to adapt. Specifically, the objectives were:

1. To determine the likely changes in surface/ground water resource availability for the selected catchments, including estimates of changes in annual, seasonal, and extreme climate variability;
2. To identify the key drivers and parameters likely to influence each sector under conditions of climate change and potential water scarcity, in order to assess their adaptive capacity;
3. To develop a conceptual framework for evaluating how each sector might respond to climate change, to assess the range of adaptation options available, and the sensitivities to adaptation.
4. To model future catchment level water demands by agriculture and leisure, for selected UKCIP02 scenarios;
5. To recommend effective policy regimes for regulating future water demand, and to develop specific recommendations for each sector for enhancing adaptation.

The project integrated expertise from the social, engineering, economic and natural science disciplines, using hydrological and hydrogeological models, a crop yield model, a catchment level land management model, a sports turf irrigation model, farmer and green keeper interviews, and a knowledge elicitation tool within the assessment. The UKCIP02 database was used to define selected future climate conditions for the selected catchments, using the high and low emission scenarios for the 2020s and 2050s.

2 The case study catchments

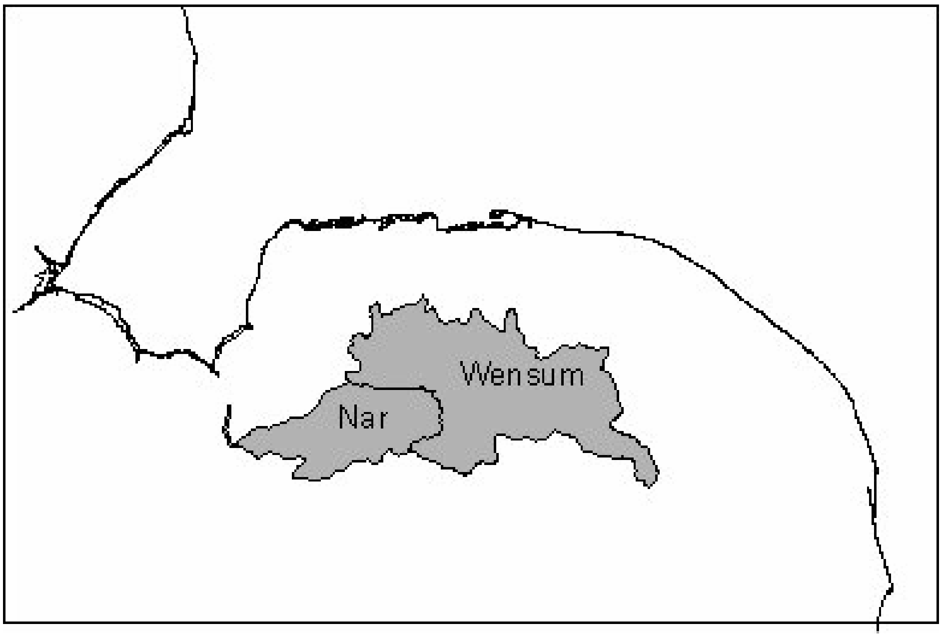
Tonny de Vries and Keith Weatherhead

2.1 Location

The two catchments selected as case studies for the hydrological, crop yield and land-use elements of the project are the Nar and the Wensum upsteam of Norwich, both located in north Norfolk (Figure 2-1). The Nar catchment is within the Environment Agency's CAMS area 23 and the Wensum catchment is part of CAMS area 20.

This area is characterised by intensive farming. Irrigation is an essential component of production of high value crops in the region, serving to increase crop yield and particularly quality.

Figure 2-1. Location of the case study catchments in North Norfolk.



2.2 Farm types

Information on farm types and sizes is available at county level from the Defra Agricultural and Horticultural June Census. Norfolk is one of the main centres of sugar beet farming and (to a lesser extent) potatoes. General cropping (which includes potato, sugar beet and field-scale vegetable production) and cereal farms account for 40% of the farm holdings. Livestock farms account for less than 20%. Almost a third of farms are classified as 'other', which includes specialist farms and those of limited economic value. Farm sizes vary significantly, with nearly half of the holdings less than 5 ha, and 16% larger than 100 ha.

2.3 Irrigation

Data on irrigation at catchment level has been obtained from the 2001 survey of irrigation of outdoor crops (Weatherhead and Danert, 2002), subject to confidentiality constraints. Table 2-1 show estimates of the crop areas irrigated in CAMS 20 and 23 in 2001. Potatoes (main crop and early) predominate, accounting for 70% (CAMS area 20) and 52% (CAMS area 23) of the total irrigated area. Vegetables and small fruit are also important in CAMS 20 (8% and 6% respectively). Vegetables are relatively important in CAMS 23 (23%).

Table 2-2 shows the irrigation methods used in the two CAMS areas. Hose reels, fitted with either guns or booms, are the predominant method, used on over 90% (CAMS 20) and 98% (CAMS 23) of the area irrigated.

Table 2-1. Irrigated area (ha) by crop in CAMS areas 20 and 23.

Crop category	CAMS area 20	CAMS area 23
Early potatoes	274	0
Main crop potatoes	5,259	1,317
Sugar beet	369	283
Orchard fruit	~	~
Small fruit	619	~
Vegetables	511	576
Grass	~	0
Cereals	129	~
Other crops	509	273
Total	7,907	2,531

Source: Derived from 2001 Irrigation survey (Weatherhead and Danert, 2002)
~ -data not available for confidentially reasons (<5 respondents)

Table 2-2. Irrigation methods in CAMS areas 20 and 23 (% of irrigated area).

Irrigation method	CAMS area 20	CAMS area 23
Sprinkler	4	~
Hose reel with gun	80	86
Hose reel with boom	11	13
Centre pivot	~	0
Trickle	1	~
Other method	~	~
Total	100	100

Source: 2001 Irrigation survey (Weatherhead and Danert, 2002)
~ – data not available for confidentially reasons (<5 respondents)

2.4 Licensed abstraction

There are 41 agricultural irrigation abstraction licences in the Nar catchment, just over half from ground water, and 70 in the Wensum catchment, nearly two thirds from ground water. (Table 2-3).

Table 2-3. Abstraction licences for agricultural irrigation purposes, in 2001

Catchment	Ground water abstraction		Surface water abstraction	
	No. of licences	% of total	No. of licences	% of total
Nar	20	49	21	51
Wensum	42	60	28	40

Data source: Environment Agency NALD.

2.5 Actual abstractions

Data on the volumes actually abstracted for agricultural irrigation were obtained from abstraction returns for the period 1997 to 2001. Actual abstraction is typically much less that licensed abstraction, for various reasons (e.g. weather, crop rotations, cropping pattern changes). The 20 year (1973-2002) ranked theoretical irrigation needs (depths of water needed) for main crop potatoes grown at Morley (roughly 10 miles south of the Wensum catchment) are shown in Figure 2-2. The period 1997-2001 had no particularly dry years, with 1999 and 2000 being fairly wet and 1997, 1998 and 2001 being average.

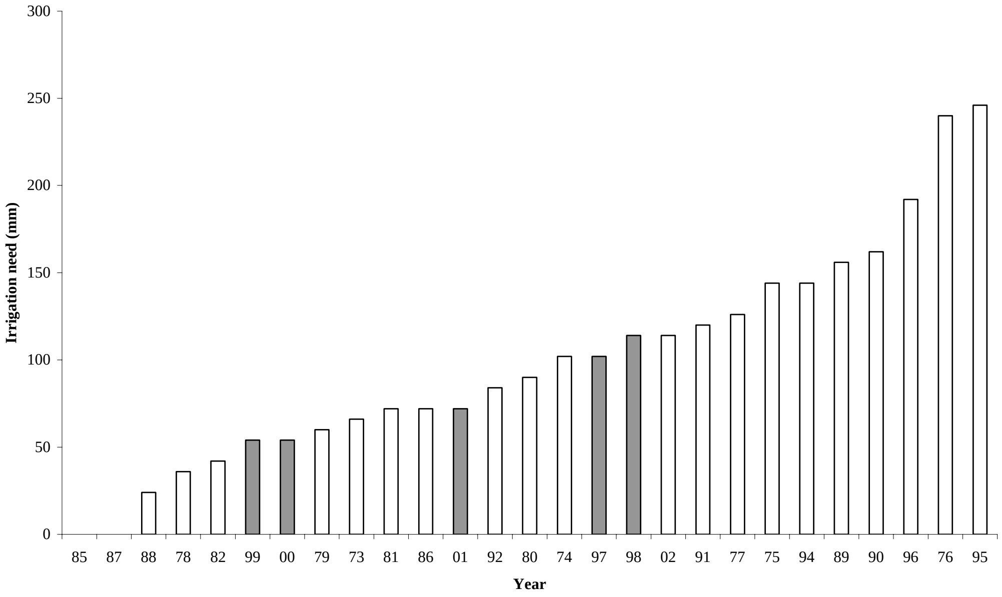


Figure 2-2. Ranked theoretical irrigation needs (mm) for main crop potatoes grown on a medium available water holding capacity (AWC) soil at Morley (Norfolk), 1973-2002.

Notes: Data missing for 1983, 1984 and 1993. Shaded columns are the years for which actual abstraction data were analysed, 1997 to 2001.

The proportions of the licensed volume that were actually abstracted during this five-year period were only 11% for the Nar and 29% for the Wensum. Some licences were hardly used at all (Table 2-4). This is especially evident in the Nar catchment, where 63% of the licenses were not used more than once. In contrast, the remainder were used in most years.

Frequent use of abstraction licenses does not necessarily mean that the licence gets used to the maximum allowable limit. For a correctly sized licence, with no alternative source used, one might reasonably expect average abstraction to be around half the annual limit. Individual returns show significant variation, with a few being used more intensively, but with many being used much less. Nevertheless, there appear to be a significant number of underused licences.

Table 2-4. Annual frequency of license use over 5 years (1997-2001).

Catchment	0-1 times	2-3 time	4-5 times
Nar	63%	0%	37%
Wensum	44%	6%	50%

Data source: Environment Agency NALD

2.6 Timing of abstraction

The monthly pattern of abstraction is shown in Figure 2-3. In the Nar catchment, some surface water is abstracted during the winter months to fill/re-fill winter storage reservoirs.

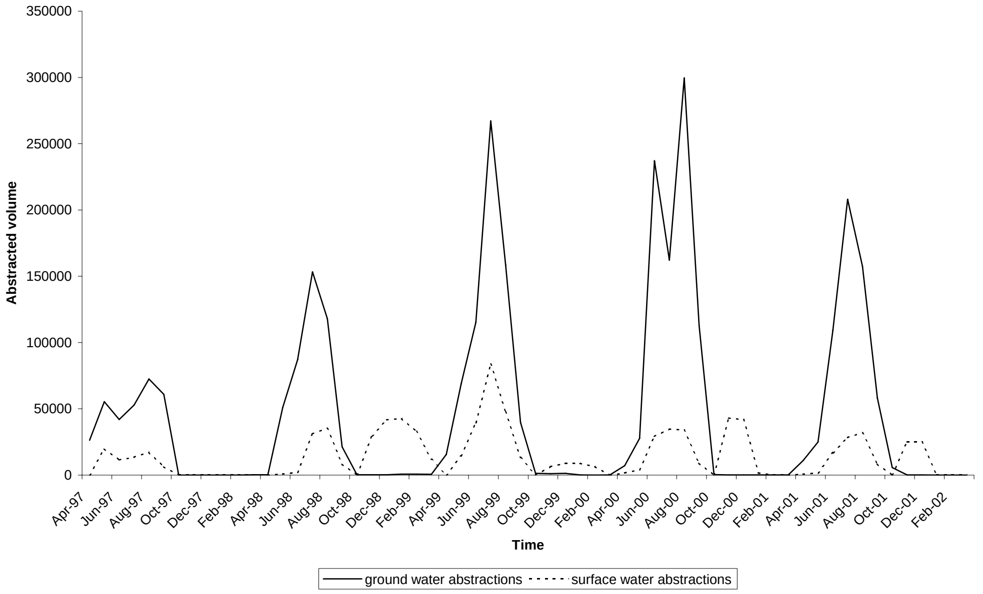


Figure 2-3. Total water abstracted for irrigation, by month, 1997-2001, Nar catchment.
Data source: Environment Agency NALD

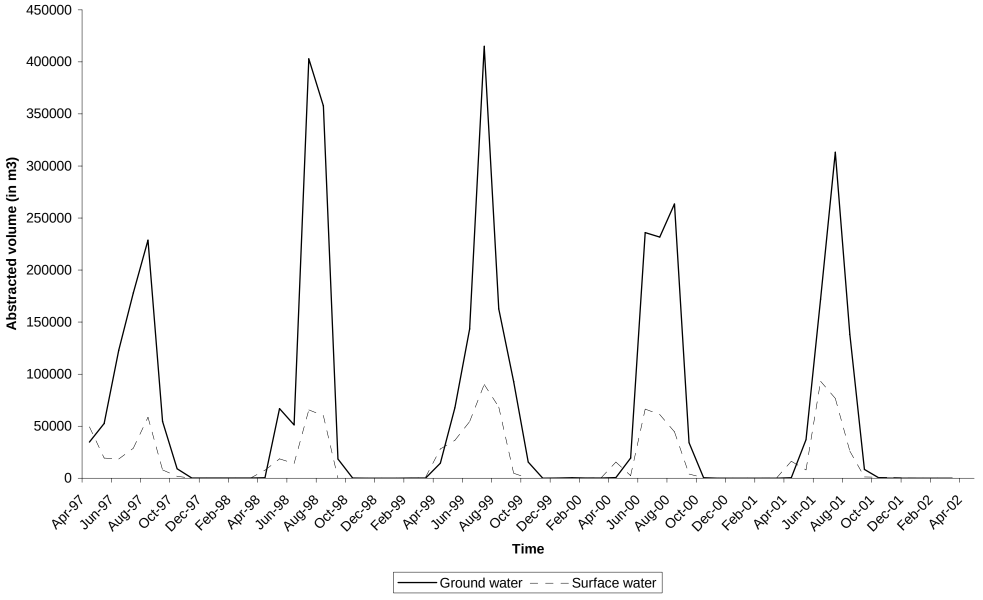


Figure 2-4. Total water abstracted for irrigation, by month, 1997-2001, Wensum catchment.
Data source: Environment Agency NALD

3 Climate change scenarios

Jerry Knox

3.1 Selection of scenarios

The climate scenarios used in this study were based on the most recent UKCIP climate change scenarios (Hulme *et al*., 2002). The UKCIP02 database provides climate change data for three time slices (2020s, 2050s, and 2080s) and for four core emissions scenarios (Low, Medium-Low, Medium-High, and High). For this study, three scenarios were selected for modelling, the 2020s high emissions scenario ("2020H") (the difference between the high and low emission scenarios is negligible in the 2020s), the 2050s low emissions scenario ("2050L") and the 2050s high emissions scenario ("2050H"). The data are for averages across 30 year time slices centred on 2025 (i.e. 2010 to 2040) and 2055 (i.e. 2040 to 2070), rather than for specific years.

The uncertainty inherent in all climate change forecast scenarios, and those added in the use of UKCIP scenarios, is discussed by Downing *et al* (2003), particularly in relation to water resource issues, where changes in extreme events may be as important as gradual changes. The results of this study must therefore be interpreted in the context of remaining uncertainty.

For the hydrological, hydrogeological, crop yield and irrigation (leisure) demand modelling, the main variables of interest were rainfall and the variables required to derive reference evapotranspiration (temperature, humidity, radiation and wind). The predicted impacts of climate change on selected variables are shown in Table 3-1.

Table 3-1. Changes in temperature and precipitation, for north, central and southern England, for the selected UKCIP02 scenarios.

UKCIP02 Scenario	**Season**	**Climate variable**	
		Average temperature (degrees)	Average precipitation (%)
2020 High	Annual	+ 0.5 - 1.5	- 0 – 10
	Summer	+ 0.5 – 1.0 north + 1.0 - 1.5 south	- 0 – 10 north - 10 – 20 south
	Winter	+ 0.5 - 1.0 north + 0.5 - 1.0 south	+ 0 – 10 north + 0 – 10 south
2050 Low	Annual	+ 1.0 - 2.0	- 0 – 10
	Summer	+1.0 - 1.5 north + 1.5 – 2.0 central + 2.0 – 2.5 south	- 10 – 20 north - 10 – 20 central - 20 – 30 south
	Winter	+ 0.5 – 1.0 north +1.0 – 1.5 south	+ 0 – 10 north + 10 – 15 south
2050 High	Annual	+ 1.5 – 2.5	- 0 – 10
	Summer	+ 2.0 – 2.5 north + 2.5 – 3.0 central + 3.0 - 3.5 south	- 20 - 30 north - 20 - 30 central - 30 - 40 south
	Winter	+ 1.0 – 1.5 north +1.5 – 2.0 south	+ 10 – 15 north + 15 – 20 south

Source: Derived from Hulme *et al* (2002).

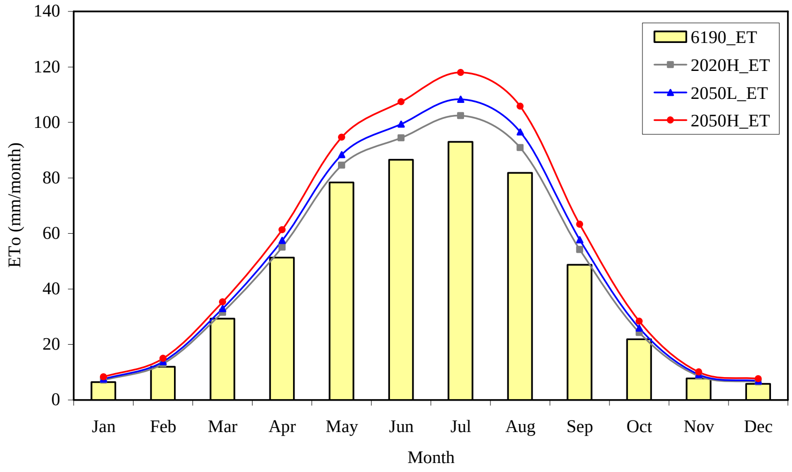
3.2 Perturbed weather data

For the hydrological and irrigation need modelling, a long-term historical weather dataset was perturbed using scaling factors derived from the 50 km x 50 km UKCIP02 baseline and scenario climatology. Daily long-term climate data were obtained from the Morley Agricultural Research Centre, located roughly 10 miles south of the Wensum study catchment. The available data, for the period 1973 to 2003, were used for the baseline climate for both catchments.

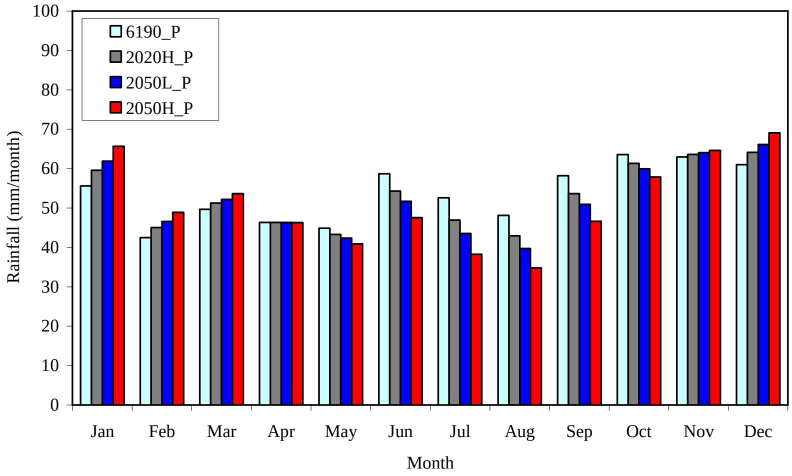
Daily climate datasets for each scenario for rainfall and reference evapotranspiration (ETo) for the site were derived (e.g. Figure 3-1) using a procedure developed by Knox *et al* (2004). This approach has the virtue of simplicity whilst maintaining a realistic temporal structure of climate data. It assumes that the relative variability in climate from day to day and year to year (i.e. the shape of the frequency distribution) remains constant.

Figure 3-1. Impacts of the selected UKCIP02 climate change scenarios on mean monthly (a) reference evapotranspiration and (b) rainfall for the Wensum catchment.

(a) Reference evapotranspiration (ETo)



(b) Rainfall



3.3 Use of the LARS Weather generator

For the crop yield modelling (and hence for the land-use modelling) a much longer time-series dataset was required. The LARS weather generator was therefore used to generate 50 years of continuous daily weather for the present climate and for each of the future scenarios. A full description is given in Hossell *et al* (2004).

4 Hydrological impacts

Nigel Arnell and Nick Odoni

4.1 Introduction and approach

River flows in the Wensum and Nar catchments were simulated under the baseline (1961-1990) and the selected future climatic conditions using two hydrological models. The primary output indicator is the flow duration curve, describing the variability in river flows from day to day, and which is the input to the Environment Agency's Resource Allocation Methodology (RAM) used to assess abstraction decisions.

Projections of future river flows are widely acknowledged to be uncertain, primarily due to uncertainty in the driving climate scenarios, and it is accepted best practice to use a range of scenarios to characterise possible future climates. However, additional uncertainty is added by the hydrological model used to convert input climate data to output river flows. The model may simulate *absolute* values of river flows inaccurately, or may simulate inaccurately the *changes* in river flows following change in input. Such errors may result from model form, parameterisation or the temporal and spatial resolution of available input data, and a range of techniques has been developed to seek to characterise the effects of model uncertainty on simulated river flows (e.g. Beven and Freer, 2001; Wagener *et al.*, 2003) by, for example, sampling across a range of possible parameterisations or model formulations.

The implications of this uncertainty for the estimated impacts of climate change, however, have been largely ignored in climate change impact studies. A small number of studies (e.g. Boorman and Sefton, 1997; Arnell, 2005) have considered the effects of alternative model structure and parameterisation on estimated changes, but these studies did not use very sophisticated treatments of model uncertainty. In the most sophisticated analysis, Cameron *et al.* (2000) used the Generalised Likelihood Uncertainty Estimation (GLUE) approach to characterise model parameter uncertainty and show that estimates of climate change impacts on the T-year flood were highly influenced by model parameterisation. The GLUE approach involves simulation of river flows with a large number of parameter combinations, producing a single "best" estimate of river flows by weighting each simulated series by a measure of the goodness of fit of the associated parameter set, and determining confidence intervals from the spread of estimates.

The approach adopted in this study involves three stages. The first stage estimates model parameters for two hydrological models, using 6 different periods of data for model calibration and 8 different objective functions, producing 96 different sets of model parameters. The second stage simulates 30-year time series of river flows under each parameter set, producing 96 time series for each scenario. These two stages together allow an assessment of the effects of hydrological model uncertainty on simulated river flows. The third stage applies a bias correction to ensure that, for each parameter set, the simulated mean monthly runoff over the period 1961 to 1990 equals the observed mean monthly runoff. The correction factors calculated for each parameter set are applied to all simulations with that parameter set. This stage is necessary because flow duration curves under current and future climate must be expressed in absolute terms (m^3/sec): a heavily biased flow duration curve would give a misleading indication of resource availability.

The two models applied are both variants of the probability-distributed model as developed by Moore (1985) and applied in a number of climate change impact assessments (e.g. Arnell, 2003; 2004). Each model is a conceptual water budget model, using daily rainfall and potential evaporation data to simulate river flows at a daily time step. The models distinguish between "quick flow", generated rapidly from inputs of rainfall, and "slow flow", generated from the slower drainage from soil and groundwater stores. Quick flow is generated from a portion of the catchment only, with the portion depending on soil moisture storage and rainfall input, hence varying from day to day. The two model types are slightly different in the manner in which the saturation excess component of the quickflow is calculated, one model incorporating the exact formulation described in Moore (1985) and used in this respect in Arnell (2003; 2004), and the other using a simplified formulation. Both models include an additional parameter ('Gbase') to govern the quicker leakage of slow flow water into the channels via groundwater pathways as the groundwater store is topped up by heavy rain. This process modification was included as it produced closer agreement between both observed and simulated runoff during the summer and early autumn, and observed and simulated baseflow indices for both of the catchments. Table 4-1 summarises the model parameters. Table 4-2 shows the periods used for model calibration, and Table 4-3 shows the 8 different objective functions used for automatic calibration.

Table 4-1. Model parameters (for both models and all parameterisations).

Name	**Units**	**Type of parameter and function**
Cmax	mm	Threshold. Determines maximum allowable soil moisture.
Smax	mm	Threshold. With Cmax and cb, constrains proportion of soil likely to be saturated following rainfall.
cb	dimensionless	Exponent. Determines propensity of rainfall going to runoff as quickflow, for a given soil moisture.
Kb	day^{-1}	Coefficient. Governs rate of drainage from soil to groundwater store.
Grout	day^{-1}	Coefficient. Governs rate of slow flow from groundwater store to catchment outlet.
Gbase	mm	Threshold. Governs proportion of slow flow which leaks to the outlet by faster pathways as the groundwater store is filled.
Srout	day^{-1}	Coefficient. Provides more realistic hydrograph for the combined runoff by quick flow and slow flow.

Table 4-2. Calibration periods (both models and both rivers).

Calibration Period	**Rainfall and PE data used as warm-up series (not included as part of calibration)**
1961-65	Observed 1961, run twice
1966-70	Observed 1964 and 65
1971-75	Observed 1969 and 70
1976-80	Observed 1974 and 75
1981-85	Observed 1979 and 80
1986-90*	Observed 1984 and 85

* There was 46 day gap in the Wensum data in late summer and autumn of 1988.

The bias correction for each parameter set consists of a daily adjustment factor. This was constructed for each parameter set by first calculating the mean flow on each day over the 30-year baseline period to produce a time series of 365 daily means, computing a 31-day running average from this mean time series, and comparing the running average for each day with the equivalent value calculated from the observed flows. This was found to be preferable to using monthly adjustment factors, which tended to produce step changes at month boundaries, and “unsmoothed” daily adjustment factors, which varied considerably from day to day. Although all the 96 simulated baseline time series have the same 30-year mean, the simulated time series and flow duration curves vary between time series due to differences in the way each variant simulates the dynamics of hydrological behaviour.

Table 4-3. Objective functions used in all calibrations.

Description	Comments
Sum of absolute differences between log simulated and log observed daily runoff	Logs used where possible to increase the sensitivity of the metrics, as the output is dominated by low flows. For the days where the Wensum observed data were missing, the differences were removed from the calculation. The 5-day data were obtained simply by summing the daily runoff in consecutive blocks i.e. 1st to 5th January, 6th to 10th January, 11th to 15th January, *et seq.*, crossing monthly boundaries as required.
Sum of absolute percentage differences between simulated and observed runoff	
log (1 – Nash-Sutcliffe index for daily runoffs)	
Sum of squared differences between log simulated and log observed runoff	
Sum of absolute differences between log simulated and log observed 5-day runoff	
Sum of absolute percentage differences between simulated and observed 5-day runoff	
log (1 – Nash-Sutcliffe index for 5-day runoffs)	
Sum of squared differences between log simulated and log observed 5-day runoff	

Notes: Calibrations were performed using a semi-randomised, self-updating algorithm, comprising 120 simulations, repeated 20 times (therefore 2,400 runs per calibration), and run as batch jobs on Southampton's 'Beowulf' cluster. This procedure was found generally to give stable solutions and satisfactory simulated versus observed plots, although some calibrations had to be repeated or extended to achieve stable results. In all, approximately 6 x 10^5 simulations were run to complete the calibration phase of the research.

4.2 Model calibration and validation: simulation of baseline flows

Figure 4-1 shows the observed and uncorrected simulated mean monthly baseline runoff for the Wensum (left) and Nar (right) catchments. The simulated values are the mean across the 96 simulations, and the bars show plus and minus one standard deviation. Across all the simulations, there is a tendency to underestimate runoff in winter (possibly due to the time resolution of the input daily data) and overestimate runoff in summer. Figure 4-2 shows the observed and uncorrected simulated flow duration curves. The simulated flow duration curve shown is the average of the 96 simulations, and the dashed lines represent plus and minus one standard deviation. In both catchments, the uncorrected simulated flow duration curves overestimate flows below the value exceeded 90% of the time.

Figure 4-3 shows flow duration curves constructed from the corrected simulated baseline daily river flows for the Wensum and the Nar. The figures show that the application of the bias correction results in more realistic flow duration curves than shown in Figure 4-2 with smaller standard deviations, although the simulated flow duration curves are still biased upwards below Q95 (the flow exceeded 95% of the time). The bias correction has less effect in the Nar catchment. The standard deviation of simulated Q95 is 5.2% of Q95 for the Wensum and 4.3% for the Nar.

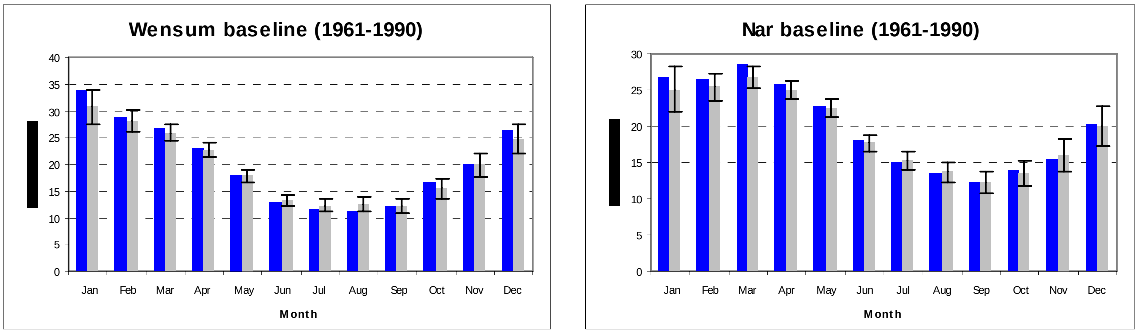


Figure 4-1. Observed and (uncorrected) simulated mean monthly runoff for the baseline period 1961-1990. The bars show plus and minus one standard deviation.

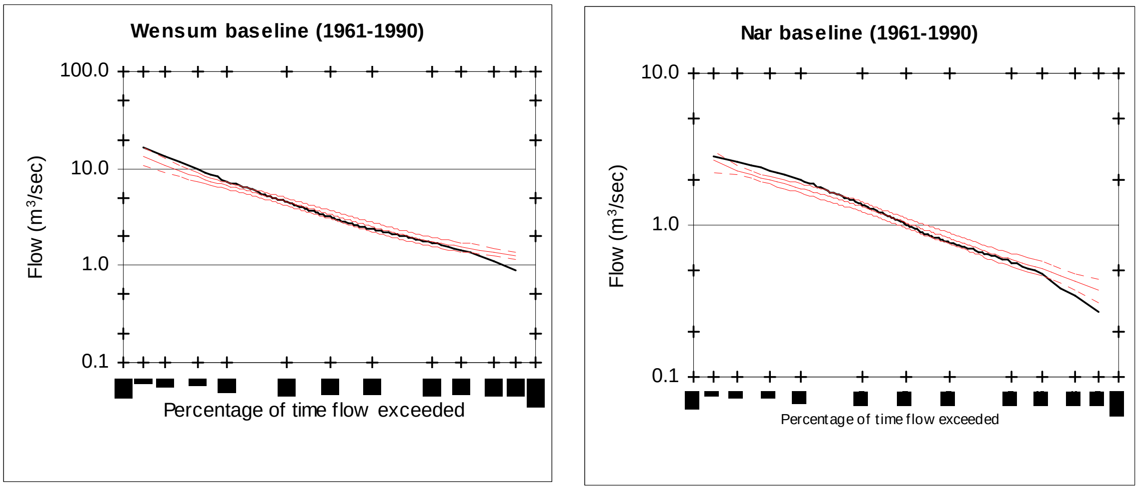


Figure 4-2. Observed and (uncorrected) simulated flow duration curves for the baseline period 1961-1990. The dotted lines show plus and minus one standard deviation.

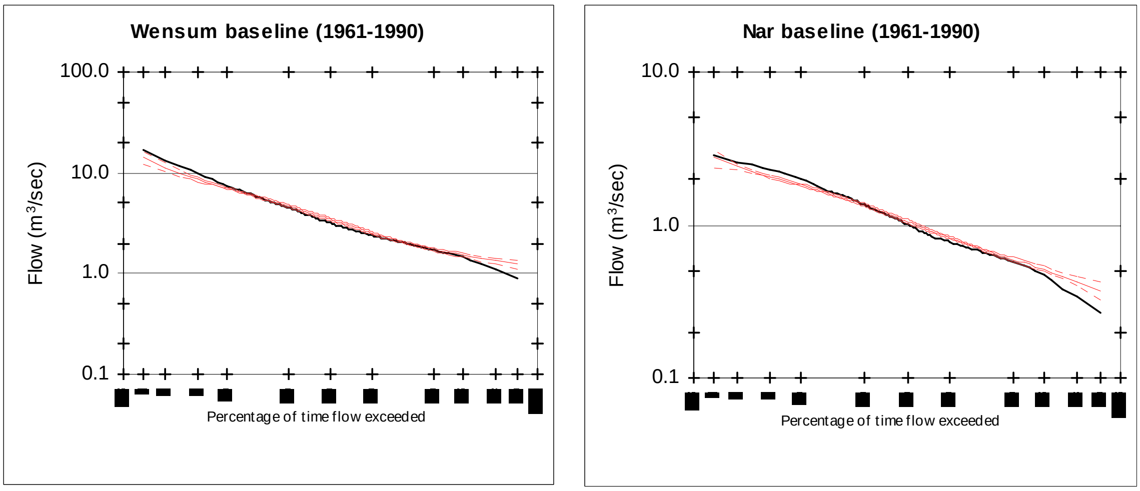


Figure 4-3. Observed and (bias corrected) simulated flow duration curves for the baseline period 1961-1990. The dotted lines show plus and minus one standard deviation.

4.3 Effects of climate scenarios on river flows

Figure 4-4 shows the effect of climate change by the 2020s and 2050s on mean monthly runoff for the Wensum (left) and Nar (right). For each time slice, the solid line represents the percentage change in the mean monthly runoff as calculated across all 96 simulations, and the vertical lines show the percentage changes calculated from the individual simulations. Runoff is reduced considerably in each month in each catchment, with the greatest percentage reductions in autumn. Most of the reduction in runoff by the 2050s occurs by the 2020s. The results are consistent with those presented in Arnell (2004) for other catchments in eastern England and the same scenarios.

Figure 4-5 shows the current and future flow duration curves for each catchment, as represented by the mean of the 96 simulations. The dotted lines show plus and minus one standard deviation around the mean (just for the baseline and 2050-high scenarios). The differences between the future and current flow duration curves are larger than the simulation error, but there is less difference between the flow duration curves for the 2020s and 2050s. Changes in Q95 are summarised in Table 4-4; the reductions are substantial. Changes are proportionally greater in the Nar catchment, where a greater proportion of river flows derives from groundwater.

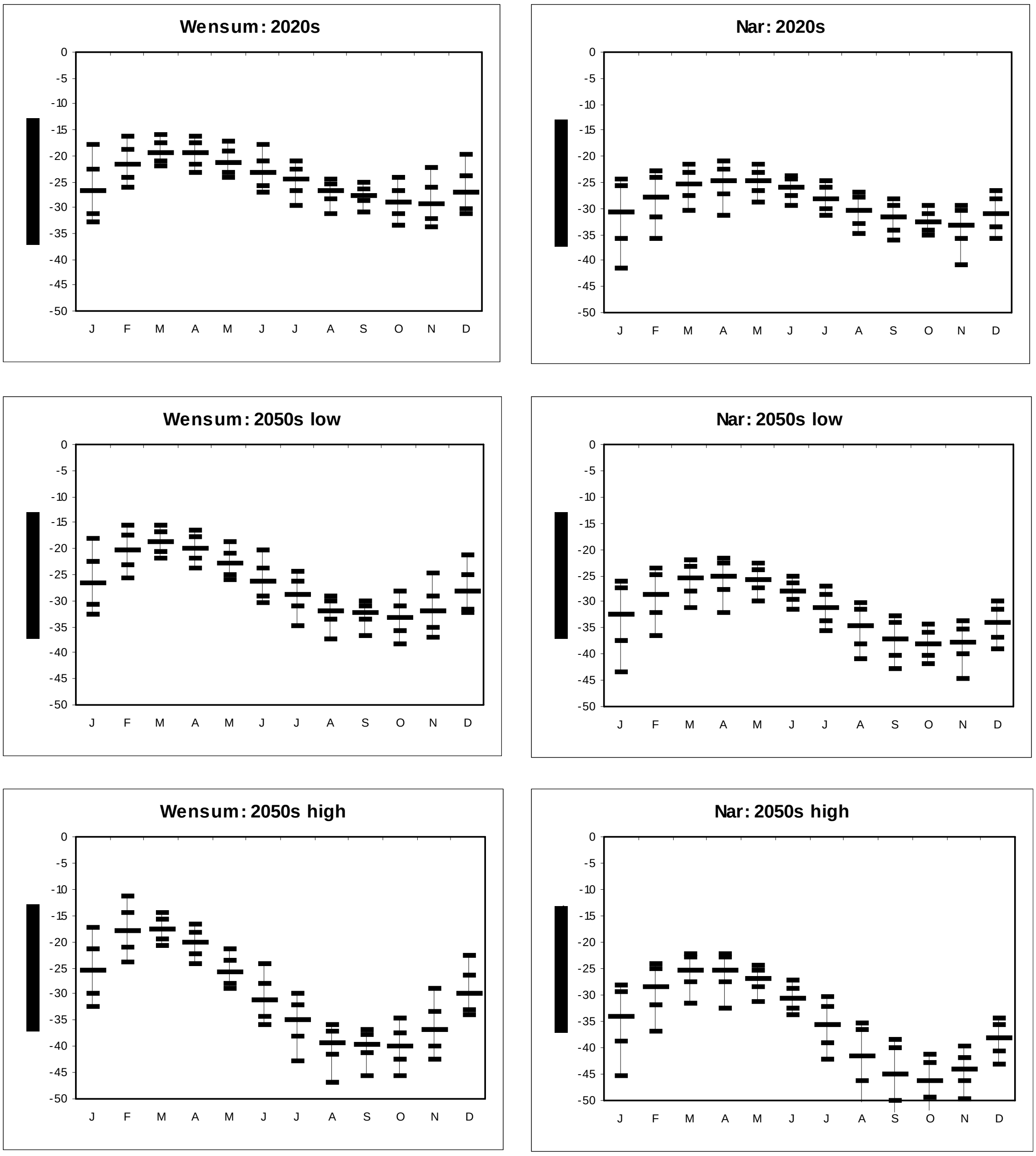


Figure 4-4. Percentage change in mean monthly runoff, under the 2020, 2050-low and 2050-high scenarios.

Vertical bars represent range in % change across the 96 simulations; long horizontal bars show the mean, and two inner short bars represent plus and minus one standard deviation.

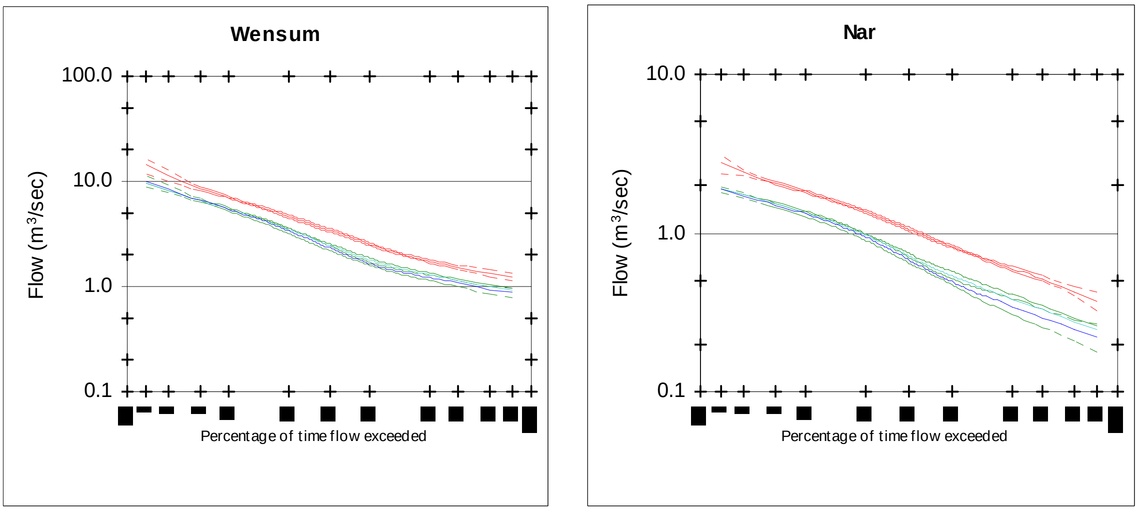


Figure 4-5. Simulated flow duration curves for the baseline period (red), 2020s, 2050-low and 2050-high scenarios. The dotted lines show plus and minus one standard deviation.

Table 4-4. Percentage change in future Q95 from the simulated baseline (1961-1990) value.

Catchment	**2020s**	**2050s-low**	**2050s-high**
Wensum	-23	-25	-30
Nar	-32	-36	-43

5 Groundwater recharge and flow modelling

Anna Saich, Cornelius Sandhu, Kevin Hiscock and Declan Conway

5.1 Climate change and groundwater resources

In the UK, groundwater recharge through percolation occurs primarily during winter, after soil moisture deficits have been replenished and before evapotranspiration increases in the following spring. The effect of climate change on recharge will depend on changes in the amount of rainfall, differences in the duration of the recharge season and the proportion of any additional rainfall that contributes to groundwater recharge (Arnell *et al*., 2001). The vulnerability of groundwater resources to variations in recharge was highlighted by the droughts of 1988-1992 and 1995 (Ragab *et al*., 1997). Potential problems associated with reduced groundwater recharge include impacts on groundwater abstractions, water quality deterioration due to reduced dilution and reductions in springflow and baseflow to rivers. Systems that are currently stressed or unsustainably managed are likely to be the most vulnerable (Arnell *et al*., 2001).

There were three stages to this study; first, groundwater recharge was calculated for the baseline and future scenarios using the perturbed climate datasets (Section 3.2) and the Environment Agency FAO groundwater recharge calculation model (Johnson, 2003, pers. comm.). Second, a calibrated and validated groundwater flow model was developed using Visual MODFLOW (v3.1; Waterloo Hydrogeologic Inc., 2003). The calculated baseline recharge then provided the input for the numerical groundwater model. Third, the groundwater model was used to assess the impacts of climate change (and different abstraction scenarios) by applying the future recharge scenarios.

The study area is underlain by a Chalk aquifer which supports river flows and provides public water supply and irrigation abstractions. The River Nar is predominantly a chalk river dominated by baseflow (with a Baseflow Index of 0.91; Institute of Hydrology, 1998), although the headwaters flow from glacial boulder clay. Springs to the east of Litcham join to form a rapidly flowing shallow chalk river (Environment Agency, 2004). The catchment area to the gauging station at Marham is 153.3 km^2. The Nar flows westwards to its confluence with the Great Ouse near King's Lynn. The River Wensum flows in a predominantly easterly direction towards Norwich, with a catchment area of 536.1 km^2 to the gauging station at Costessey Mill. The River Wensum has a shallow gradient and is supported by baseflow from the Chalk (Baseflow Index of 0.73; Institute of Hydrology, 1998). Both the Rivers Nar and Wensum are designated Sites of Special Scientific Interest (Environment Agency, 2001).

The average annual rainfall for 1981-1995 at Morley is only 640 mm, while the average annual potential evapotranspiration for the same period is 510 mm. This fine balance between rainfall and potential evapotranspiration makes the region of East Anglia vulnerable to climate change.

5.2 Results

The impacts on recharge are shown in Figure 5-1. The average annual precipitation decreases under all scenarios and by up to 5% for the 2050H scenario. There is a reduction in summer (Jun/Jul/Aug) and autumn (Sept/Oct/Nov) precipitation by up to 29% (2050H) but winter (Dec/Jan/Feb) precipitation increases by up to 15% (2050H). Future potential evapotranspiration increases throughout the year, with an average annual increase of up to 30% (2050H). The magnitude of the change is greater for potential evapotranspiration (up to 11.5 mm) than for precipitation (up to 2.8 mm). These changes in precipitation and potential evapotranspiration lead to a reduction in average annual recharge under all scenarios compared to the baseline, ranging from 10% (2020H) to 29% (2050H) in the Nar catchment. The equivalent statistics for the Wensum catchment are 9% and 25%. The greatest reductions in recharge are observed in the autumn. For some scenarios, recharge increases slightly during January and February when increases in potential evapotranspiration are offset by increases in precipitation. However, there is no summer recharge under all the climate change scenarios and, critically, a one month delay in the onset of autumn recharge is observed (Figure 5-1).

The groundwater recharge results represent the direct impact of climate change but do not address any possible adaptive response by abstractors. Potential changes in the irrigation abstraction regime were integrated by incorporating the results of the catchment management model (Section 8.3). Scenarios that include water trading were not considered. The scenarios restrict maximum abstraction availability and the model is free to abstract less than the limit; the actual abstractions modelled, as a percentage of the catchment licence total, are shown in Table 5-1, (derived from Table 8-3). Summer irrigation abstractions were assumed to occur between weeks 13 and 35 (approximately April to August), while winter abstractions are for winter storage.

The percentage abstractions given in Table 5-1 were applied to the irrigation abstraction boreholes in the groundwater model. From the results presented in Figure 5-2, a decrease in groundwater levels is apparent under all future scenarios. It is clear that the irrigation abstraction scenarios considered indicate that diminished recharge has a more severe impact on groundwater levels than changes in the irrigation abstraction regime. For example (Figure 5-2), groundwater levels at observation borehole TF91_002 (a confined Chalk borehole) show a response to the irrigation scenario applied under both the baseline and climate change scenarios whilst groundwater levels TF91_774 (an unconfined Chalk borehole) are insensitive to the irrigation abstraction scenario considered.

From the results (Table 5-2), the average change in monthly baseflows in the River Nar for the 2020H climate is -9% if summer irrigation abstractions are limited to 50%, whereas it is -11% for the 100% summer irrigation scenario. This corresponds to a move to winter storage and slightly reduces the impact of low summer and autumn flows in the River Nar catchment (Figure 5-3a). The effect is not, however, observed in the River Wensum catchment (Figure 5-3b). Figure 5-4 shows the average monthly flow in the Rivers Nar and Wensum for each of the irrigation scenarios. Again, the impacts of climate change dominate, but it is also apparent that limiting the percentage of summer abstractions slightly reduces the impact on summer river flows in the Nar catchment. Comparing the 2020H 50% and 100% maximum irrigation scenarios for the Nar shows that the volume of flow is over 2000 m^3/day greater during August if summer abstractions are restricted (Figure 5-4a).

The impact of reducing all groundwater abstractions to zero (whether for irrigation, public water supply or industry) was also investigated for the 2050H climate change scenario. As shown in Figure 5-4, river flows were still significantly lower than present day flows, indicating that the impacts of climate change cannot be compensated for by reducing groundwater abstractions.

5.3 Discussion

Despite the acknowledged limitations associated with hydrological impacts studies (Gleick, 1986) it is important to consider the potential implications of changes in regional climate. In this study, average annual groundwater recharge was shown to decrease under all scenarios considered. A slight increase in recharge during January and February is not reflected in the hydrological response. River baseflow volumes and total river flows decrease throughout the year, with the greatest reductions in the summer and autumn and for the 2050H scenario. Summer irrigation abstractions are shown to accentuate the summer and autumn low flows in the River Nar. The influence of ceasing all groundwater abstractions was considered for the most severe climate change scenario (2050H). A significant reduction in river flows still occurred indicating that adaptation through groundwater abstraction optimisation will not be sufficient to maintain current river flows.

Anticipating the consequences of climate change is particularly important for regions with finite water supplies, such as East Anglia. Reductions in groundwater levels indicate the limited resource availability and, as transmissivities decrease with depth, borehole yields may also be reduced. Water supply problems are likely to be severe considering the projected increase in demand and the depletion of groundwater resources due to reductions in recharge. Competition between agriculture, public water supply and environmental needs is likely to intensify, and demand management will be important.

Reductions in river flows will impact river ecology and surface water abstractions. Potential adaptation strategies include groundwater augmentation (artificial storage and recovery; Brouyère *et al*., 2004), careful management of the timing and location of public water supply abstractions and the location of discharges of return waters (Adams *et al*., 2000). The uncertainties associated with climate change impacts studies necessitate a flexible approach which should be refined as more accurate information becomes available.

Table 5-1. Summary of the percentage abstraction of total licensed water for the Rivers Nar and Wensum catchments from the farm management model. (Data from Table 8-3).

Climate change scenario	Maximum summer abstraction availability	Baseline		2020		2050	
		Summer	Winter	Summer	Winter	Summer	Winter
River Nar catchment							
Low	100%	62.76	0.00	-	-	69.81	0.00
High	100%	62.18	0.00	65.93	0.00	72.53	0.00
High	50%	0.00	46.39	0.00	49.56	0.00	53.88
River Wensum catchment							
Low	100%	97.03	0.00	-	-	99.11	0.00
High	100%	97.30	0.00	99.00	0.00	94.32	5.18
High	50%	0.00	92.26	0.00	95.74	0.00	95.96

Notes: (i) 2020L climate change scenario was not considered during the groundwater modelling, (ii) the slight discrepancy between baseline ‘high’ and ‘low’ summer abstraction for the 100% scenario results from the way the farm management model is run, but are within 1% of each other

Table 5-2. Comparison of the effects of the climate change and irrigation scenarios on river baseflow and total flow for the River Nar.

The percentage changes compared for the defined irrigation baseline scenarios are given in parentheses

River Nar		2020H 100%	2020H 50%	2050L 100%	2050H 100%	2050H 50%
Minimum change in average monthly baseflow [m^{3}day^{-1}]		-7232 (-8.8)	-5539 (-6.7)	-10372 (-12.7)	-15402 (-19.6)	-15199 (-19.8)
Average change in average monthly baseflow [m^{3}day^{-1}]		-8775 (-11.1)	-6959 (-8.7)	-12451 (-15.7)	-18922 (-23.8)	-18828 (-23.4)
Maximum change in average monthly baseflow [m^{3}day^{-1}]		-11029 (-14.9)	-9263 (-12.4)	-15805 (-21.3)	-24460 (-31.7)	-24397 (-31.3)
Change in average seasonal baseflow [m^{3}day^{-1}]	Spring	-8169 (-9.1)	-6165 (-6.9)	-11803 (-20.3)	-18196 (-20.3)	-18191 (-20.3)
	Summer	-7583 (-10.4)	-5889 (-7.9)	-10731 (-14.8)	-16177 (-22.3)	-15970 (-21.5)
	Autumn	-9666 (-14.0)	-8001 (-11.4)	-13407 (-19.4)	-19684 (-28.5)	-19538 (-27.9)
	Winter	-9746 (-10.8)	-7855 (-8.7)	-13933 (-15.5)	-21634 (-24.0)	-21612 (-24.0)
Minimum change in average monthly flow [m^{3}day^{-1}]		-5285 (-4.1)	-3427 (-2.7)	-7140 (-5.5)	-12034 (-9.3)	-12017 (-9.3)
Average change in average monthly flow [m^{3}day^{-1}]		-11390 (-11.5)	-9575 (-9.6)	-15794 (-15.9)	-23872 (-23.7)	-23778 (-23.4)
Maximum change in average monthly flow [m^{3}day^{-1}]		-19790 (-19.6)	-18136 (-17.3)	-28074 (-27.1)	-43704 (-37.6)	-43569 (-37.2)
Change in average seasonal flow [m^{3}day^{-1}]	Spring	-8918 (-8.0)	-6914 (-6.2)	-12677 (-11.4)	-20149 (-18.1)	-20144 (-18.1)
	Summer	-12756 (-15.5)	-11062 (-13.2)	-16740 (-20.3)	-24131 (-29.2)	-23923 (-28.5)
	Autumn	-16946 (-16.5)	-15281 (-14.7)	-24017 (-23.3)	-35288 (-34.3)	-35141 (-33.8)
	Winter	-7602 (-6.1)	-5744 (-4.6)	-10779 (-8.7)	-16921 (-13.6)	-16900 (-13.6)

Table 5-3. Comparison of the effects of the climate change and irrigation scenarios on river baseflow and total flow for the River Wensum.

River Wensum		2020H 100%	2020H 50%	2050L 100%	2050H 100%	2050H 50%
Minimum change in average monthly baseflow (m^{3}day^{-1})		-19245 (-7.4)	-19365 (-7.5)	-27762 (-10.9)	-41203 (-17.0)	-41449 (-17.0)
Average change in average monthly baseflow (m^{3}day^{-1})		-26209 (-9.8)	-26311 (-9.8)	-37587 (-14.0)	-56539 (-21.0)	-56642 (-21.0)
Maximum change in average monthly baseflow (m^{3}day^{-1})		-36564 (-14.5)	-36657 (-14.5)	-53619 (-20.4)	-82334 (-30.3)	-82348 (-30.3)
Change in average seasonal baseflow (m^{3}day^{-1})	Spring	-23624 (-8.1)	-23714 (-8.2)	-34670 (-11.9)	-52808 (-18.2)	-52796 (-18.2)
	Summer	-21026 (-9.1)	-21151 (-9.1)	-29586 (-12.8)	-43610 (-18.8)	-43885 (-18.8)
	Autumn	-30717 (-13.0)	-30828 (-13.0)	-43058 (-18.3)	-62310 (-26.5)	-62497 (-26.4)
	Winter	-29779 (-9.2)	-29861 (-9.3)	-43371 (-13.4)	-67591 (-21.0)	-67559 (-21.0)
Minimum change in average monthly flow (m^{3}day^{-1})		-5142 (-1.1)	-5224 (-1.1)	-7366 (-1.6)	-20341 (-4.3)	-20301 (-4.3)
Average change in average monthly flow (m^{3}day^{-1})		-28400 (-8.8)	-28502 (-8.8)	-43128 (-13.2)	-68024 (-20.4)	-68127 (-20.3)
Maximum change in average monthly flow (m^{3}day^{-1})		-53084 (-17.5)	-53203 (-17.4)	-88333 (-25.2)	-140245 (-34.9)	-140452 (-34.8)
Change in average seasonal flow (m^{3}day^{-1})	Spring	-19477 (-5.3)	-19567 (-5.3)	-31482 (-8.6)	-53760 (14.6)	-53747 (-14.7)
	Summer	-35964 (-13.5)	-36090 (-13.5)	-49409 (-18.6)	-70969 (-26.7)	-71245 (-26.6)
	Autumn	-46730 (-13.2)	-46841 (-13.2)	-72928 (-20.6)	-111408 (-31.4)	-111525 (-31.4)
	Winter	-13645 (-3.1)	-13728 (-3.1)	-20966 (-4.8)	-39535 (-9.0)	-39503 (-9.0)

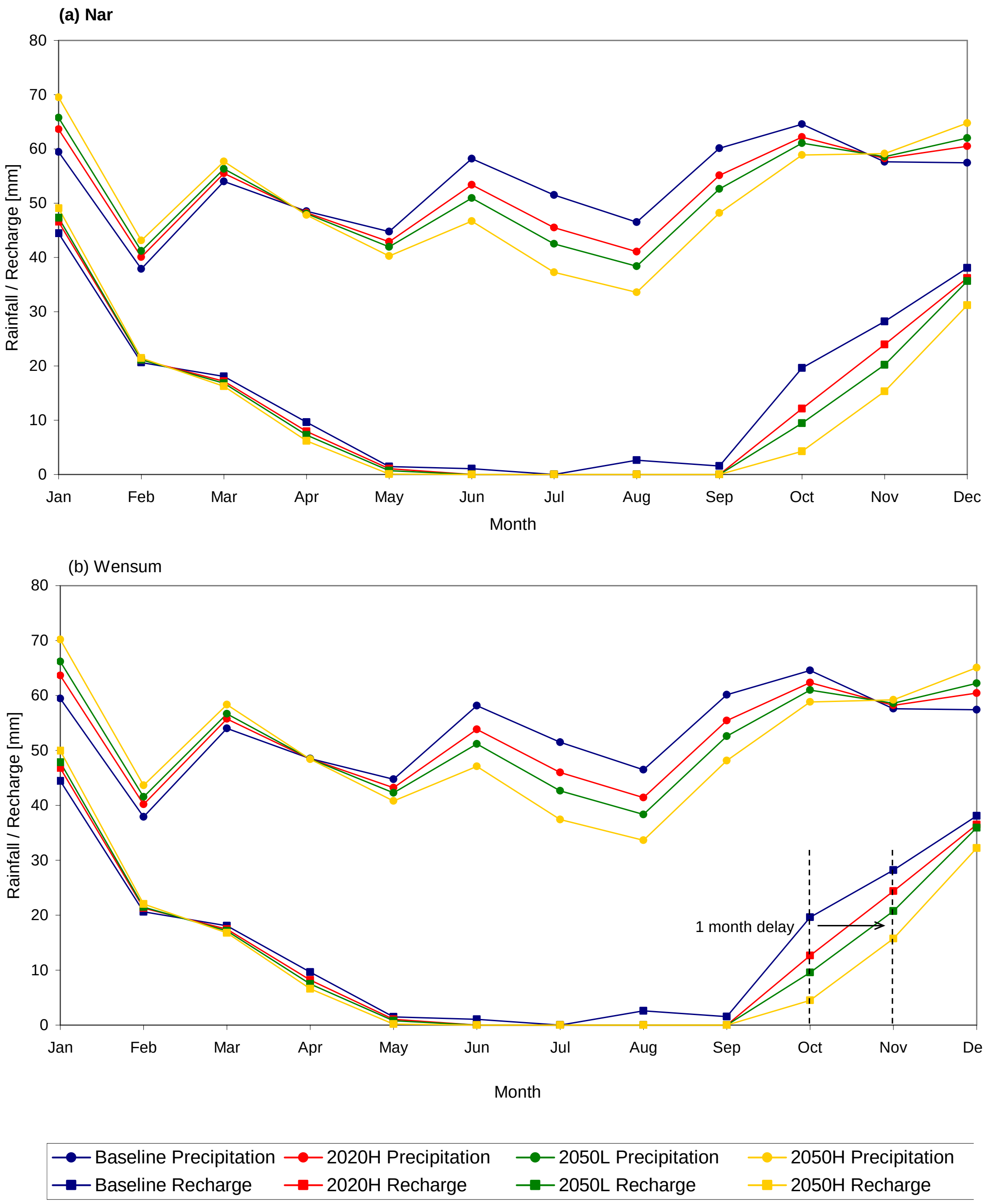


Figure 5-1. Average monthly precipitation and recharge for (a) the River Nar catchment and (b) the River Wensum catchment for the baseline and climate change scenarios.

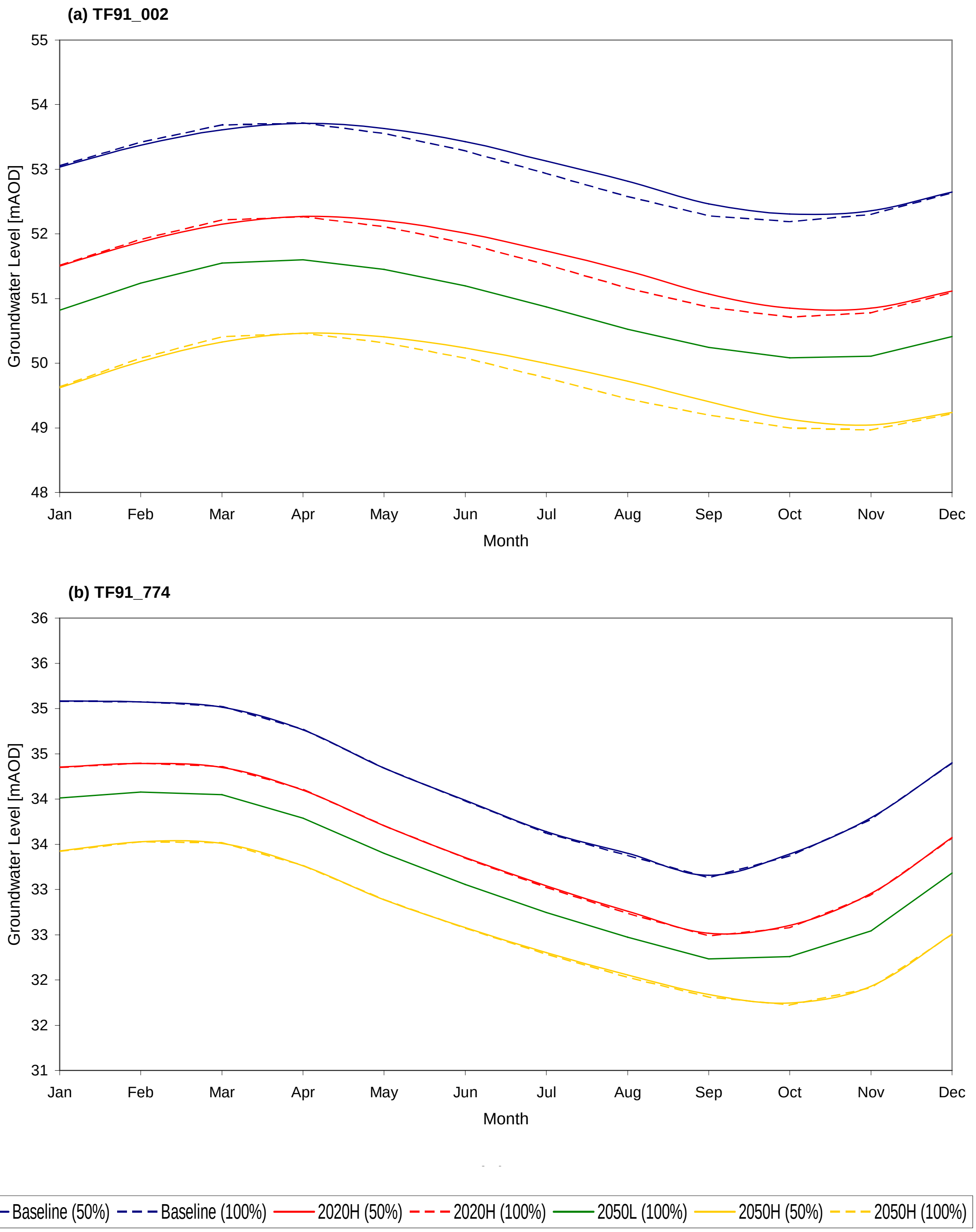
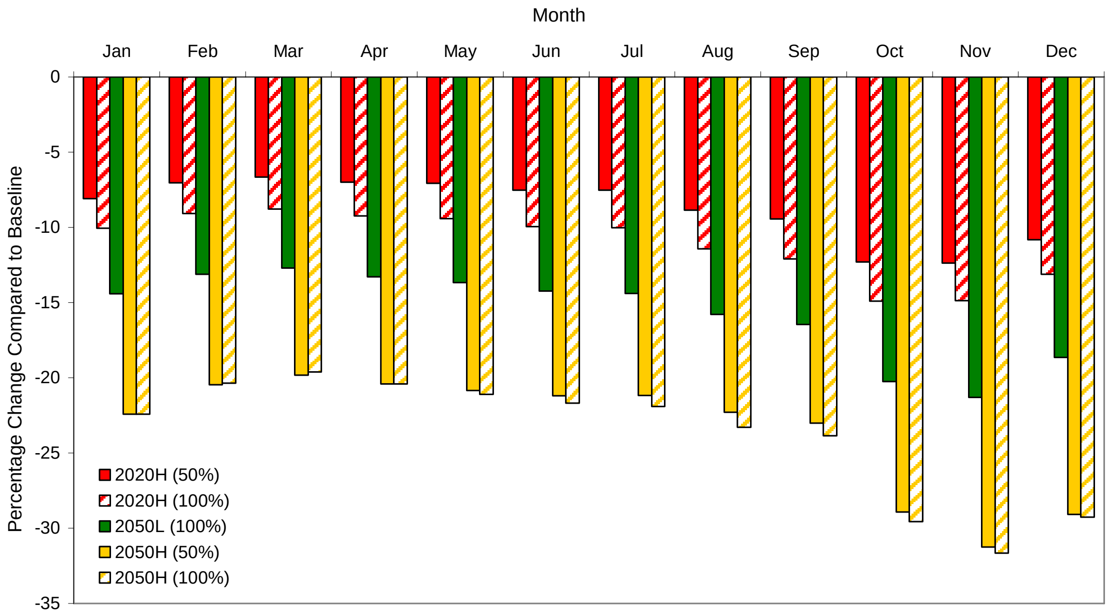


Figure 5-2. Average monthly groundwater levels for two selected observation boreholes, (a) observation borehole TF91_002 where the aquifer is confined by boulder clay, and (b) TF91_774 where the chalk is overlain by glacial sands and gravels, for the defined irrigation scenarios.

(a) Nar



(b) Wensum

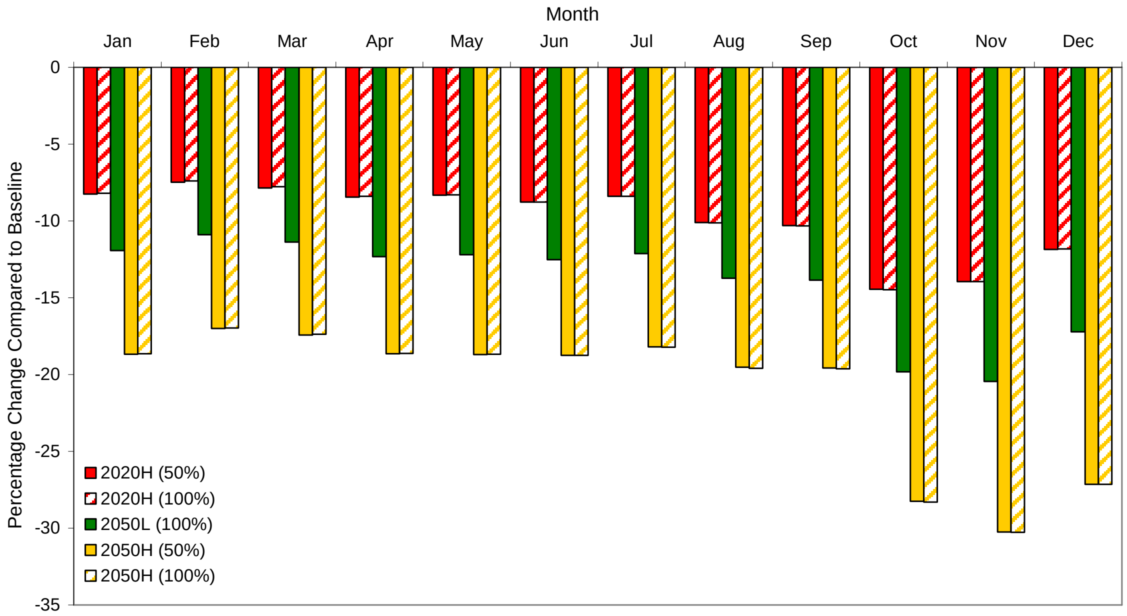


Figure 5-3. The percentage change in average monthly baseflow for (a) the River Nar and (b) the River Wensum for each of the climate and irrigation scenarios. The percentage changes compared to the corresponding irrigation baseline scenarios are given in parentheses.

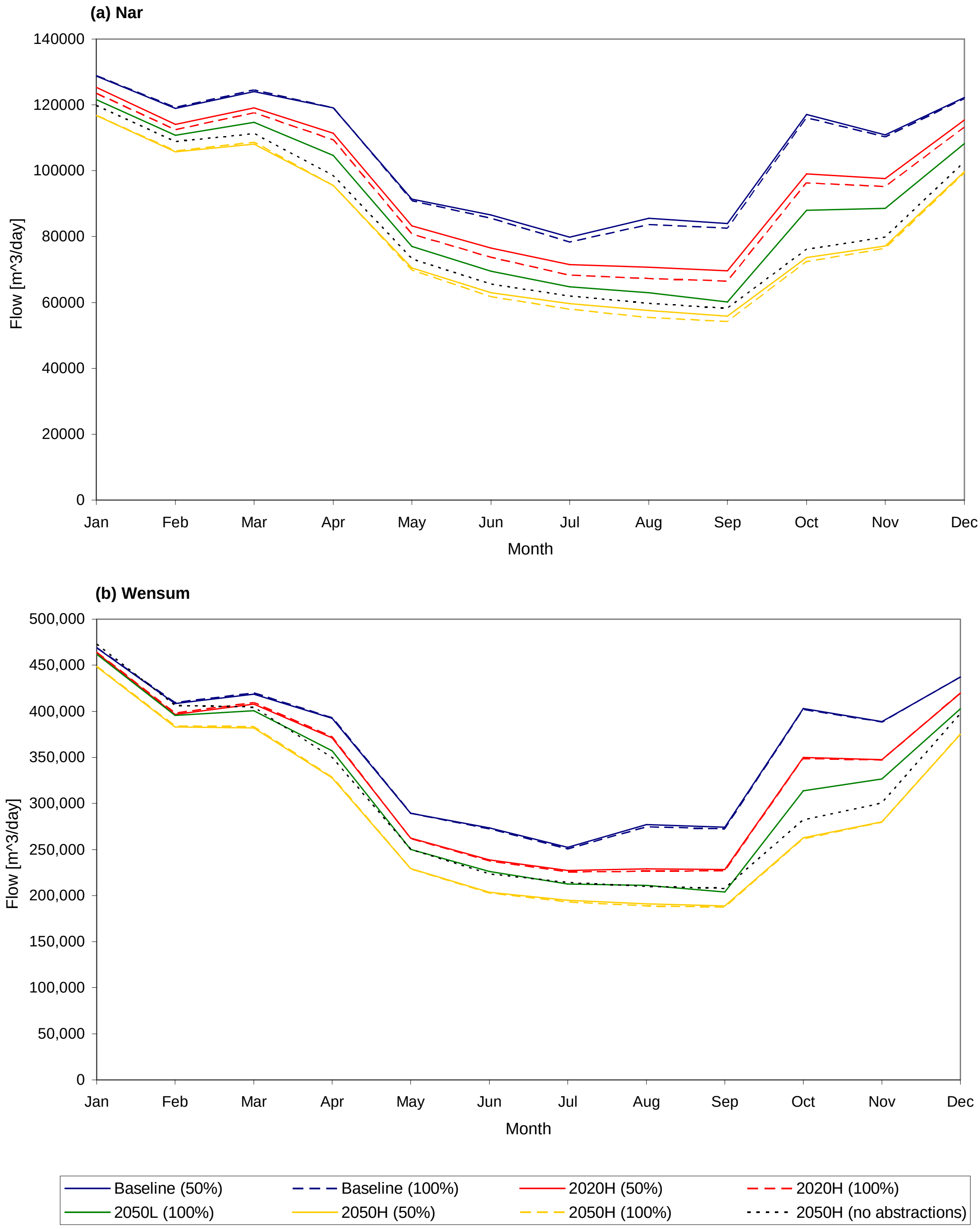


Figure 5-4. Average monthly flow in (a) the River Nar and (b) the River Wensum for the defined irrigation scenarios.

6 Impacts on abstraction licensing

Keith Weatherhead

6.1 CAMS and the River Nar

The management of water resources at catchment level in England and Wales is undertaken through Catchment Abstraction Management Strategies, or CAMS (Environment Agency, 2002). There are 129 CAMS areas covering England and Wales. The Nar catchment is located within the Environment Agency's CAMS area 23 (North West Norfolk) and the Wensum catchment is part of CAMS area 20 (Broadland Rivers). The strategy for CAMS area 20 is not yet finalised; discussion here is therefore based on the strategy for the Nar catchment (Environment Agency, 2005).

Each catchment is itself divided into Water Resource Management Units (WRMUs), comprising the surface waters upstream of a specified assessment point and the associated Groundwater Management Units (GWMU). The relevant unit for this study is WRMU8, "River NAR U/S", i.e. the Nar upstream of Marham gauging station. The associated groundwater unit is the local chalk aquifer feeding the river (but excludes the underlying but hydrologically unconnected Sandringham Sands). The river ecology has a "high" sensitivity to abstraction, and is designated an SSSI as a chalk river.

In brief, the methodology used to inform the CAMS for surface water relies first on the production of a naturalised flow duration curve for the river. This is used with an "environmental weighting" set for the river to determine the Environmental River Flow Objective (ERFO), in terms of a target flow duration curve. The methodology seeks to retain a range of flows, rather than a single minimum flow. Comparing the actual flow duration curve, assuming firstly that maximum licensed abstraction is occurring, and then actual abstractions (usually much less) are occurring, allows the river to be defined into one of four categories, water available, no water available, over-licensed, or over-abstracted. In concept at least, the difference between the naturalised flow duration curve and the ERFO curve represents the water that can be licensed for abstraction.

For WRMU8, the surface water has been assessed as over-abstracted, and the groundwater as over-licensed. The two are strongly connected and will be managed in the same way. Normally for an over-abstracted river, particularly an SSSI, the Agency would be seeking to recover resources, whether through negotiation, non-renewal of time-limited licences, or ultimately licence revocation. In this unit however, the Agency considered that the over-abstracted status appeared to be strongly related to a single public water supply groundwater abstraction at the western (downstream) end of the unit, and the impacts were possibly only localised. Under the present strategy therefore, resources will not be actively recovered, but surface water will be closed to further abstractions at all medium and low flows (<Q32, i.e. for 68% of the time) and groundwater will be closed to all further abstraction. Further action may be taken in subsequent CAMS (revised on a 6 year cycle), when further information is available.

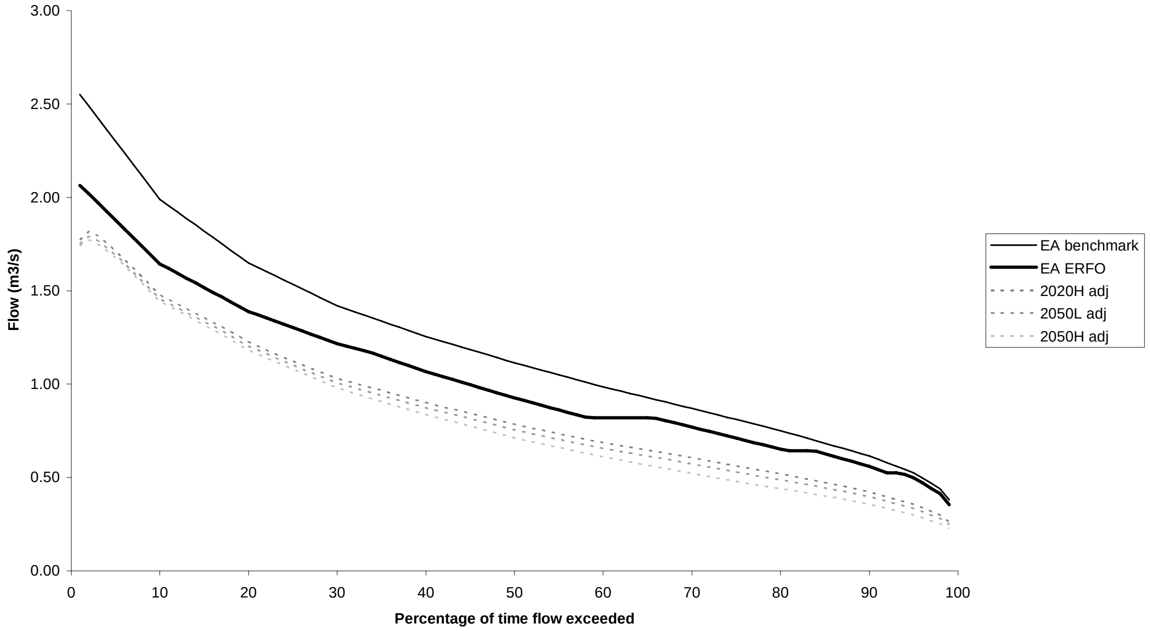
Thus, even without climate change impacts, this unit has water resource problems if demand increases. Groundwater is closed to additional abstraction, and the prospects for additional river abstraction are very poor. A Q32 constraint may make even winter abstraction for reservoir storage unreliable, since that 32% of time will not occur uniformly between years; at the least large pumping capacity would be required to fill the reservoir quickly during high flows. There must also be serious concerns over existing abstraction licences in the long-term, given the status of over-abstracted; however it is not clear whether any impact would be on the public water supply abstraction only or on other licences.

6.2 Impacts of climate change

To consider the impacts of climate change on abstraction licensing, the changes in the flow duration curve modelled in Section 4.3 have been superimposed on the naturalised flow duration curve used in the CAMS, to produce flow duration curves for the 3 climate change scenarios. The results are shown in Figure 6-1. The upper line is the present naturalised flow duration curve, and the second line is the ERFO established from that for this river. The three future scenario flow duration curves are all substantially below the present ERFO.

If the future scenarios had fallen above the ERFO, it would have been possible to ascertain any change in the water availability status and the extent by which licences would have to be decreased (or could be increased) to maintain environmental objectives. In this case however it appears that the ERFO cannot be maintained even if all abstractions, including the public water supply abstraction, were to cease. This is the case even by the “2020s” (conceptually the 30 year period centred around 2025).

Figure 6-1. Comparison of future flows with present Environmental River Flow Objective.



6.3 Implications for licensing

How the government and the Environment Agency would react to such reductions in water flows is unclear at present, but has profound implications for all abstractors. The present CAMS process makes no provision for climate change.

If the Agency is determined to protect the ERFO, then in the short-term, licences containing hands-off flow (HOF) conditions would become progressively less reliable, whilst irrigation abstraction licences without HOF conditions would be increasingly subject to “Section 57” abstraction restrictions. Ultimately all abstraction licences would become unusable due to HOF conditions and/or would have to be revoked (without compensation after 2012 if causing serious and significant environmental damage; Water Act 2003). The public water supply companies would have some priority, and they also have more resilience due to their wider network and multiple sources allowing conjunctive use of surface and groundwater. If restrictions became widespread, they could also apply for drought orders to continue abstraction.

Alternatively, the Agency could revise the ERFO. One option would be to routinely rebase the ERFO onto the new flow duration curve as conditions change. However, this would always be many years in retrospect, due to the time delay in the CAMS process and the need for long-term flow records. Basing ERFO on future projections of flow is possible, but requires confidence in the projections. There may also be issues with international and European obligations if rebasing causes environmental damage.

For the farmer, this raises additional uncertainty to the inherent uncertainty in climate change predictions. It seems reasonable to say that, if these scenario predictions are correct, that there are serious water resource constraints ahead. The reduction in high flows also suggests that winter storage reservoirs may themselves not be a total solution in the very long-term, although certainly preferable to summer river abstraction.

7 Impacts on agricultural crop yield

Jo Hossell and Bethan Clemence

7.1 Modelling

A generic semi-empirical crop model (ACCESS II) was selected to estimate the crop yields for different climate conditions. This type of model allowed the focus of the work to be directed towards how the changes in soil and climate conditions affect crop yield, rather than introducing a third level of uncertainty, i.e. how well different types of models simulate different crop growth.

ACCESS II was developed from the EPIC-PHASE model (Loveland *et al*., 1995). It consists of linked daily plant growth and daily soil water balance sub-models, which take detailed inputs about the "driving" meteorological data and the crop management parameters; and predicts the performance of the crop and ultimately crop yield. In order to do this, the model must consider the state of the crop, and its development. The amount of water available for crop growth is defined by the soil water balance contained within the model. Armstrong *et al*. (1996) provide a detailed description of the water balance model used. The modelling of an explicit water balance requires a complete physical description of the soil profile. Three soil types were chosen to represent generic heavy (Hanslope), medium (Batcombe) and light (Frilford) soils. Whilst it is may not be an precise reflection of the soil within the catchment, the use of generic soil types does allows for the model output to be related to other locations.

The model includes a simple vernalisation function for autumn sown crops. The function was based on accumulated vernalisation degree-days, a technique taken from Hough (1990). The model parameters for sowing and harvesting dates for each crop were added to the model based on Nix (1999) values for these dates and experience of ADAS consultants on the variation in crop management for different soil types. The parameters used in the model for each of the crops, including the crop diary values are shown in Appendix 1.

All crops were considered to be limited by water availability. In addition, the effect of irrigation on sugar beet and potatoes was calculated by further runs simulating three levels of irrigation:

- Low – irrigation up to May 31st
- Medium – irrigation up to July 10th
- High – irrigation up to August 15th

In each of these runs, 25 mm of water was applied (to simulate the use of a hose reel rain-gun) every time the soil moisture deficit (SMD) reached 35mm during the growing season (after March 10th).

The model uses daily values of rainfall, temperature, and estimates of radiation and potential evapotranspiration . These were derived from the UKCIP02 scenarios (Hulme *et al*., 2002) through the use of the LARS weather generator (see Appendix for details of the LARS model methodology).

A total of 15,600 model runs were undertaken; 13 crops, or crop management regimes, run on 3 soil types, over 200 scenario years and within 2 catchments. The crop types were winter wheat, winter barley, spring barley, sunflowers, winter oilseed rape, potatoes (non-irrigated and 3 levels of irrigation) and sugar beet (non-irrigation and 3 levels of irrigation).

Each crop was modelled for 4 climate scenarios: 1961-90 baseline, 2020s High emissions, 2050s Low and High emissions. No alternative emission scenarios were used for the 2020s run, as the resulting climate changes are very similar for the catchments being studied. For each scenario, 50 years of “typical” weather data were available from the LARS weather generator. However, with autumn sown crops (wheat, oilseed rape, and winter barley) only 49 years of model runs were available, since no yield is produced in the first data year.

Simple validations of the model for both the soil water component and the crop growth component were reported by Armstrong *et al.* (1996). Validation on UK data undertaken as part of a MAFF funded project (CC0333) concluded that the crop model overestimates actual yields but does provide a good indication of relative differences in yield between years and between sites (Hossell *et al.*, 2001).

The model does not implicitly include the effects of increased atmospheric CO_2 concentration on plant growth and crop yield. Most of the literature on CO_2 effects on crops is based on experiments that have been undertaken outside of the UK. In addition, most of the crops covered by this project have not been included in such experiments. Experimental work by Harrison *et al*. (1995) showed that the beneficial effect of atmospheric CO_2 on yield varies by crop type. However, given the uncertainty over estimates of its effect for different crops, it was felt that imposing a linear and uniform yield change on the model yields would provide a more appropriate, though conservative, estimate of future yields. A 'rule of thumb' of a 0.1% increase in yield for every 1ppmv increase in CO_2 derived from the estimates of Kimball (1983), was used to calculate the CO_2 fertilisation factor for the crops. This value was used as a scaling factor in adjusting all projections of future yields of C3 crops before using them as input in the Farm-Adapt model (Section 8.2). For simplicity, however, the discussion of results below covers the model yields unmodified by any CO_2 effects.

The model results were compared in a number of ways, to examine for and explain any differences between yields. Initially a comparison was made of the baseline conditions against observed yields. The effect of location (catchment), soil type and different irrigation regimes were then examined for the baseline conditions. The effects of future climate on yields and the interaction with soil, location and irrigation were also considered. Examination of the 2050s Low emission yields showed that they are similar to the 2020s high emission yields for all soils, hence the results also focus in on the effects on the 2020s and 2050s high emission effects.

In all cases the analysis used the Kolmogorov-Smirnov runs test calculated in Statistica v6.0 (Statsoft Inc, 2001). This non-parametric version of the t-test measures for differences in the shape of the distribution (not just the means) from the model runs, since the reliability of a crop is as crucial to a farmer as its yield in anyone year.

7.2 Baseline climate results

A comparison of the baseline yields against observed according to national averages derived from Nix (1999) indicated that the model does over-estimate the yield of most crops, since it assumes optimum management and no pest or disease effects and no limit nutrient in availability. For the water demanding crops of potato and sugar beet, however, the position is somewhat reversed with yields being on the low side of what is normal. This is not surprising for un-irrigated or low irrigation levels, since most of the crops in these catchments will be fully irrigated. Figure 7-1 shows the ranked baseline yields for winter wheat in both catchments as compared to maximum and minimum observed yields.

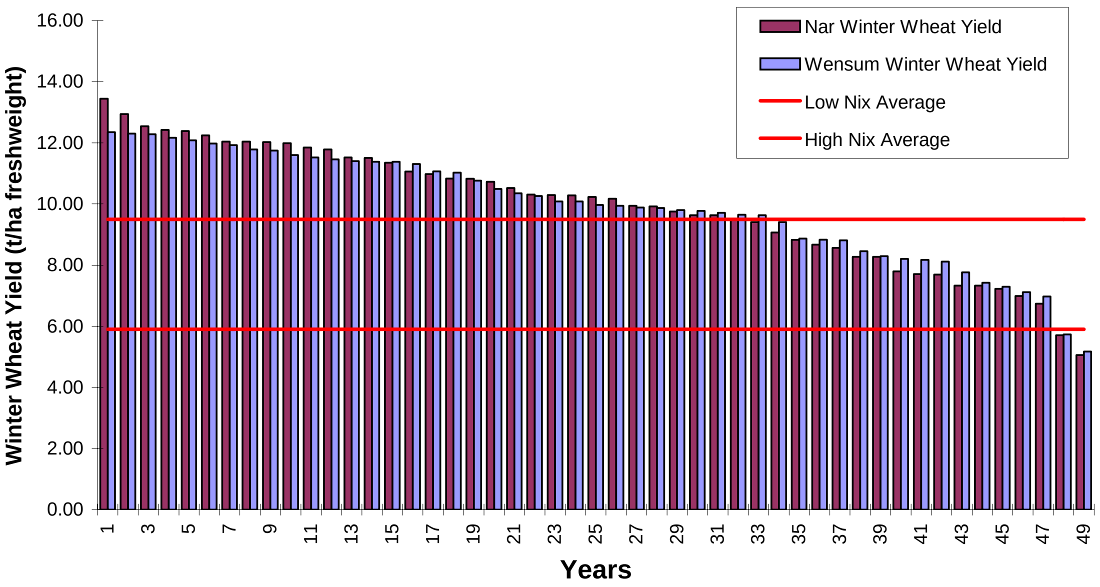


Figure 7-1. Comparison of model baseline yields for winter wheat on medium soils with Nix (1999) national averages. Yield data have been ranked.

Yields for some crops are higher in the Nar catchment than in the Wensum but there is no significant difference between the yields of any of the crops on the same soil type between catchments. Not surprisingly, soil type does have a significant effect upon the yields modelled under baseline conditions. For potatoes and sugar beet, the effect of full irrigation is enough to overcome any soil moisture differences between the soil types for the baseline yields. Where no irrigation is provided for sugar beet and for sunflower the crops performs equally badly on light and medium soil types, but yields are significantly improved on heavy soils. However, soil type also has a crucial impact on the quality of root crops and the ease of their production. Heavy soils are not generally used for potato or sugar beet production for this reason. Figure 7-2 shows the yields for irrigated crops on the different soil types in the Wensum.

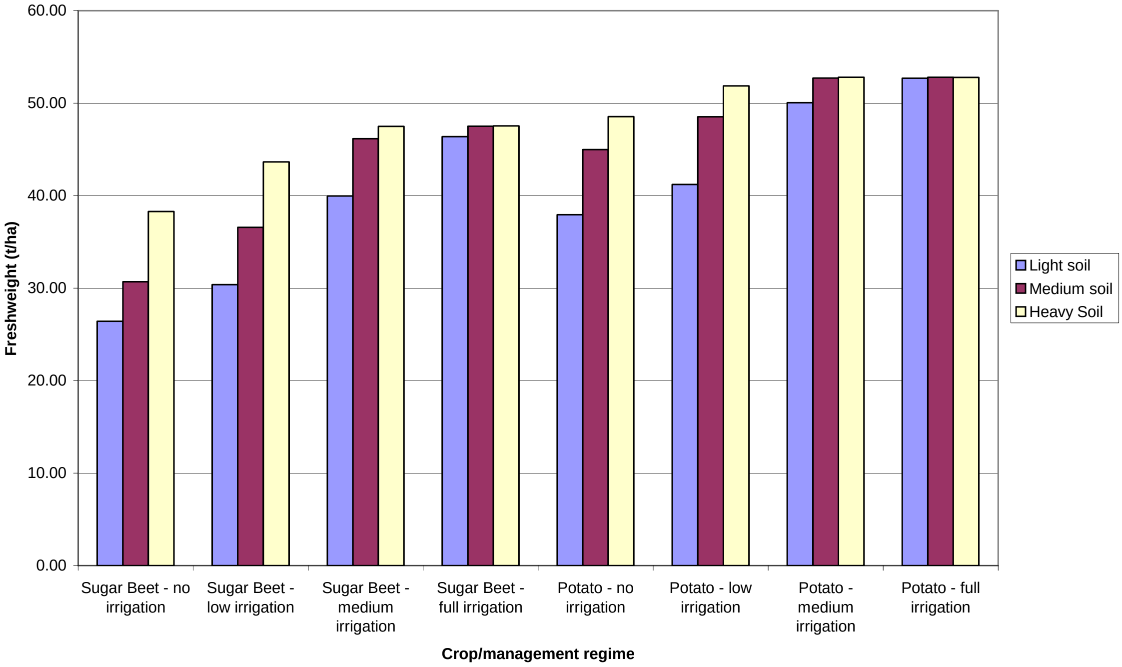


Figure 7-2. Baseline yields for potatoes and sugar beet on the 3 soil types in the Wensum.

7.3 The effects of future climate

Table 7-1 shows the baseline mean yield and the percentage change and significance of differences for each crop for the 2020s High and 2050 High emissions runs as compared to the baseline.

Table 7-1. Yields for baseline climate (t/ha) and % change under the 2020s and 2050s high and high emission scenarios, by catchment and soil type. Excludes CO_2 fertilisation effects.

	Catchment	Nar					
Soil type	Crop/Scenario	Baseline	2020s High	2050s High	Baseline	2020s High	2050s High
Light	Spring Barley	5.54	-2.68	-15.00	5.20	-7.95	-11.89
	Winter Barley	7.75	6.35	-3.13	7.42	-0.96	-1.70
	Winter Wheat	7.94	2.04	-3.71	7.61	-2.95	-1.81
	Winter OSR	3.10	-5.82	-11.56	2.77	-16.24	-16.79
	Sunflower	2.56	6.35	-3.13	2.55	4.53	-7.28
	Sugar Beet - no irrigation	26.37	0.07	-17.13	26.41	-23.78	-23.50
	Sugar Beet - low irrigation	30.00	1.27	-8.90	30.40	-17.82	-13.26
	Sugar Beet - medium irrigation	38.70	4.06	4.89	39.97	-8.21	-2.08
	Sugar Beet - full irrigation	45.03	6.70	5.95	46.39	5.69	1.75
	Potato - no irrigation	38.80	-0.68	-9.17	37.95	-8.90	-10.09
	Potato - low irrigation	41.59	1.15	-2.01	41.21	-3.98	-1.73
	Potato - medium irrigation	50.00	1.26	3.31	50.05	2.11	1.71
	Potato - full irrigation	53.17	0.22	-0.45	52.71	2.69	-2.00
Medium	Spring Barley	6.29	2.52	-9.43	6.20	-2.07	-10.42
	Winter Barley	4.71	7.23	3.49	9.63	-3.09	-7.76
	Winter Wheat	9.95	7.21	5.68	9.91	3.76	4.85
	Winter OSR	4.66	-1.02	-18.72	4.63	-13.93	-29.30
	Sunflower	2.69	7.23	3.49	2.71	5.92	-1.70
	Sugar Beet - no irrigation	30.50	4.65	-7.54	30.70	-18.80	-18.31
	Sugar Beet - low irrigation	36.13	5.05	-0.54	36.59	-10.34	-3.76
Medium	Sugar Beet - medium irrigation	45.41	3.60	4.05	46.16	0.14	-0.19
	Sugar Beet - full irrigation	46.47	9.01	5.24	47.50	5.05	1.04
	Potato - no irrigation	45.47	1.71	-3.45	44.99	-4.23	-6.81
	Potato - low irrigation	49.49	1.54	-0.14	48.52	0.62	0.08
	Potato - medium irrigation	53.15	0.02	-0.43	52.73	2.24	-1.87
	Potato - full irrigation	53.30	0.19	-0.65	52.81	2.69	-2.07
Heavy	Spring Barley	6.84	-0.47	-15.66	6.69	-2.51	-13.83
	Winter Barley	10.14	-3.33	-11.60	9.90	-3.32	-9.88
	Winter Wheat	10.38	5.00	0.29	10.54	1.81	-0.37
	Winter OSR	4.92	-4.05	-22.93	4.86	-12.13	-31.37
	Sunflower	2.83	5.70	3.04	2.82	7.14	-0.08
	Sugar Beet - no irrigation	37.61	3.74	-5.11	38.30	-12.02	-13.21
	Sugar Beet - low irrigation	42.69	4.20	0.72	43.66	-5.16	-3.39
	Sugar Beet - medium irrigation	46.32	5.01	4.45	47.49	3.68	0.46
	Sugar Beet - full irrigation	46.46	9.05	5.31	47.54	5.30	0.92
	Potato - no irrigation	48.92	0.76	-3.75	48.55	-2.62	-6.64
	Potato - low irrigation	52.36	0.03	-0.98	51.87	1.25	-2.27
	Potato - medium irrigation	53.36	-0.23	-0.78	52.81	2.53	-2.11
	Potato - full irrigation	53.33	-0.06	-0.74	52.79	2.67	-2.07

Note: figures underlined (red) are significant at the 95% confidence level.

In general, only the low and un-irrigated sugar beet and potato, plus oilseed rape show decreased yields under the 2020s scenario. All other crops show slight increases. The spatial variation of climate change means there is a greater difference in yields between catchments under the 2020s scenario than under the baseline conditions, with yields showing decreases in the Wensum for low and un-irrigated sugar beet and potatoes, and oilseed rape, that are significantly greater than those for the Nar. Similarly, increases for the irrigated crops are generally greater (and significant) in the Nar on the light soils than in the Wensum catchment.

Oilseed rape yields decline in both catchments but the drop is significant in the Wensum. By contrast, sunflower (which is used interchangeably with oilseed on farms in France) shows a significant increase in yields on medium and light soils in both catchments, as does winter wheat on the two heavier soils in the Nar. Spring Barley, winter barley and oilseed rape all show significant decreases in yield across all soils and both catchments. Oilseed rape in particular loses up to 30% of its baseline yield in the Wensum. Other crops in both catchments generally show a decrease in yields, but the losses are generally not significant and are small enough to be countered by the CO_2 fertilisation effect.

Under the 2050s High emissions scenario only medium and full irrigation is enough to offset the drier conditions and produce a significant benefit to sugar beet yields. Again the drier conditions in the Wensum are evident with even fully irrigated potatoes on medium and heavy soils show a significant decrease in yield (Figure 7-3).

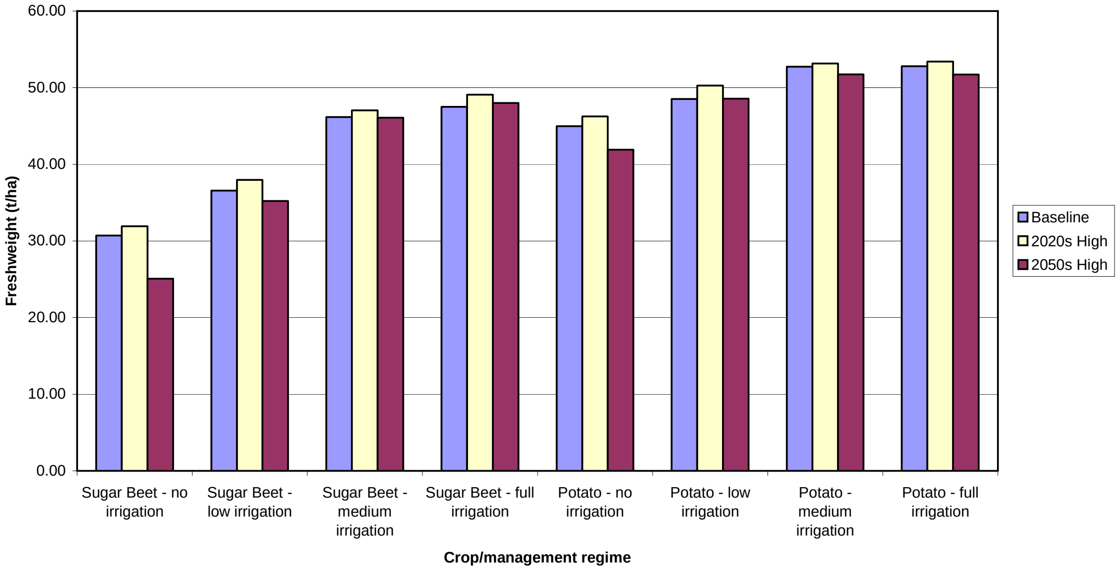


Figure 7-3. Sugar beet and potato yields on a medium soil in the Wensum under baseline and 2020s and 2050s high emission scenarios.

It is only under the 2050s High scenario that climate change begins to have a significant impact on a wide range of crops. There may also be some substitution of sunflower for oilseed rape, if the yield increases in the former make the crop economic to produce. Similarly it would be expected that winter barley may substitute for spring barley. However, it should be noted that the modelling did not consider changes in management that farmers may undertake to offset some of the negative effects of increasing temperature and soil moisture deficits, such as changing to drought tolerant cultivars or earlier sowing of spring crops. However, it does seem likely from these results that irrigation provision as well as increased irrigation levels will be necessary particularly in the Wensum catchment under these conditions. It is unlikely that sugar beet or potato could be produced on the light soils in the Wensum without these changes.

8 Land management model: methods and outputs

Stephen Ramsden and James Gibbons

8.1 Introduction and summary of approach

The land management model was developed to explore the effect of climatic change on agriculture at the catchment level. The approach was driven by the question *How will farmers adapt to climate change in the Nar and Wensum catchments?* The model integrates outputs from the hydrological modelling (*How will changes in water availability affect farmers?*) and crop modelling (*How will changes in crop yield affect farmers?*). These input data are uncertain and variable: this uncertainty is explicitly included in our modelling and results. There are four key components to the model. First, management decisions are taken at the farm- rather than catchment-level. Second, farmers make decisions based on historic data. Third, interactions can occur between farms. Fourth, some adaptations involve multi-year commitments. The model can easily be configured to model other UK catchments, given sufficient input data.

8.2 Land management model description and development

The model runs a group of farms simultaneously, sequentially and continuously over the period of interest. Each farm is represented by a separate MIP (mixed integer programming) problem. The model runs on a yearly time-step; for each time-step there is i) a planning stage, representing farmer decision making for that year and ii) a resolution stage where the planning stage is assessed in light of the actual outcome. Information available to the farm planning stage is based on the outcome of previous years, while investment decisions carry over to subsequent years. Farms can interact through trading of abstraction licenses. We model three sub-periods, each of 30 years, based on the UKCIP scenarios, 'baseline' (current conditions), '2020s' (expected crop yields and irrigation demand in the 2020s) and '2050s' (expected crop yields and irrigation demand in the 2050s). For each sub-period 50 possible crop yields, and associated irrigation requirements, were available from the crop yield modelling, while other inputs were predetermined.

At the farm-level, the model is based on a version of the Farm-adapt model (Ramsden *et al*., 1999; Gibbons and Ramsden, 2005). Farm-adapt is a MIP model that maximises farm net margin (total value of output less variable and quasi-fixed capital costs) by optimising crop, animal, labour, machinery, storage, housing and irrigation mix over the period of a year, divided into 52 weeks. Some simplifications were made to Farm-adapt to reduce the size of the matrix to be solved for each farm and to reduce the number of computationally expensive integer variables. The main simplification was to the rotation component; previously the farm area was split up into equal sized blocks and crop areas were allocated to these blocks. In the simplified version this block structure was replaced with rules, for example first-winter-wheat area was constrained to be less than or equal to the break crop area. Using integer variables in linear programming problems allows a more accurate representation of farms, for example, machinery can only be purchased in whole units. Unfortunately, integers considerably increase the complexity of solving the problem. As a compromise between these conflicting objectives of accurate representation and reduced complexity, Farm-adapt was modified so that farm-level machinery numbers were determined using a simple heuristic algorithm. First, the linear problem was solved, and then additional rows were added to the problem matrix to round up machinery numbers for each farm to the next whole integer, finally the problem was re-solved to the global solution. While this algorithm inevitably produces sub-optimal solutions in terms of farm net-margin, it may be more representative of actual farms, which are often over mechanized.

Each farm modelled has an allocated farm area, available crops, initial animal housing, soil type, initial crop storage, water abstraction license, farm management rating and a farmer expectation algorithm (see below for a more complete description of the last two). The farms were parameterised to be representative of the Nar and Wensum catchments. Defra June census figures (Defra, 2005) were used to determine farm size distribution and farm type mix. Farm size of the modelled farms was allocated at random using a lognormal distribution. Two farm types were modelled a combinable-crops farm (available crops were wheat, spring barley, winter barley, oilseed rape, sunflowers and setaside land), and a root-cropping farm (additional available crops were potatoes and sugar beet). Sunflowers were included to test whether climate change may result in farmers adopting exotic crops. In total 29 farms were modelled in the Nar catchment (10 combinable cropping, mean size 570 ha, and 19 root cropping mean size 391 ha) and 93 in the Wensum catchment (42 combinable cropping, mean size 209 ha and 51 root cropping, mean size 270 ha). On both farm types, three wheat crops were available (1st, 2nd and 3rd) to reflect the rotational position (2nd wheat following 1st, 3rd wheat following 2nd). For the root-cropping farms the actual Nar and Wensum abstraction licences (Section 2.4) were allocated; the largest licenses were allocated to the largest farms. Farms were allocated to soil type (light, medium or heavy) in proportion to the soil types in the catchment (Knox, pers. comm). Root-cropping farms were preferentially allocated to light and medium soils.

As the project was concerned with water use, special effort was made to represent irrigated crops accurately. Two irrigated crops were modelled, sugar beet and potatoes. These crops represented a high value irrigated crop (potatoes) and a lower value irrigated crop (sugar beet which currently is largely grown un-irrigated). For each irrigated crop, four levels of irrigation were available, full, none and two intermediate levels. The intermediate levels restricted the period in which irrigation was available, rather than allowing reduced irrigation throughout the growing season. The intention of this approach was to model the farmer planning to irrigate fully and actual irrigation demand exceeding expected irrigation demand.

An important model component is the capturing of the long-term effect of large investment decisions. This effect is achieved by making the life span of investment in reservoir capacity, animal housing and crop storage 20 years. That is, if the decision is made to invest in a reservoir, the irrigation capacity is available for the following 20 years and the cost of investment is paid off over the same period. Investments in machinery are on an annual basis taking into account depreciation. Investment decisions can be made in any year during a model run. For example, although no farms modelled have an existing reservoir capacity, investment in reservoirs can be made during the baseline period. This mechanism allows farms to adapt to alternative scenarios (e.g. reduced abstraction or abstraction license trading).

At each model time step, it is possible that the farmer planning stage will conflict with the actual outcome. For example, actual crop irrigation demand may exceed available water. The resolution stage adjusts the farm plan to take account of any discrepancy. In the simple case farm net margin is adjusted if crop yields are greater or less than expected. More complicated resolution is required when actual crop irrigation requirements exceed expectations. When this situation occurs there are two levels of adjustment. First, any unused irrigation capacity is used to supply additional water with a corresponding increase in farm costs. Second, if the unused irrigation capacity is insufficient the irrigated crop yields are reduced. For example, if the farmer has planned to maximally irrigate 25 hectares of potatoes and irrigation water is insufficient the actual potato yield realised will correspond to the actual irrigation level applied, which will be all the available water.

As each run of the model randomly samples from the input data repeated runs of the model will produce different outcomes. Therefore, sufficient repeated runs will characterise the output space. The model is computationally intensive, so there is a trade-off between complete characterisation and available modelling time. For each scenario, the model was run 100 times.

8.3 Scenarios modelled and model runs

For each catchment, 5 scenarios were run (Table 8-1); the scenarios were selected: (i) to explore any difference between the catchments; (ii) compare the UKCIP low and high scenarios, and (iii) to test the impact of trading of abstraction licenses and iv) to examine the effect of reduced summer abstraction.

Table 8-1. Summary of scenarios.

Abbreviation	**Catchment**	**UKCIP scenario**	**Water Trading**	**Summer abstraction**
Nar_L0_100	Nar	L	Off	100%
Nar_H0_100	Nar	H	Off	100%
Nar_H0_050	Nar	H	Off	50%
Nar_H1_100	Nar	H	On	100%
Nar_H1_050	Nar	H	On	50%
Wen_L0_100	Wensum	L	Off	100%
Wen_H0_100	Wensum	H	Off	100%
Wen_H0_050	Wensum	H	Off	50%
Wen_H1_100	Wensum	H	On	100%
Wen_H1_050	Wensum	H	On	50%

Key: Nar_L0_100 indicates run for the Nar catchment, low emission scenario, no water trading and up to 100% of licensed abstraction permitted

8.4 Summary of results

Owing to the large quantity of results generated, only a small selection can be presented. The results presented are based on the catchment totals, aggregating the individual farms, and biased towards abstraction and irrigation. The results are summarized as the mean of all the runs for each period, with standard deviations indicating the variation. To exclude any start-up effects and transition effects between periods the summaries exclude the first eight years of the baseline period and first five years of the 2020s and 2050s.

The catchment net margins (Table 8-2) give an indication of the relative farm profitability under the different scenarios. Comparing the baseline figures for the L0_100 and H0_100 scenarios, which are based on runs drawn at random from the same inputs, gives an estimate of the sampling error. Given sufficient model runs, the figures should be the same, for the Nar they differ by 5.9 % and for the Wensum 5.2%. However, these figures are small compared to the difference between periods and scenarios. Generally, there is an increase in net margin from the baseline to the 2020s and from the 2020s to the 2050s; this increase is attributable to the increase in crop yields. The large standard deviations indicate that the variability of the data is high, suggesting large year-to-year variations in net margin. Table 8-2 illustrates typical variation in farm net margin, at the catchment level, over the course of one run. As might be expected, limiting summer abstraction reduces net margin in both the Nar and Wensum. More surprising is the reduction in net margin in the Nar catchment, for the baseline and 2020s periods, for the water-trading scenarios compared to no water trading scenarios. This result is explained by the model’s use of historic data: previous dry years will result in the model leasing in more abstraction license even if irrigation demand is low in the current year and vice versa. In the Wensum catchment where there is less ‘slack’ licensed abstraction capacity, water trading increases net margin.

Table 8-2. Farm actual net margin, excluding MTR decoupled payment. Figures in brackets are standard deviations.

Run	Baseline	2020s	2050s
Nar_L0_100	253,800 (1,077,624)	1,134,974 (1,388,827)	2,080,772 (1,273,342)
Nar_H0_100	269,606 (1,083,596)	1,202,972 (1,384,319)	1,817,489 (1,159,324)
Nar_H0_050	-749,180 (1,159,285)	24,384 (1,409,896)	637,641 (1,123,505)
Nar_H1_100	-21,778 (1,315,019)	940,938 (1,696,470)	1,980,584 (1,318,261)
Nar_H1_050	-840,020 (1,176,531)	-28,753 (1,493,817)	536,375 (1,235,318)
Wen_L0_100	-1,101,149 (2,041,733)	23,179 (2,540,933)	1,953,690 (2,781,629)
Wen_H0_100	-1,161,486 (2,003,065)	1,616 (2,520,533)	1,020,052 (2,487,008)
Wen_H0_050	-2,201,304 (2,007,545)	-1,193,915 (2,535,267)	-165,180 (2,491,642)
Wen_H1_100	-760,125 (2,118,198)	323,241 (2,517,862)	1,325,022 (2,623,749)
Wen_H1_050	-1,924,497 (2,125,871)	-766,043 (2,579,128)	267,789 (2,680,772)

Irrigation abstraction, as a percentage of the total licensed abstraction for each catchment differed between the catchments and scenarios (Table 8-3). Variation in abstraction levels within scenarios and periods is low. Abstraction levels in the Wensum were higher than those in the Nar. The most striking difference between the scenarios is the switch from summer abstraction to winter abstraction when summer abstraction was reduced by 50%. In few scenarios and periods does substantial summer and winter abstraction occur together, an exception is the first Wensum water-trading scenario. Generally, abstraction increases from the baseline to the 2020s and from the 2020s to the 2050s. Water trading has a bigger impact in the Nar catchment where there is more unused abstraction capacity than in the Wensum. However, with water trading and reduced summer abstraction almost all the abstraction capacity is utilised in the Wensum catchment. Investment in reservoir capacity (Table 8-4), closely follows the abstraction pattern: there is substantial investment in reservoirs when summer abstraction is reduced by 50%. It is notable that reservoir capacity is greater than actual winter abstraction in both catchments. This result is attributable to two factors i) reservoirs in the model are constructed in units of 20,000 m^3 so capacity will always be greater than demand and ii) reservoirs are constructed at the farm-level and life-span is 20 years, so it is possible for capacity to ‘over-lap’.

Table 8-3. Abstraction summary, as percentage of total licensed water in each catchment. Figures in brackets are standard deviations.

Run	Winter			Summer		
	Baseline	2020s	2050s	Baseline	2020s	2050s
Nar_L0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	62.76 (5.38)	66.36 (5.81)	69.81 (5.89)
Nar_H0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	62.18 (5.16)	65.93 (5.39)	72.53 (5.30)
Nar_H0_050	46.39 (4.16)	49.56 (4.30)	53.88 (3.62)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Nar_H1_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	66.37 (6.82)	75.59 (8.97)	93.22 (8.44)
Nar_H1_050	48.76 (4.40)	52.08 (4.73)	56.89 (4.43)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Wen_L0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	97.03 (2.29)	98.99 (1.05)	99.11 (2.48)
Wen_H0_100	0.00 (0.02)	0.00 (0.00)	5.18 (3.26)	97.30 (1.69)	99.00 (0.96)	94.32 (3.44)
Wen_H0_050	92.26 (5.40)	95.74 (1.87)	95.96 (1.99)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Wen_H1_100	0.00 (0.00)	0.00 (0.00)	3.50 (2.56)	99.99 (0.25)	100.00 (0.00)	96.50 (2.56)
Wen_H1_050	99.83 (1.20)	100.00 (0.00)	99.99 (0.24)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

Table 8-4. Reservoir capacity as percentage of catchment licensed water. Figures in brackets are standard deviations.

Run	Baseline	2020s	2050s
Nar_L0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Nar_H0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Nar_H0_050	75.84 (13.87)	78.44 (11.64)	83.44 (9.51)
Nar_H1_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Nar_H1_050	80.06 (14.20)	82.88 (12.12)	88.04 (10.41)
Wen_L0_100	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Wen_H0_100	0.00 (0.00)	0.00 (0.00)	7.88 (5.28)
Wen_H0_050	145.80 (26.86)	150.10 (23.83)	149.88 (22.25)
Wen_H1_100	0.00 (0.00)	0.00 (0.00)	5.69 (4.34)
Wen_H1_050	165.65 (29.97)	164.03 (26.32)	163.77 (21.30)

Within each scenario, there are only very small changes in potato area among periods (Table 8-5). In contrast, sugar-beet areas fluctuate among periods as well as scenarios. Figure 8-1, Figure 8-2 and Figure 8-3 illustrate this difference. The increase in sugar beet area in the 2020s is largely unirrigated; increases in unirrigated sugar beet yield increase the return for the crop. Among the scenarios, those with more available water (with water trading or full summer abstraction) potato areas are higher than the scenarios where abstraction is limited. There is not a clear pattern to the changes in sugar beet area. A plausible explanation for the differences between sugar beet and potatoes is that the model maximises the area of the high value potato crop and irrigates potatoes at the expense of sugar beet, surplus irrigation water is then applied to the sugar beet crop. Examining the crop irrigation levels (Table 8-6) provides some support for this hypothesis. However, interpreting these results is not straight forward as they are a function of irrigation demand and supply, i.e. irrigation could be low because either crop demand is low, or because irrigation supply is low. With this caveat, it is apparent that under the least abstraction limited scenario (the Nar with water trading and 100% summer abstraction) sugar beet is irrigated at a higher level than in the other scenarios.

Table 8-5. Percentage area of irrigated crops. Figures in brackets are standard deviations.

Run	**Potatoes**			**Sugar beet**		
	Baseline	2020s	2050s	Baseline	2020s	2050s
Nar_L0_100	10.18 (0.76)	10.16 (0.77)	10.18 (0.79)	1.91 (1.49)	3.50 (1.71)	4.10 (1.56)
Nar_H0_100	10.04 (0.76)	10.02 (0.80)	10.01 (0.81)	1.87 (1.47)	3.55 (1.65)	2.98 (1.41)
Nar_H0_050	7.56 (0.43)	7.60 (0.43)	7.61 (0.43)	2.26 (1.60)	3.68 (1.66)	2.88 (1.55)
Nar_H1_100	10.51 (0.80)	10.56 (0.81)	10.60 (0.82)	2.03 (1.52)	3.71 (1.58)	4.08 (1.14)
Nar_H1_050	7.80 (0.46)	7.86 (0.45)	7.87 (0.46)	2.01 (1.46)	3.76 (1.69)	2.95 (1.60)
Wen_L0_100	8.55 (0.48)	8.60 (0.50)	8.87 (0.53)	2.83 (2.22)	1.06 (1.43)	4.68 (2.43)
Wen_H0_100	8.60 (0.48)	8.67 (0.51)	8.84 (0.48)	2.91 (2.30)	1.07 (1.51)	2.23 (1.84)
Wen_H0_050	8.34 (0.54)	8.40 (0.56)	8.53 (0.55)	3.12 (2.25)	1.12 (1.52)	2.41 (1.91)
Wen_H1_100	8.76 (0.70)	8.79 (0.66)	9.03 (0.68)	2.97 (2.22)	1.05 (1.49)	2.06 (1.81)
Wen_H1_050	8.71 (0.55)	8.77 (0.54)	8.96 (0.53)	2.90 (2.22)	1.14 (1.52)	2.28 (1.80)

Table 8-6. Mean irrigation level for irrigated crops, where 1=none, 2=early season, 3=early and mid season, 4=all season.

	Potatoes			Sugar beet		
Run	Baseline	2020s	2050s	Baseline	2020s	2050s
Nar_L0_100	3.13	2.93	2.82	1.53	1.52	1.51
Nar_H0_100	3.16	2.96	2.86	1.52	1.50	1.72
Nar_H0_050	2.75	2.56	2.67	1.30	1.27	1.29
Nar_H1_100	2.94	2.82	2.94	1.42	1.64	2.24
Nar_H1_050	2.81	2.60	2.71	1.32	1.31	1.32
Wen_L0_100	2.05	2.01	1.81	1.11	1.10	1.10
Wen_H0_100	2.02	2.00	1.85	1.10	1.10	1.06
Wen_H0_050	1.97	1.98	1.81	1.08	1.08	1.05
Wen_H1_100	2.20	2.14	1.97	1.12	1.09	1.05
Wen_H1_050	2.18	2.12	1.95	1.12	1.08	1.05

Figure 8-1.Variation in farm net margin, at the catchment level, for run 1 of the Nar_H0_100 scenario.

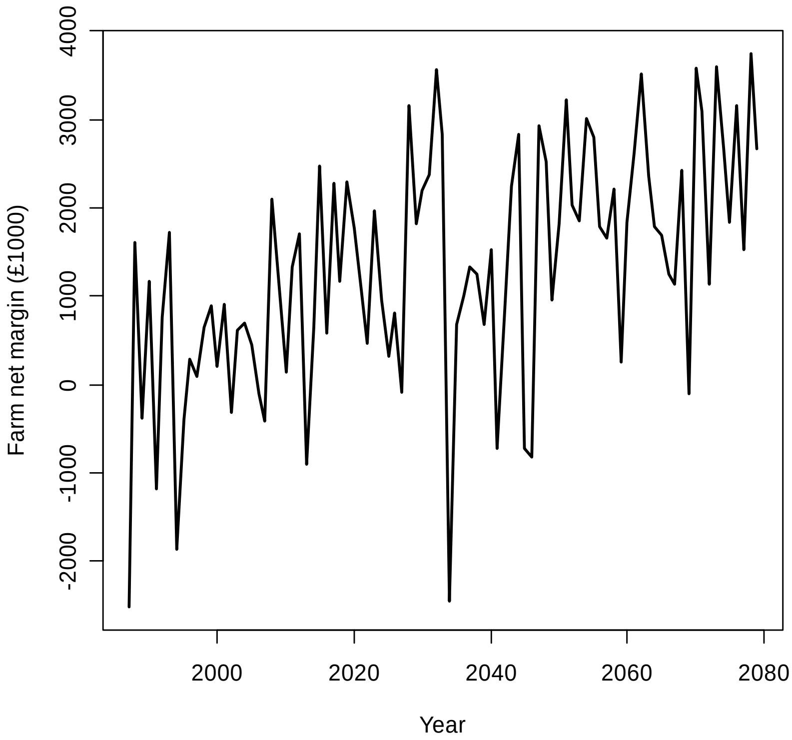


Figure 8-2. Variation in potato area, at the catchment level, for the Nar_H0_100 scenario. The line is the mean of all runs, the grey area is bounded by the 5th and 95th percentiles.

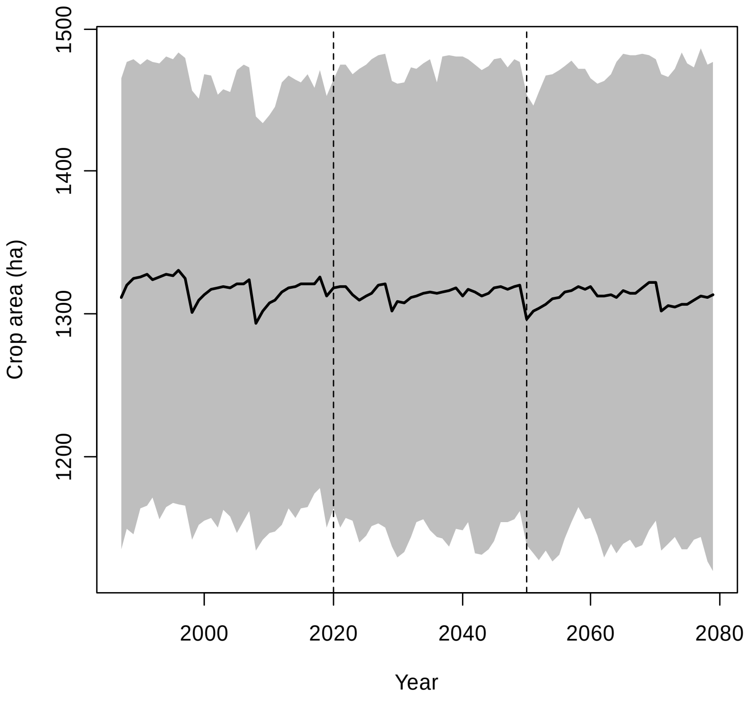
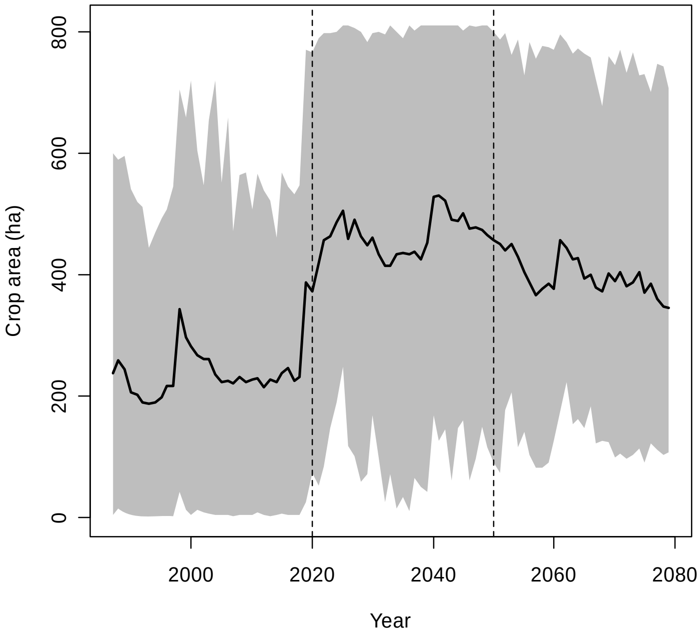


Figure 8-3. Variation in sugar beet area, at the catchment level, for the Nar_H0_100 scenario. The line is the mean of all runs, the grey area is bounded by the 5th and 95th percentiles.



For crops other than irrigated crops, there were few changes between periods. Winter wheat area increased from the baseline to the 2020s and from the 2020s to the 2050s with a corresponding decrease in winter and spring barley area. For example, for the Nar_H0_100 scenario, from the baseline to the 2050s winter wheat area are increased by 51% while spring barley area decreased by 45% and winter barley area decreased by 9%. These figures are typical of the other scenarios. The other result of note is that while small areas of sunflowers were grown, oilseed rape remained the main break crop in all periods and scenarios.

8.5 Discussion

From the results, it is clear that under all the scenarios explored, high value irrigated crops (represented by potatoes) will still be grown in both catchments under climate change. However, increased irrigation demand will increase, and in catchments where abstraction is limited, the high value crops will be irrigated at sub-optimal levels. The irrigation levels of the lower value irrigated crops will be reduced to maintain the area of the higher value crop. For the non-irrigated crops, the changes predicted are driven by the modelled yield increases, which are relatively greater for winter wheat than the other crops. These yield increases largely drive the predicted increase in farm net margin. It should be noted that the increases in yield are largely a result of the CO_2 fertilisation effect assumed.

Reduced water availability and hence limited summer abstraction will result in further adaptation. These adaptations are in the same direction as above, with irrigation to the high value crops reduced, but irrigation to the lower value crops reduced more. A more significant adaptation is investment in winter storage and the resulting shift to winter abstraction. While this investment enables the maintenance of irrigated crops there is a large impact on farm net margin. The change also makes farm businesses more vulnerable to poor years. As the farms as modelled make investment decisions independently, there is an over-investment in reservoir capacity at the catchment level. This over-investment could be avoided by pooling reservoir capacity among farms.

Water trading as an adaptation has a large impact, especially in catchments where there are unused catchment licences (Nar). Trading allows a small increase in irrigated crop area, and the maintenance of irrigated crops under climate change. However, there is some evidence that under some circumstances trading can have a negative effect on farm net margin, for example, when farms buy abstraction licences and invest in irrigation following a dry year. This highlights the problem that farmers face when adapting to unknown outcomes; adaptations based on imperfect knowledge can lead to sub-optimal solutions when compared to those that would result if the farmer had perfect knowledge.

9 Agricultural adaptation: options and constraints

Tonny de Vries and Keith Weatherhead

9.1 Adaptation options

Faced with water scarcity, an agricultural irrigator has options that include trying to increase water resources, reduce water demand through higher efficiency or better management, accept the yield and quality losses in dry summers, or reduce or cease growing irrigated crops. These have been reviewed by Weatherhead *et al*. (1997). Climate change adds further uncertainty, in that there are likely to be additional changes in markets (and competitors) for the irrigated produce, yield and quality changes of the existing crops (as discussed earlier), possible new crops and/or irrigation needs for currently un-irrigated crops, and probably changes in the availability and reliability of existing water sources.

9.2 Farmer attitude interviews

A series of interviews were conducted to determine how farmers view the need to adapt to climate change, how they have dealt with water shortages in the past, how they deal with them now and how they are likely to deal with water shortages in the future. Ten holders of abstraction licences for agricultural irrigation were interviewed, from locations across East Anglia. Interview notes were taken and later transcribed. All interviewees were assured confidentiality; interviews were not recorded.

The farms ranged in size from 160 to 4000 ha with an average size of 1213 ha. On average 76% of the area can be irrigated. All farms are family-owned but in some cases a farm manager runs the day-to-day operations. The main irrigated crop is potatoes. Other irrigated crops are carrots, onions, parsnips, salad crops and beans. Sugar beet and wheat are occasionally irrigated. Rain-fed crops include wheat, barley, maize, grass, field beans and oil seed rape. Some farms also keep cows or pigs. Most farmers have more then one licence and most have access to a mix of ground and surface water or use only ground water. Half have obtained winter abstraction licences and built reservoirs.

Past water shortage coping strategies

In the past have you had problems with water shortages?

Seven of the ten farmers had experienced water shortages in the last ten years. These were in 1995-1996 and to a lesser extend 1991; 1976-1977 was also remembered as a drought. As Figure 2-2 earlier shows, these years were very dry, with high irrigation demands.

The timing of a drought determines its effect on the crops. Most irrigation happens during crop establishment (March-April) and the main growing period (May-July). In 2003 a high potential soil moisture deficit (308 mm) occurred, reaching a peak in mid October, but by which time most crops had been harvested. Only one of the ten farmers mentioned 2003 as a dry year.

What was the cause of these water shortages?

The shortages were a result of insufficient aquifer recharge and low water levels in the rivers. The Environment Agency was able to foresee some of the ground water shortages and a number of farmers were asked to voluntarily reduce abstractions in order to prevent forced bans later in the season. Voluntary reductions worked well in some catchments, although there have been discussions on the legality of these kinds of reductions. A second worry about voluntary reductions was whether they would set precedents for future years, letting the EA believe that the farmers have no real need for the water. Not all voluntary reductions worked out as well as hoped and in a few cases were followed by a forced ban. As a result some of the farmers reported they are no longer willing to cooperate on voluntary reductions.

In other catchments sudden (forced) abstraction reductions were introduced, sometimes followed by a total ban. Total abstraction bans without prior reductions have also occurred.

How did the water shortages affect your business?

Water shortages affected irrigation in several ways. Irrigation was limited to certain times, less water could be applied during an irrigation turn and the irrigation interval became longer. In a few cases the least drought sensitive crops, non-essential crops or marginal value crops were stopped being irrigated. The water shortages caused some yield losses but this was sometimes offset by record prices (£220/t compared to £60/t for 2004). None of the farmers had lost a complete crop due to water shortages.

How did you deal with the water shortages?

Dealing with water shortages can be done in the short or the long term. Short term measures usually involve concentrating irrigation on the most valuable crops. To prevent future shortages five farmers have built and one is planning to build on-farm storage reservoirs. The storage reservoirs are refilled during the winter months when water is more available and abstraction charges are lower (usually 1/10th of summer abstraction charges). Two farmers engaged into talks with the Environment Agency to find a solution to water shortages. A water transfer scheme was arranged with one of them, where water can be transferred through a series of ditches from an area with sufficient water to drier parts. In exchange the farmer loses 10% of the transferred volume with each transfer. One farmer has chosen boom irrigation rather than rain guns, which allows greater precision.

Which other water shortage coping measures did you consider? Why didn't you implement them?

Another farmer had considered building a reservoir but lack of suitable land and difficulties with access to surface water had prevented this. Trickle irrigation was considered by one farmer as a means to obtain higher irrigation efficiencies. There is however a large cost associated with trickle irrigation, both for the initial investment as well as for operation and maintenance. They considered that in the current situation and climate, trickle irrigation is not viable for field crops. Using treated water from a primary sewage treatment plant was considered on one farm, but difficulties with possible contamination of produce and supermarket quality control made this unfeasible.

Impacts of abstraction licence changes

How would a reduction in your total licensed volume affect your business?

Four farmers reported that their licences are sufficiently big that a 10% decrease in the total licensed volume will not have any effect on their irrigation practises. A further four farmers use all of their water and a 10% reduction would mean that irrigation has to be focussed on the more valuable crops or the area of the irrigated crops would need to be reduced. Two farmers mentioned that it depends on which licence will be cut. They fully use one or more licences, but have further licences that are not used to the maximum. It was also mentioned that there is a difference whether the yearly maximum volume is cut or the daily abstraction limit is cut.

If the total licensed volume is cut by 25% all but two farmers said they would noticed a difference. The resulting actions differ, 2 farmers said that they would take the risk that in extreme years (1 in 5 driest year) they are short of water. One farmer said investment priorities would need to change, whereas another would have to use more mains water. On one farm the cropping pattern may need to change as many crops would be difficult if not impossible to grow. In general with a 25% reduction most would feel some effect or, as one farmer said, would start to feel very nervous.

A 50% reduction in total licensed volume would start to seriously affect the business according to most farmers that were interviewed. Cropping pattern would need to be changed and lower value irrigated crops would need to be cut out. Some farmers would struggle to keep the farm going and one farmer mentioned that a 50% cut could be catastrophic if permanent.

At a 100% reduction all farmers would have to stop irrigation. Some farmers would move to non-irrigated agriculture or livestock. Several mentioned that a move out of agriculture would be the only possibility. Converting the farm to park land and concentrating on tourism is a possibility for some.

What kind of measures would you take if your total licensed volume was significantly reduced?

The most obvious choice for most farmers is to change the cropping pattern and/or move to winter storage reservoirs. Trickle irrigation was mentioned by one farmer but that is currently not an option due to difficult soils and hard water, but as he said: "If the price of potatoes is right, anything can happen". Some farmers already will only rent in land if it has an abstraction licence. Other possibilities include water trading, share farming and using contractors.

What kind of measures would you take if the reliability of your licences was significantly reduced?

Investing in more storage reservoirs seems to be the preferred option among the interviewed farmers, closely followed by changes to the cropping pattern (i.e. cut down on acreage, cut down on marginal value crops). Reliability is extremely important. Irrigated crops can be very costly to put in (£3000/ha was quoted for potatoes); most farmers would not risk this with an unreliable source of water.

What kind of measures would you take if all your licences were revoked?

The majority of the farmers thinks that without abstraction licenses they would not be able to continue farming. As one farmer said: "No licence equals no business". Moving to cereals was only considered a viable option by two farmers.

Impacts of economic changes

Economic changes can be an important factor in the on-farm decision making process. After all, farmers are interested in making a profit just like any other business person. The price of the crop ultimately determines the difference between making a profit or a loss.

Do you think the following economic changes would affect you approach to irrigation and how?

Strengthening/weakening of the pound

About half of the farmers do not think the strength of the pound has any effect on their business. The other half thinks there is some benefit in a weakening of the pound. This would curb imports from abroad allowing them to compete with cheap produce from abroad. A weakening of the pound is seen to bring higher end prices and ultimately higher income for the farmer.

Reduction in subsidies

None of the interviewed farmers irrigate crops that are subsidised. Any increase or decrease in subsidies is therefore unlikely to have any effect on irrigation practices.

Changes in the market

Large imports, mainly from the Netherlands and Belgium, have driven prices of potatoes and onions down. Further pressure comes from the new Eastern European EU countries. As several farmers mentioned the key is quality. Irrigation allows high quality produce which is what the consumers want. Unless there is a change in consumer attitude irrigation, a number of farmers think that irrigation will remain important.

Other economic influences

By far the largest worry for farmers is their contracts with the larger supermarkets. A large percentage of their produce eventually ends up in the major supermarket chains. De-selection can be disastrous as it is not easy to find a new market. The rules set by the supermarkets for the quality of the crop are strict and standards are high.

Would an increase in water abstraction charges influence your approach to irrigation?

Current abstraction charges are between £0.02/m^3 and £0.03/m^3 for summer water. None of the interviewed farmers seemed to think a small increase (up to £0.05/m^3) in the abstraction charges would make a significant difference in their irrigation practices. Four farmers mentioned the fact that water is a relatively inexpensive commodity which adds a large value to the farm. One farmer said that his licences cost around £5000 per year but added a (land) value of £800,000 to his farm.

An increase to £0.10/m^3 would make most farmers think more carefully where they use their water and on what crops. At £0.20/m^3 most would either stop irrigating or seriously rethink their cropping pattern.

As for an increase in winter abstraction charges, no one could even imagine an increase in those prices and one farmer said he would fight an increase in those with all his might. That is not to say that they would just accept any increase in summer abstraction charges.

At what price do you expect farmer to buy or sell summer water?

It has proven very difficult to actually establish a price at which people would buy or sell water. There has been little or no trade of water as yet and no one has any idea what it might cost. Two farmers mentioned that prices being mentioned at the recent UKIA Spring Conference (February 2005) seemed very reasonable. Another price that was suggested was the actual (yearly) cost of the licence.

In some catchments there is very little opportunity for trading as everyone has more than enough water for themselves and do not (at the moment) require anymore. In another catchment there are actual licences for sale. The problem is that the present selling procedure is so similar to applying for a new licence (i.e. complicated) that farmers are put off. The Environment Agency in the area is very hesitant about new licences and trading of existing licences, especially since the CAMS process in the catchment has not been completed yet.

Impacts of climate change

Climate change will clearly have a significant influence on farming practices in the future. With the expected warmer drier summers and milder wetter winters, irrigation may become more important.

All the farmers interviewed were aware of what is being reported in the media about climate change and are well informed on the subject. Some say they have already seen the effect of climate change. They reported that winters have become much milder in the past 10-15 years. There used to be lots of snow in the winter, but now hardly any falls. As for other signs of climate change they are not so sure. Not all farmers believe climate change is going to happen. On 2 farms rainfall records have been kept (one going back to 1894). These records show an increase of summer rainfall in the past 10 years, making it very difficult for the farmer to believe that the climate is changing.

What effect do you think climate change will have on your business?

Many of the farmers feel that climate change will be a slow gradual process (if it happens at all). This will give them plenty time to slowly adapt and find solutions. Having a secure water supply is an important issue for continued irrigation. Applying for a storage reservoir and changing the cropping pattern seem the most logical options. Climate change may allow some new types of crops to be grown (grapes, sunflower and oranges were mentioned), while others may no longer be suitable. Further investments in new technology may be necessary to successfully adapt to climate change. Climate change is not necessarily a bad thing, as one farmer said: "No frost would be good"

What kind of measures would you take if the climate changes (other than for water shortages)?

As a few farmers said, a secure water source is the most important part of irrigation. This is true in the present and possibly more so in the future. The measures farmers will take to deal with climate change are largely the same as they would for any water shortage. This mostly consists of building storage reservoirs and/or changing the cropping pattern. One farmer thought it might be possible in future to reduce the amount of land required for growing (irrigated) crops due to higher production because of the increased CO_2 and/or temperature.

What would prompt the implementation of future measures?

Climate change will be a gradual process and therefore adaptation will be gradual too. What is possible today may no longer be viable in 5 years time. Agriculture in the UK is dependent on summer rainfall. If that decreases, irrigation will increase in importance.

Are there any other factors or threats that would change you approach to irrigation?

Irrigation very often determines the quality of a crop. One farmer said: "As long as people eat and there is an affluent society, there will be a demand for (high quality) irrigated crops." Adaptation to water scarcity will happen quite easily as irrigated agriculture relies on water. Any other changes may need some more force in the form of legislation or pressure from the public.

In 50 years time do you think your farm will still be an irrigated farm?

More than half of the interviewed farmers think their farm will still be an irrigated farm in 50 years time. The remaining ones have farms in areas where water resources are already under pressure or have limited access to new water resources.

9.3 Other forms of adaptation

For the farmers that were interviewed the preferred forms of adaptation are building (individual) storage reservoirs and changing cropping patterns. Other forms of adaptation are possible and have already happened.

In Lincolnshire groups of farmers have participated in water transfers schemes. Water Transfer Ltd. (Boston) is a large group of 64 farmers. They all irrigate from the drainage system. The new scheme allows extra water from two nearby rivers to be let into the drains in times of shortage. Farmers still hold individual licenses. Farmers from Water Transfer Lincoln Ltd. combined their individual licences and they were replaced with a single licence covering all the land used by the members. The scheme is very flexible which allows farmers to better match their needs to available water resources. Any water not needed by one farmer is added to the common pool and can be used by another. Another benefit is that bureaucracy is greatly decreased as there is only 1 licence rather than 19 separate ones. Also in Lincoln, an 18 ha reservoir is in the process of being built. This reservoir will enable irrigation on a number of tenanted holding with a total of 520 ha and will hold enough water for two seasons (Hendrikz, 2004).

Water trading is by many seen as a solution to water shortages. Many water-short farmers would like to buy some of the existing sleeper (unused) licences and some of those are quite willing to do so. Abstraction licence trading will be allowed as a result of the Water 2003, but as yet there are no clear rules as to what is allowed and what isn’t. Any trade will have to be approved of by the Environment Agency and they can reject any application which may cause harm to the environment or other users. The process which determines whether or not a trade is allowed would probably be similar as that for a new licence and may be rather lengthy. This would make temporary trades very difficult to establish. The potential for trade is large. Many abstraction licences are never used and more are only partially used. Trading would allow water to be used where most needed. The danger however is that in areas where water resources are already under pressure, the re-activation of sleeper licence can cause an even greater conflict between the environment on the one side and the abstractors on the other. This requires very careful monitoring of all catchments and it may be necessary to revoke some licenses or prevent certain trades from taking in order to stabilise abstractions at a sustainable level.

9.4 Discussion

Understanding how farmers currently deal with water scarcity provides insights into how they are likely to deal with water scarcity as a result of climate change. All interviewed farmers have previously experienced water shortages and restrictions on abstractions. They are aware of the importance of a secure and reliable water supply. Many farmers have formed water abstractor groups and have entered in to dialogue with the Environment Agency. In some areas abstractors have agreed to (temporary) voluntary reductions in abstraction in order to protect (ground) water supplies. This is not always sufficient and one farmer did experience a total ban on abstraction after first voluntarily reducing his abstraction and as a result is no longer willing to consider voluntary reductions.

Although none of the interviewed farmers currently experience problems with water shortages, all have started to secure extra water supplies. The preferred method for most is to apply for more summer licences (for surface water as well as ground water), but these are difficult to come by. Winter storage reservoirs have been built by 3 farmers; a fourth considered building one but has no direct access to surface water. Re-use of waste water was also considered by one farmer as an alternative water supply, but he feared that produce would be difficult to sell due to contamination fears from the supermarket. Most reported to be interested in buying water from other abstraction licence holders on a permanent basis. The market for temporary trade was thought by the respondents to be small as most growers have contracts with super markets and would not want to jeopardise these contracts in any way by having to depend on an unreliable water supply.

All farmers interviewed are aware of the threat of climate change. They realise that it will have an effect on their farming practices and that at some point in time they will need to adapt to the changing climate. They mentioned that extreme weather events will take very careful planning as this will have the biggest impact. However they are not overly concerned at the moment. Climate change is seen as a long term problem that will only gradually change their business. On the short term there are far more important issues. The relationship with supermarkets is the main worry as contracts can be lost at any time. Other issues include the expansion of the European Union and legislative changes.

When asked if they thought their farm would still be an irrigated farm in 50 years time, a number did not think so. One farmer thought it would be very difficult to maintain current practises as there is already a large amount of pressure from public water supply and the environment and that irrigation at his farm would most likely not be able to continue if this further increases. A second farmer thought that global trading would cause him to be out-competed by others. Not all interviewed farmers see a future without irrigation. One farmer thinks there is enough water available for in his catchment for further abstractions, especially during the winter and is confident that this will be enough to keep his farm in operation.

All farmers that were interviewed thought there was little they could do to improve their irrigation water management. They believe that it is already optimal. There is also little scope as they see it for changes in soil or crop management for the same reason. As the climate changes over the years there may be some possibilities to change cropping pattern, but farmers think this will not be soon.

The fact that climate change is not a particular worry at the moment does not indicate that water scarcity is also not a problem. All interviewed farmers are very concerned about the security and reliability of their water supply. All have been hit by water scarcity in the past and all have taken steps to mitigate this problem.

Many options for adaptation are available, some more practical then other. The potential for instance for the re-use of lower quality water such as pack house waste water or treated sewage effluent is rather small. Similarly desalinisation of brackish or sea water is not likely to become the next major source of irrigation water. Two trends seen at the moment is to try and secure more water from alternative sources and a move away from irrigation to rain-fed agriculture. As climate change starts to make its impact these changes will become more pronounced. When no further water sources are available in a catchment, water trading may be the only option to secure further water supplies.

10 KnETs: understanding farmer adaptation

Cindy Warwick and Sukaina Bharwani

10.1 Introduction

This project developed a knowledge elicitation tool (KnETS) (Bharwani, 2006) for application to farmer adaptation in East Anglia, as an innovative approach to understanding how and why actors make decisions. As stakeholders are playing an increasingly proactive role in protecting the water environment the management and use of water resources depend to a large extent on human decisions. Therefore, farmers' perceptions and attitudes to risk and uncertainty, the economy and the environment need to be evaluated. Understanding social *perceptions* and *attitudes* to water scarcity is a vital issue as traditional models of uniform, fully-informed, rational actors are becoming less representative of decision-making as it occurs in real life.

Full details of KnETs application to farmer adaptation to climate change and water stress in East Anglia have been described in an internal project report.

10.2 Objectives

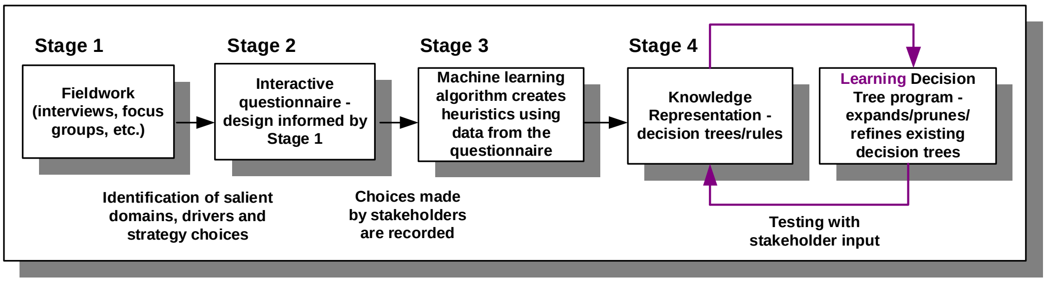
Overall, the work undertaken had two key objectives. The first objective was to increase understanding of pressures acting on farmers and their possible responses to these pressures. The work therefore involved identifying key drivers and parameters likely to influence farmer decision-making, exploring how these drivers are interpreted by farmers and understanding how pressures could lead to the implementation of different possible adaptation options.

The second objective of the work was to trial an innovative method of knowledge elicitation, KnETs, as a way of increasing this understanding of adaptation. The project worked to explore the potential of KnETs as a field work tool and its potential as a basis for the development of an agent-based model (ABM) for further exploring farmer behaviours.

10.3 KnETs design and application

The process of KnETs application involves the development and application of an interactive questionnaire with local stakeholders. Results of the questionnaire can then be run through a machine learning algorithm to generate decision-trees of stakeholder behaviours that can be discussed and refined with the stakeholder group (Figure 10-1).

Figure 10-1: Schematic diagram of knowledge elicitation (KnETs) process.



There are 3 components of the interactive questionnaire: scenario domains; management goals; and adaptation options. Domains are used to define different aspects of a decision-making scenario and domain variables are set in different combinations through program iterations. A farm management goal must be selected by the interviewee for each scenario created. A list of possible goals is set in the program but this list can be extended by the programmer according to interviewee feedback.

Adaptation options are actions that the interviewee would undertake in order to achieve their management goal under the given scenario.

In this project, the starting point for domains options and goals was taken from work previously conducted to create an *interdisciplinary* knowledge elicitation *process* which focuses on commercial farmers in East Kent (Bharwani, 2004). That work was used as an initial prompt for the discussion and design of the questionnaire to be implemented under this project. The development of the project-specific tool focussed initially on how to adapt the tool to the specific research questions being asked in the project and adjusting for the differences between farming characteristics and interests in Kent and East Anglia. The structure and content of the interactive questionnaire was further developed using interviews and paper questionnaire responses collected from farmers in East Anglia within another part (Section 9.2) of the project. This set the context specificity and customised terms of reference. Expert opinion within the project team was used to translate farmer information into scenario domains and adaptation options and to look beyond typical scenarios to define the stresses to be explored through the project remit. This work led to the design of a project-specific KnETs application which varied substantially from the Kent application with respect to domains, goals, adaptation options and some aspects of operation.

The KnETs application was applied with a test farmer to determine the completeness, understandability, applicability and usefulness of the domains, goals and options chosen by other experts as well as the program's ability to handle the responses provided. In response to the test farmer's comments on the interactive questionnaire, the domains, goals and options were modified to ensure they represented his terms of reference, as far as is possible (see Table 10-1, Table 10-2 and Table 10-3). The farmer's interview responses (direct responses to KnETs-generated questions and responses to general questions related to proposed changes to the programme) were then used with the new version to generated data on decision-making criteria. A sufficient accumulation of such data would allow recurrent patterns to be identified using a machine learning algorithm and the creation of decision-trees and heuristics of behaviour. An extended version of this process, with additional farmers, would allow the creation of decision-trees from the data generated which may aid an understanding of the farmers' views of multiple stresses, constraints to adaptation and possible responses.

Table 10-1. KnETs domains.

Domain	**Domain variables**
Climate	Current climate Warmer drier summers and warmer wetter winters Warmer drier summers and warmer drier winters More extreme droughts
Crop returns	Higher crop returns Lower crop returns
Market type and contract security	More supermarket domination (with contracts) More supermarket domination (with no contracts) Less supermarket domination
Licence type/water stress	Summer abstraction licence (reliable) Summer abstraction licence (reduced reliability) Winter only abstraction licence No abstraction licence higher water abstraction charges (double or more)

Table 10-2. KnETs farm management goals.

Goals
Investment for expansion
Investment to improve current operations
Investment for sustained production
Investment for necessary maintenance only
Minimal-to-no investment

Table 10-3. Adaptation options.

Options for increasing water availability
apply for summer abstraction licence
buy summer abstraction licence from another abstraction license holder
apply for winter abstraction licence and build reservoir (individual)
apply for winter abstraction licence and reservoir (communal)
use (more) mains water
collect (harvest) rain water
use lower quality water (e.g. nitrate-rich ground water, pack house waste water)
use treated sewage effluent (re-use)
use of drainage water
use desalinised brackish or sea water
Options for improving water management
increase efficiency through better equipment
increase efficiency through use of ‘trickle’
increase efficiency through improved scheduling
move crops to soils with larger water holding capacity
Options for changing crop management/cropping system
focus irrigation on high value crops during drought
intensify cropping (higher yield per area)
decrease irrigated area
decrease area of lower value (irrigated) crop
change to crops with higher returns to water
stop irrigation and - keep licence - trade licence temporarily - sell licence permanently

10.4 Outputs

Farmer responses to scenarios created in the original KnETs application along with notes about option selection are presented in an internal project report. Information collected from the farmer was useful in revising the interactive questionnaire and highlighting technical issues associated with application but, unfortunately, not enough information could be collected in the interview to form a decision-tree. It was determined that due to the number of options selected under each scenario, a large number of iterations would be required to collect sufficient information for tree formation. The number of iterations accomplished in future interviews would be increased by the work done during the first interview to revise the interface to increase understand-ability. Programme application would also be accelerated if the technical changes proposed to facilitate the selection of multiple options could be implemented.

Though decision-trees could not be created, it is important to note that the application of the KnETs process did lead to the identification of scenarios where the farmer would consider entering the licence trading market, as a buyer or as a seller. Therefore if the programme could be taken forward to create decision-trees for different types of farmers there would be the potential for programming an ABM that would examine the possibilities of interactions taking place in an abstraction licence trading market.

10.5 Summary and way forward

KnETs does have potential for useful application in the further understanding of farmer adaptation to climate change and water stress. The opportunities for application are 3-fold.

KnETs has definite application as a tool for formalising knowledge collection. Technical adjustments must be made to facilitate the selection, editing and management of groups of options and further farm interviews are required to refine the KnETs domains, goals and adaptation options. Of particular concern is the further testing of farm management goals and the contract security and market type domain. Interviews used to refine domains and goals can also be used to collect the depth of information required for proper decision-tree formation. With the technical adjustments and further testing, problems can be overcome and a tool for collecting and validating qualitative interview data is possible. Application of KnETs in this particular context could show how the package of management options considered by a farmer changes in response to different system pressures.

KnETs has potential for linkage to agent-based modelling. If the KnETs process was extended and relevant categorisations of farmers were interviewed, analysis of outcomes could focus on the adaptive capacity of different farm types and management strategies. There is particular potential for taking this forward with respect to licence trading as the interactivity of agents could best be explored through the ABM format. This is a potential area for future work.

KnETs has potential for promoting social learning in the farming community. By discussing possible future scenarios with farmers and interactively exploring the repercussions of adaptation-option selection, the programme could increase farmer understanding of the situation in which they operate, potential future challenges and how to proactively adapt to best meet these challenges.

Once tool design has been refined and technical developments have taken place, interactive interviews that include not just KnETs data entry but also decision-tree formation and discussion can take place for social learning through the discussion of option-selection implications and outcomes. Application of the KnET with farmers of different wealth and farm-type profiles will then allow the development of community ABMs that could consider the dynamics of group, as well as aggregated individual, behaviour.

11 Leisure (sports-turf); impacts and adaptations

Jerry Knox and Keith Weatherhead

11.1 Introduction

The leisure (sports-turf) industry represents a rapidly growing and important sector within the UK economy. The natural sports surfaces sector comprises golf courses, race courses and stadia (e.g. cricket, football, rugby, tennis). This study focused on golf, the sector most dependant on water abstraction and, from an irrigation water resource perspective, most vulnerable to climate change.

The factors influencing water use in golf vary markedly from those of other sectors dependant on irrigation abstraction (e.g. agriculture). In contrast to maximising crop yield and quality, the main objective of sports-turf irrigation is to produce and maintain safe, high quality playing surfaces. On all modern golf courses, irrigation is an essential tool in the maintenance and management of sports turf surfaces. It serves to control the growth and quality of the turf, to maximise playability, to maintain the aesthetic conditions required by players, and to deal with the vagaries of UK summer weather. In providing an optimum playing surface, managers are also trying to alleviate compaction, maximise aeration and control drainage. Irrigation helps to achieve these goals. Although irrigation is important for optimising turf growth (roots require both oxygen and water in the root zone to thrive) it is important in other ways. In particular, soil water content affects bounce and playability. It is also important for other sports turf management practices (e.g. fertiliser applications, top dressing).

Climate change will impact on the maintenance, management, playability and presentation of golf courses. It could significantly influence agronomic turf management practices (e.g. pest and disease control) and the requirements for irrigation and drainage (both infrastructure and management). The predicted more frequent hotter summers with higher temperatures will also impact on the ambient conditions usually enjoyed during a typical summer for playing golf.

This chapter assesses the impact of climate change on water for golf, the adaptation options available and the responses available to this sector. It integrates information and data derived variously from literature review, an industry survey, computer modelling, detailed site studies and interviews with key informants in the sports turf industry. The study focuses on the implications of climate change on golf from a national (industry) perspective, rather within the two catchment case studies.

11.2 Current usage and underlying trends

There exists very little published information on the nature and composition of irrigation water use within the golf sector. A survey conducted by Herrington and Hoschatt (1993) provided a useful insight, but major changes in water regulation and rapid growth in the golf industry over the last decade mean the findings are now outdated. In this study, new data has been derived from a national survey of golf course irrigation, conducted in 2003 (a very dry year in turf irrigation terms). This information has been combined with Environment Agency (EA) abstraction data to provide a spatial and temporal assessment of water demand, underlying trends and water resources impacts. In 2000 there were reported to be 2049 golf courses in England and Wales (Ennemoser, 2005). In this study, in 2003 approximately 2140 golf courses were identified. Using a GIS, the spatial distribution of golf courses has been mapped (Figure 11-1) and aggregated by EA Region (Table 11-1). The number and location of golf courses within each EA CAMS area were also mapped.

11.3 Environment Agency abstraction data

The EA has records of almost all abstractions for spray irrigation, including golf courses, since the Water Resources Act (1963) came into force. Data for 2003 from their national abstraction licensing database (NALD) have been analysed. The total number of abstraction licenses, total licensed and total abstracted volumes for spray irrigation on golf courses in England and Wales, by EA Region, are given in Table 11-2. In 2003 there were reported to be 833 abstraction licenses for golf course spray irrigation. This represented 2% of all abstraction licenses in force in that year. Half of all golf course abstraction licences were located in three regions, namely Thames (18%), Anglian (16%) and Midlands (15%). The total licensed volume for golf course irrigation in 2003 was estimated to be 10112 Ml. This represents 3% of the total volume licensed for spray irrigation in England and Wales, with agricultural spray irrigation accounting for the remainder. The total volume abstracted for golf irrigation in 2003 was estimated to be 4315 Ml, representing 43% of the total volume licensed for golf irrigation. The average licensed and abstracted volume was 11084 m^3 and 5848 m^3, respectively, although significant regional variations exist.

Figure 11-1. Spatial distribution of golf courses in England and Wales, by EA Region, in 2003.

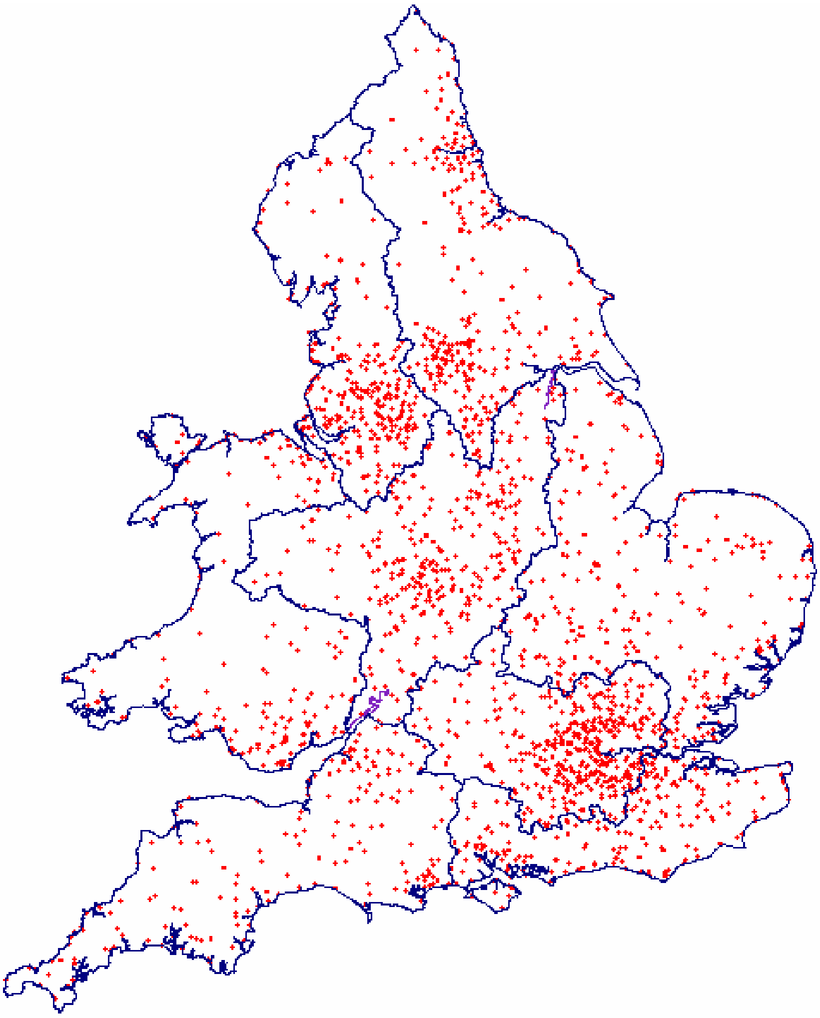


Table 11-1. Estimated number of golf courses in England and Wales, by EA Region, in 2003.

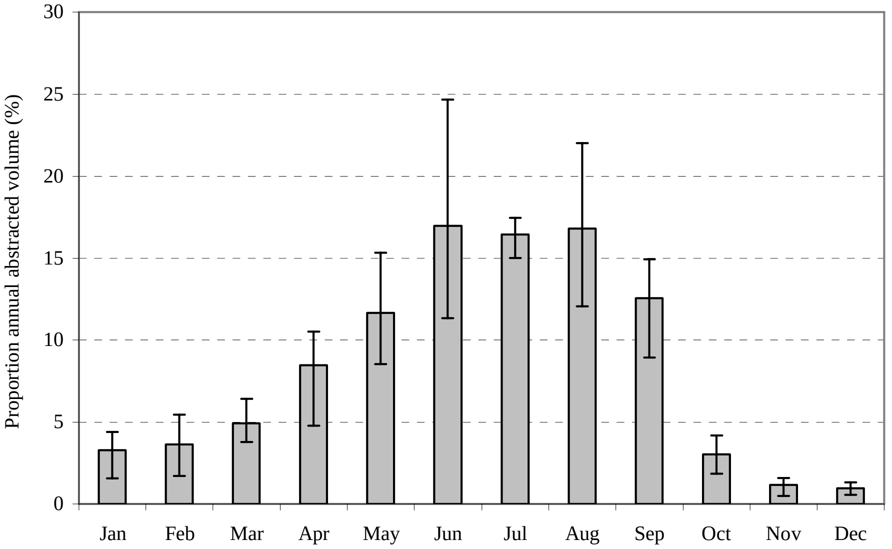
EA Region	Number of golf courses	% of total
Anglian	256	12
Thames	421	20
Southern	222	10
North East	280	13
North West	273	13
Midlands	308	14
South West	189	9
EA Wales	191	9
Total	**2140**	**100**

Table 11-2. Total number of abstraction licences, total licensed (m^3) and abstracted volumes (m^3) for golf course spray irrigation, by EA Region, in 2003.

EA Region	Total number of licences	Total licensed volume (m^3)	Average licensed volume (m^3)	Total abstracted volume (m^3)	Average abstracted volume (m^3)
Anglian	131	1376100	10505	570793	4357
EA Wales	51	457072	8962	191839	7378
Midlands	127	1751436	13791	920243	8682
North East	77	559060	7261	216147	3325
North West	102	530771	5204	200424	3132
South West	108	788208	7298	162382	3690
Southern	84	980634	11674	423087	5567
Thames	153	3668714	23979	1629755	10652
Total	**833**	**10111995**	**11084**	**4314671**	**5848**

Nationally, golf course irrigation is a relatively minor abstraction; but it is predominantly consumptive, peaks in the driest years and in the driest months, when water resources are scarcest. It is the seasonal timing of golf irrigation demand, peaking during the summer months that may be particularly susceptible to changes in climate (Figure 11-2).

Figure 11-2. Mean monthly timing of golf irrigation abstraction, expressed as proportion of annual average abstraction (%), based on 2002-04. Bars show the variation over the three years.



The EA data suggest that three quarters of all water for golf course irrigation is abstracted and used direct. Although lakes are used as water hazards, their role as winter storage reservoirs is not widespread (yet), due to the aesthetic and environmental impacts of empty lakes during summer months. The EA abstraction records do not include water from the public mains supply for irrigation.

11.4 National survey of golf irrigation water use

To compliment the EA abstraction data, a national survey of golf course irrigation water use was undertaken. This elicited information on the areas irrigated, volumes of water applied, water sources, operational (management) issues and attitudinal views on adaptation to climate change. The survey was supported by the English Golf Union, the British and International Golf Green-keepers Association, the Institute of Groundsmanship, the British Turf and Landscape Irrigation Association and the National Turfgrass Foundation. These organisations have also provided an essential link for disseminating the study findings. The survey was targeted to 2140 golf courses; 400 surveys were returned representing a response rate of 19%. The findings are summarised below.

Parts of the course irrigated

A typical golf course comprises of 18 holes, with each hole having a tee, fairway, approach and green. Most have an irrigation system, but only irrigate a small proportion of the course (Table 11-3).

Table 11-3. Summary of survey findings reporting the parts of the course irrigated.

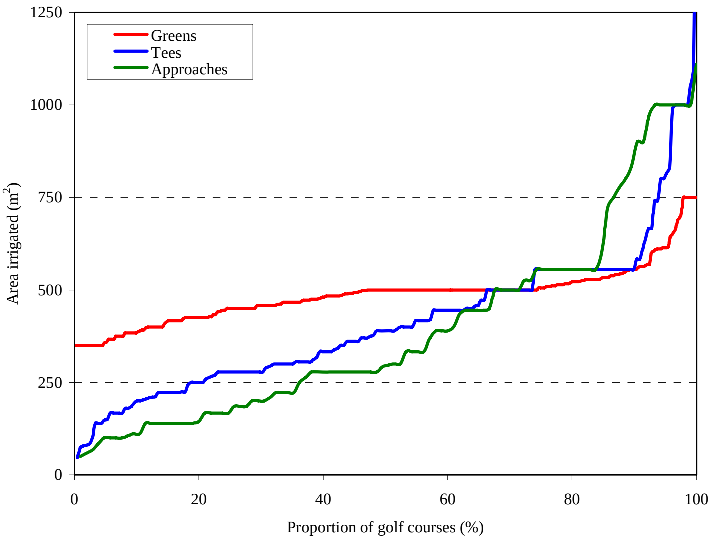
Part of course	Proportion of course irrigated			
	All	Some	None	Total
Tees	60	19	20	100
Greens	99	1	0	100
Approaches	26	29	55	100
Fairway	8	10	82	100

The data confirms that almost all irrigated golf courses water the greens and, to a lesser extent, the tees. Half of all courses also irrigate (either fully or partially) the approaches, but only a small minority (<10%) irrigate the fairways. The greens and tees are the most important parts with respect to maintaining turf quality and playability. Full fairway irrigation systems are only installed on the major prestigious courses or those with exclusive membership. However, with climate change, it is likely that a significant proportion of golf clubs will extend their irrigation systems to cover other parts of their course in order to maintain aesthetics and playability, particularly during dry summers. Increasing the irrigated (command) area would have major impacts on the volumes of water abstracted.

Irrigated areas and volumes of water applied

Using the survey data, the typical areas irrigated (m^2) and volumes of water applied (m^3) were derived. On a typical hole, the median size of an irrigated green, tee and approach is $500m^2$, $390m^2$, and $300m^2$, respectively (Figure 11-3). The median size of an irrigated fairway is $5300m^2$. The total irrigated area (comprising greens and tees) for a typical 18 hole golf course is between 1.5 ha and 2.0 ha. In contrast, a golf course with a full fairway system would typically irrigate between 8 ha and 12 ha.

Figure 11-3. Estimated areas irrigated (m^2) for each part of the course.



In 2003, the typical depths of water applied varied between 200 and 300 mm, depending on the parts of the course irrigated. For an 18 hole golf course irrigating greens, tees and approaches this represents a dry year irrigation demand of between 5300 m^3 and 6500 m^3. This compares closely with the average volume applied (5800 m^3) in 2003 based on the EA abstraction data (Table 11-2). In contrast, a full fairway system irrigating approximately 10 ha typically applied 30,000 to 35,000 m^3 (a five fold increase in irrigation water demand).

11.5 Climate change impacts on sports surfaces

Changes in climate, notably temperature and rainfall (and their consequent impacts on soil moisture) will have significant impacts on sports turf management. Agronomic practices and the design and management of irrigation and drainage infrastructure are likely to be most affected. A series of structured interviews were conducted with key informants in the golf industry to identify the likely impacts. Their feedback is briefly summarised below.

Temperature

The UKCIP02 scenarios suggest an increase in average temperature, across all seasons, ranging from +0.5 to +1.0 degree (2020H) to +1.5 to +2.5 degrees (2050H). For each scenario, the greatest increases are in summer in the southern parts of the UK; these will increase the ‘thermal growing season’ for turf grasses, with each degree of annual warming causing a lengthening of the thermal growing season of about three weeks in southern areas and of about one and a half weeks in northern areas. This will have implications on grass growth and maintenance operations (Windows, 2003). For example, an extended growing season will result in increased mowing frequencies during the autumn and winter months. This may cause other problems, including compaction, leading to localised drainage problems and turf damage. High temperatures will also result in higher rates of evapotransiration; golf courses will therefore need to deal with more frequent summer droughts.

More persistent droughts combined with wetter winters could also stimulate other turf problems, such as moss colonisation. For example, in 2003, the summer drought was reported to have weakened many turf swards. The onset of a wet winter then resulted in the extensive moss colonisation on many golf course greens and fairways. Predictions for hotter, drier summers coupled with warmer, wetter winters would result in more widespread moss establishment (Windows, 2003).

Rainfall

The UKCIP02 scenarios suggest a reduction in annual precipitation, although there are strong seasonal variations. For example, reductions of 10% to 20% in summer precipitation are predicted in the 2020s, increasing to 30% by the 2050s. In contrast, winter precipitation is predicted to increase by up to 10% in the 2020s and by 20% in the 2050s. These seasonal changes in the distribution and intensity of rainfall are expected to have major impacts on sports turf management. More intense, frequent winter rainfall will necessitate better drainage to sustain playability during the winter months. Courses may need to design drainage systems to cope with higher peak rainfall events, higher stream levels and water tables, and the increased flooding risk from local streams and rivers. Higher winter season precipitation will also lead to faster runoff, with possible implications for water quality. More intense summer rainfall events are also likely to cause localised flooding leading to more frequent temporary closure of greens and fairways.

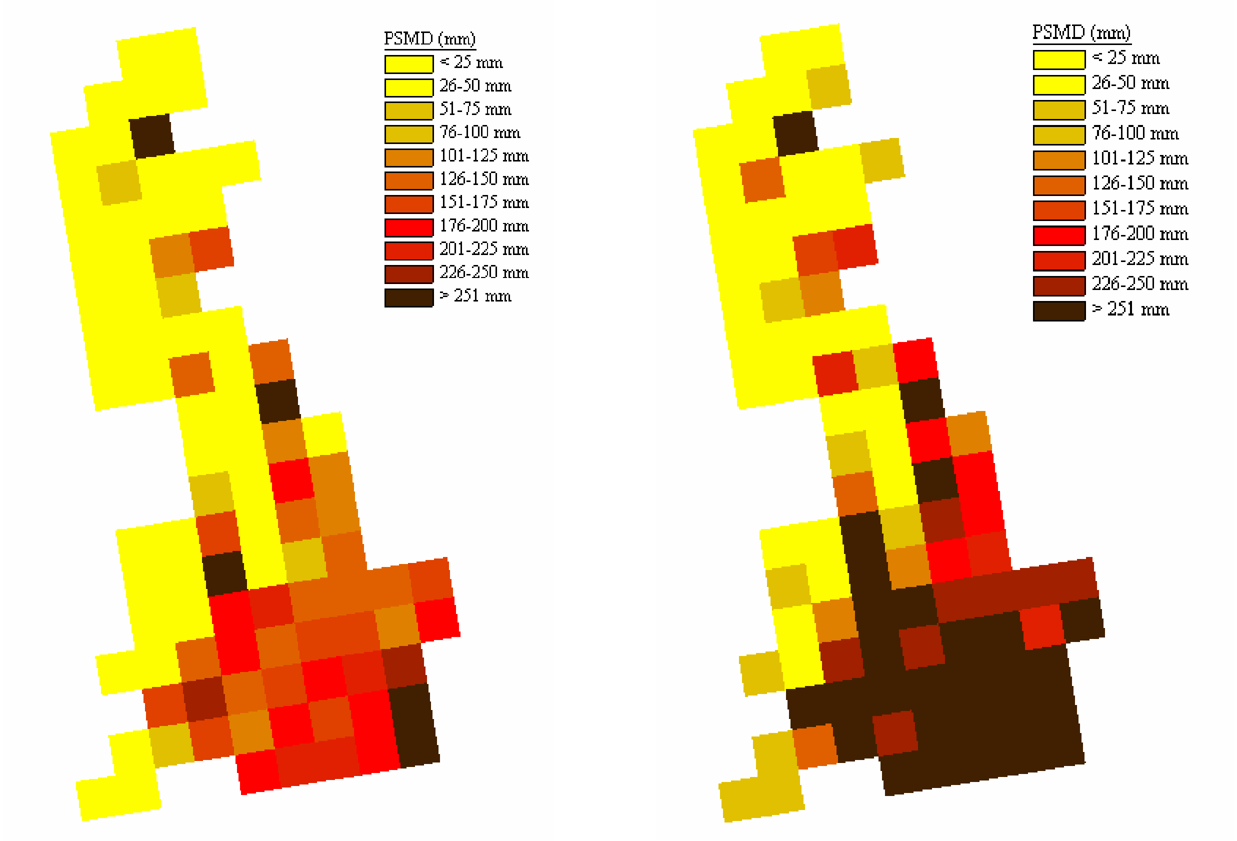
Soil moisture and irrigation demand

The climatic drivers of turf irrigation demand are precipitation and evapotranspiration. Potential soil moisture deficit (PSMD) is a useful variable to describe their combined effect, reflecting the balance between rainfall and turf water use in the summer months. Using a methodology developed by Knox *et al* (2005), maps showing the predicted changes in PSMD for each UKCIP02 scenario have been produced (Figure 11-4). These show significant increases in PSMD, particularly in eastern and south eastern England. By the 2050s, large parts of England could have an average PSMD in excess of 250 mm.

Figure 11-4. Potential soil moisture deficit for the baseline and selected UKCIP02 scenarios.

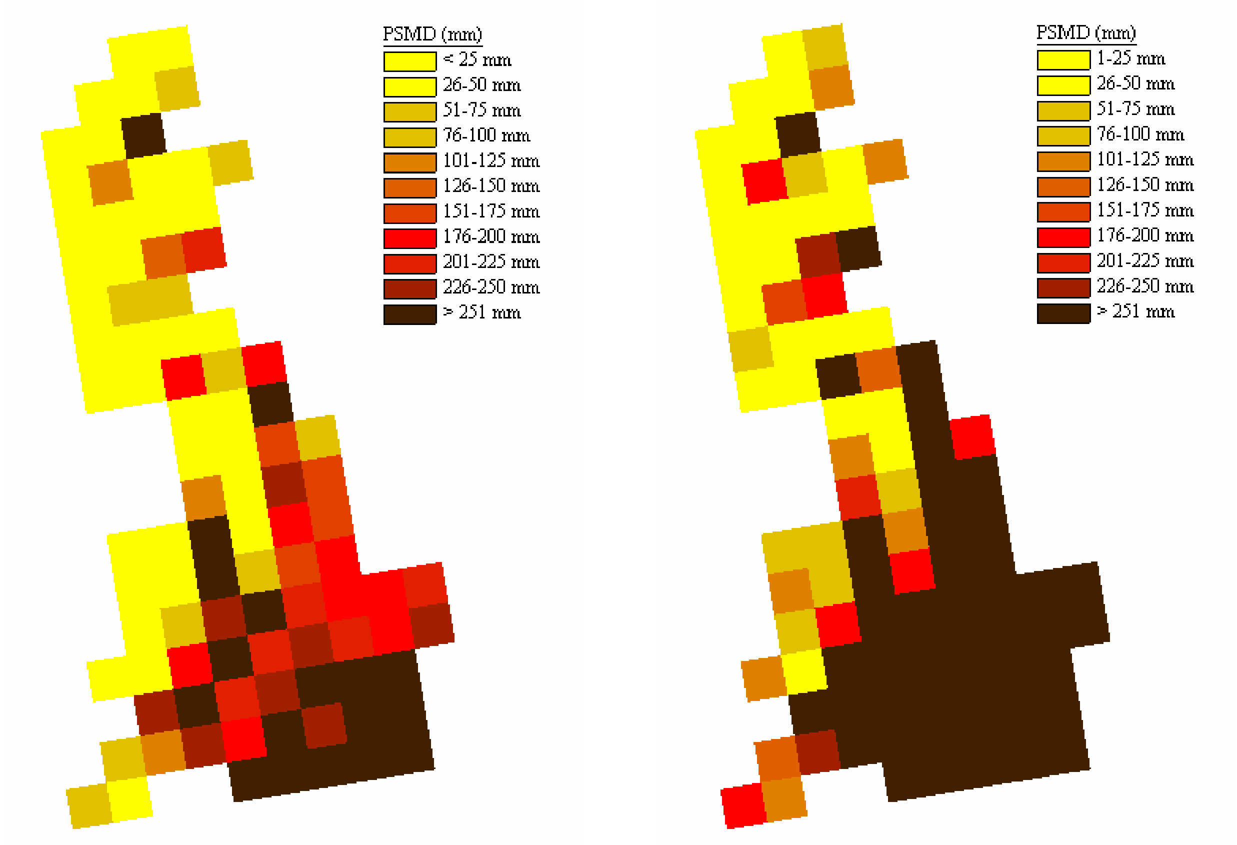
(a) UKCIP02 Baseline 1961-90

(c) UKCIP02 2050 Low



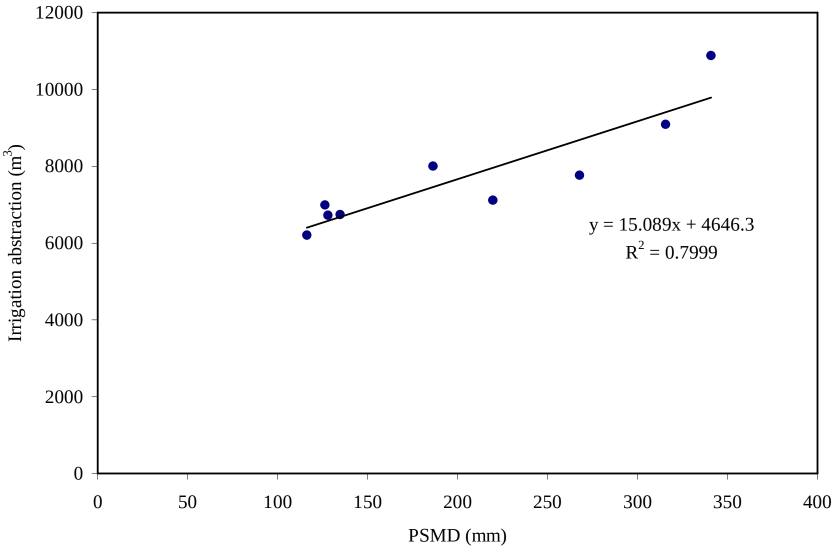
(b) UKCIP02 2020 Low

UKCIP02 2050 High



Maps of spatial and temporal changes in PSMD has previously been used to estimate the impact of climate change on agricultural water demand (Downing *et al*., 2003), using established relationships between PSMD and water use (e.g. Knox *et al*., 1997; Knox and Weatherhead, 2000). In order to assess the likely impacts of climate change on golf irrigation demand (volumetric), a number of golf courses located in agroclimatically contrasting regions were first identified. Their historical patterns of annual water use (based on computer and abstraction records) were then analysed and correlated against the annual maximum PSMD for each site in each year. An example is shown in Figure 11-5, based on abstraction and climate data for 1997-2005.

Figure 11-5. Correlation between agroclimate (PSMD, mm) and irrigation abstraction (m^3) for one case study golf course.



The analysis confirms that PSMD is well correlated with golf irrigation abstraction and usable as an agroclimate indictor. The analysis suggests that for every 50 mm increase in PSMD, there will be a corresponding 10% increase in irrigation demand. By combining the linear regression from this relationship with predictions of future PSMD (Figure 11-4), an estimate of the impact of climate change on golf irrigation abstraction can be derived. For example, the long-term average PSMD for a site in eastern England (currently 200 mm) is predicted to increase by approximately 50% by the 2020s and 100% by the 2050s (these increases are consistent with Downing *et al*., 2003); golf irrigation demand is thus predicted to increase by approximately 20% by the 2020s and up to 40% by the 2050s.

Climatic change could also indirectly impact on the types of turf used for golf course construction. For example, warm season grasses, more typical to the USA, could become the preferred choice for UK summer conditions, although the threat from seasonal water logging could restrict plant growth and turf survival during the winter months.

Clearly, the potential impacts of climate change on turf irrigation water demand (ignoring influences of CO_2) would have a major impact on irrigation abstractions in catchments (CAMS) where golf courses are currently concentrated. The situation would be exacerbated if golf courses were required to increase their irrigated areas to accommodate client/member pressures for improved playability as a consequence of more frequent dry summers, typical of 2003.

11.6 Adaptation

Future changes in water availability, due to either regulatory change (abstraction licensing) and/or climate change, would clearly have major implications for the irrigated golf sector. To minimise impact, the golf industry would need to build adaptive capacity at a national level and deliver a range of adaptation actions at the club level.

Regulatory (abstraction) restrictions

A postal survey and series of structured interviews with approximately 15 golf courses were conducted to elicit information relating to the likely impacts and adaptation strategies that might arise from changes in abstraction regulation (licence allocation). Key informants were asked to estimate the impact that incremental reductions in their licensed volume would have on their golf business (Table 11-4). Reductions of 10% in either summer or winter abstraction were considered to have minimal impact. Under these circumstances, many golf courses would supplement their water demand from public mains supply. Reductions of more than 25% were considered to have a much greater impact, particularly for those dependent on summer abstraction. Reductions of 50% in either summer or winter abstraction were considered to have a major impact on the viability of many golf clubs.

Table 11-4. Perceived impacts on golf business arising from reductions in licensed irrigation volume, expressed as % of total responses.

Volumetric reduction	**Summer abstraction**			**Winter abstraction**		
	Little or no change	Some change	Major change	Little or no change	Some change	Major change
10%	67	33	0	100	0	0
25%	0	33	67	50	50	0
50%	0	0	100	0	50	50
100%	0	0	100	0	50	50

Climate change impact

Under conditions of reducing water availability, golf courses have two options (i) obtain more water and/or (ii) reduce their irrigation water requirements. As part of the national survey of golf irrigation water use, respondents were provided with a list of coping strategies and asked to identify the two most likely options that they would adopt, in response to climate change. The aggregated findings based on approximately 400 respondents are summarised in Table 11-5.

Table 11-5. Summary of adaptation strategies based on national survey of golf courses, expressed as % of total responses.

Strategy	**Adaptation option**	**%**
Increase water availability	Buy water from another abstractor	6.4
	Buy additional public mains water	19.3
	Develop winter storage	36.0
	Harvest rainwater	29.0
	Re-use waste water from clubhouse	9.4
Total		**100**
Reduce irrigation water needs	Install new infrastructure to reduce leakage	13.5
	Install new equipment (improve irrigation uniformity	28.7
	Use scheduling to increase irrigation efficiency	19.9
	Weather forecasting to improve effective use of rainfall	16.9
	Increase shading and wind shelter	1.9
	Restrict watering to greens and tees during droughts	19.1
Total		**100**

The data suggests, with respect to increasing water availability, that the preferred adaptation is to develop winter storage. Harvesting rainwater from the course (via the drainage network) and buying additional public mains water were also popular options. Trading water and re-use of waste water from the clubhouse were not perceived to be a priority. With respect to reducing volumetric irrigation demand, investments in new technology and infrastructure to improve irrigation efficiency and reduce water losses (leakage) were identified as being most likely adaptations. Even without climate change, these options are already being implemented, mainly in response to the requirements within the abstraction licensing regime to demonstrate efficient use of water. These findings are consistent with the data obtained from the national survey of irrigation water use. That survey suggested that almost half (43%) of all golf irrigation abstraction is currently from public mains supply. The remainder is from direct abstraction, split roughly equally between surface (23%) and groundwater (29%). Rainwater harvesting using the course drainage network represents a minor source of water (3%) but is becoming a more popular option, particularly as summer water availability becomes less reliable.

The structured interviews were also used to elicit information regarding the extent to which the range of adaptation options identified in the national survey of irrigation water use (Table 11-5) had actually been considered and/or practically implemented (Table 11-6).

Table 11-6. Assessment of water shortage coping strategies; summary of responses from key informant interviews (values expressed as % of total).

Water shortage coping strategy	**Have done**	**Considered implementing**	**Tech possible, no plans**	**Technically impossible**	**Total**
Increase water availability					
Obtain additional summer abstraction licence	25	6	25	44	100
Obtain winter abstraction licence and build winter storage (individual)	25	25	25	25	100
Obtain winter abstraction licence and build winter storage (communal)	17	0	33	50	100
Buy water on a temporary basis from another abstractor	0	13	31	56	100
Buy water on a permanent basis from another abstractor	0	19	25	56	100
Convert to public mains water	38	6	50	6	100
Harvest rainwater	19	25	44	13	100
Re-use waste water from clubhouse	6	25	56	13	100
Use desalinised or brackish water	0	0	19	81	100
Improve water management					
Increase efficiency through better equipment	53	33	13	0	100
Increase efficiency through better scheduling	63	19	19	0	100
Increase efficiency through better use of rainfall	50	25	25	0	100
Change soil and/or turf management					
Specify more moisture retentive soils for green construction	40	20	33	7	100
Take measures to encourage deeper rooting of turf grass	88	6	6	0	100
Introduce lower water use or drought tolerant grass varieties	50	25	25	0	100
Restrict watering to greens and tees during drought	73	13	13	0	100
Decrease irrigated area	53	27	20	0	100
Improve soil structure through aeration programme	100	0	0	0	100
Increase shading and wind shelter	31	13	38	19	100
Other					
Stop irrigation, trade licence temporarily	0	0	27	73	100
Stop irrigation, keep licence	0	0	27	73	100
Stop irrigation, sell licence	0	0	27	73	100

The analysis confirms that for many golf clubs, converting to public mains supply is a coping strategy that is already being widely adopted. Many are also now considering implementing measures to harvest rainwater and re-use water from their clubhouses. Water trading (either temporarily or permanently) is not considered to be a realistic alternative for securing water. Many courses have already implemented agronomic changes in their sports-turf management to improve water efficiency; including for example, improving soil structure through aeration programmes, encouraging deeper rooting turf-grass, and restricting water to greens and tees during periods of drought. Many of these coping strategies will become much more widespread under conditions of climate change.

11.7 Summary

A national study of golf course water use confirms that irrigation is an essential component in the maintenance and management of natural sports-turf surfaces, serving to optimise playability and aesthetics.

Golf course irrigation water use constitutes a relatively minor abstraction (3% of total annual spray irrigation abstraction), but it is predominantly consumptive, and concentrated in the summer months, in the drier years, when river flows are lowest. Water demand is also growing steadily.

The study revealed that courses are equally split between mains water and direct abstraction. Many use a combination of water sources to protect their playing surfaces during periods of water shortage. Under conditions of water scarcity, many would be able to adapt by restricting irrigation to greens and tees, and/or combine the use of reservoirs with re-use and water harvesting. However, client/member pressure is for irrigated surfaces, designed to emulate high quality playing surfaces from overseas.

The golf sector is likely to be particularly sensitive to changes in temperature and rainfall, and their consequent impacts on soil moisture. Agroclimatic and water demand modelling suggests climate change will have a major impact on golf irrigation water use. Golf irrigation water demand is predicted to increase by approximately 20% by the 2020s and up to 40% by the 2050s, before considering any increase in the area irrigated.

Adaptation options and responses have been investigated. Under conditions of reduced water availability, many courses would be able to adapt by restricting irrigation to greens and tees. Combined with small reservoir storage and/or increased mains water use, their abstractions may be small enough to avoid the abstraction licensing regime, but with possible negative impacts on other abstractors, including the environment. This suggests possible investments for winter reservoirs, water re-use and water harvesting may become the preferred option. In a free trading water market, golf courses are likely to out-bid farmers growing low-value crops.

12 Conclusions and recommendations

Keith Weatherhead

This project studied irrigation water resource impacts and adaptation responses within the agricultural and leisure (golf) sectors.

The water resource, crop yield and land-use modelling was focussed on just two catchments (the Nar and Wensum), using outputs from just one climate change model (UKCIP02). The results must therefore be approached with some caution. However, the framework developed does appear to work, and would provide the basis for extending this work to a larger selection of catchments (those where irrigation abstraction is important and water resources are likely to most highly stressed), and for validating the results using a range of climate change models. It will be also beneficial to rework the calculations using the probability-based data expected in the next set of UKCIP climate change information ('UKCIPnext').

The results obtained in these two catchments suggest there is a clear risk of major restrictions on future abstraction for agricultural and leisure irrigation, and the need for significant adaptive responses. For the scenarios tested, the hydrological modelling predicts large reductions in river flows throughout the year. If the Environment Agency, as regulators, attempt to protect the current environmental river flow objectives, all abstractions would have to cease. The abstractions for irrigation and leisure would have lowest priority and are likely to be impacted first, either through hands-off flow conditions already set in the licences or through “Section 57” restrictions. Even if the Environment Agency agree to relax flow environmental as flows decrease, the lag until data becomes available puts the lower priority users at serious risk.

The yield modelling showed some changes by the 2020s and in the 2050L scenarios, but it is only in the 2050H scenario that a wide range of crops are adversely affected. It seems though that more irrigation and higher irrigation levels will be necessary, particularly in the Wensum catchment. A major uncertainty on future yields remains the fertilisation impact of higher atmospheric CO_2 levels. Available data until recently pointed to significant yield increases; however results from some large-scale field trials on cereals have raised doubts. Unfortunately, there is still no experimental data on the impacts on potatoes and vegetables at field scale.

The catchment land-use modelling investigated how farmers might be expected to react. The methodology assumed the farm objective of maximising farm incomes, but it allowed for uncertainty, variability and the stochastic nature of decision-making, producing a more sophisticated (and complex) output than from standard linear programming. The outputs point to cropping pattern changes, reduced irrigation of low value crops, and investment in reservoirs; these are consistent with the results from the farmer interviews.

These outputs were themselves used in the groundwater modelling. This confirmed the substantial reductions in river flow seen in the hydrological model, and also showed substantial lowering of groundwater levels, even if all abstraction is stopped. Notably, the reductions in recharge are a more significant driver than changes in abstraction.

The knowledge elicitation tools (KnETs) developed promise an innovative future approach for improving understanding of farmer behaviour, and providing the decision-making algorithms necessary for agent-based models. However, the work in this study revealed the complexity of farmer decision-making when responding to water shortages, since every farm is different and there are substantial uncertainties. Further development and testing is required to make this a usable tool.

The interviews with farmers and sports-turf managers provided information on how they have adapted to water scarcity in the past, and their attitudes to adaptation in the future. Of course, climate change impacts are wider than water shortage, and these other impacts may change the feasibility of some responses. It appears most believe they have a range of coping strategies and longer-term options. However, they did not consider there was substantial scope for saving water from higher efficiency, one of the Agency’s main targets at present.

Many farmers have considered winter abstraction and storage reservoirs. Defra and the Environment Agency have been active in promoting these as environmentally preferable to summer abstraction, though the high cost is deterring most farmers at present. The risk of lower winter river flows points to an inherent limitation to this strategy; care must be taken to ensure farmers are not persuaded to over-invest in reservoirs in a given catchment. All reservoirs should be designed to be filled rapidly in case flows are unreliable, and possibly to store some water from wet years to dry years.

Most farmers indicated that changes in cropping pattern would be one of the preferred adaptations. Removal of low value irrigated crops would save some water, but the irrigation survey data showed that most irrigation was already largely restricted to high value crops in these catchments.

Golf courses do not have the option of switching from turf, but irrigation may have to be restricted to greens and teas, the trend towards sand-based greens reversed, and different grass cultivars considered. Courses are in intense competition for members, corporate events and major tournaments; leadership from the governing bodies may be required to promote these changes.

Abstraction licence trading did not feature strongly in the interviews. This may be because at the time of the research, the Environment Agency has not published details of the mechanisms and restrictions involved, and the first round of CAMS documents does not discuss local opportunities. In an over-abstracted catchment, trading cannot increase the total water available, and will only redistribute water that is already being abstracted; however this still raises opportunities for moving water to higher value crops and helping protect farm margins. This may need further research once the opportunities have been clarified. The significant number of underused licences in these over-licensed catchments may be giving an incorrect signal to abstractors, by suggesting they have unused water available; in practice the water is probably not there to abstract.

Rainwater harvesting from roofs and abstraction below the $20m^3$/day *de minimis* level for licensing may provide adequate water for small users; e.g. horticultural units and golf courses irrigating greens and teas only. Re-use of grey water may be a solution for turf-grass, but raises microbiological contamination fears for food crops, particularly those destined for supermarkets. Interestingly, all these options also reduce river flows, a point that is not stressed by those promoting them. For some high value users, a switch to mains water may be financially feasible. This at least allows abstraction in less stressed areas, but it is arguably wasteful to treat irrigation water to drinking standards.

One issue that remained outside this project, due to its case study focus, was the impact on UK irrigators of climate change elsewhere, for example the impacts of droughts in other European countries (particularly Spain) on prices and market competition; any climate change adaptation advice or policy needs to take this into consideration.

Overall, the framework developed appears successful. The results suggest there are adaptive options available, but that there are financial constraints. Most farmers are aware of climate change, but are focussed on shorter-term issues, and believe they can adapt later as necessary. Any adaptation now is occurring as a response to fears of water scarcity and regulation, rather than climate change *per se*.

Recommendations

This project has highlighted the importance of adaptation to meet what are likely to be major reductions in water availability, as least in southern and eastern England. The research has highlighted the need for the regulators (Defra/Environment Agency) to address the issue of how reducing water resources will be allocated between existing abstractors and environmental river flow objectives. Climate change needs to be built into the information available from CAMS.

The regulators also need to critically re-appraise the present focus on raising efficiency, and produce guidelines for licence trading that allow water to move to the highest value user. The promotion of reservoirs needs to be handled with care, in view of possible lower winter flows in some catchments.

Some further research is recommended:

- To confirm the results under different climate models, and under the ‘UKCIPnext’ scenarios;
- To apply the framework to other catchments;

- To continue development of the knowledge elicitation tool as a means of understanding farmer behaviour, and providing decision-making algorithms for an agent-based model;
- To undertake case studies of selected farms and other abstractors, comparing the different adaptation options and their financial and environmental impacts;
- To develop and use a water trading model to simulate the impacts of abstraction licence trading and shared reservoirs;
- To assess the potential impacts on UK irrigators of climate change elsewhere.

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Appendix: Publications and presentations

The following publications and presentations have wholly or partly drawn on the outputs of this project. Further papers are in preparation.

Refereed Journal Papers accepted:

Knox JW, Weatherhead EK and Hess TM (accepted subject to revision) Modelling impacts of climate change on soil moisture: implications for irrigation. Climatic Change

Papers presented

Cornelius Sandhu, Kevin Hiscock, Declan Conway (2004). Sensitivity of groundwater resources in eastern England to climate change; EGU 1st General Assembly, Nice 25 – 30 April 2004.

De Vries TT and Weatherhead EK (2005) Adapting to irrigation water scarcity due to climate change in eastern England. World Water and Environmental Resources Congress, Alaska.

Knox, J.W. (2004) Protecting water resources for golf course irrigation in England and Wales. National Turfgrass Foundation Annual Symposium, Southport, November 2004.

Weatherhead, E.K. and Knox, J.W. (2004). Assessing the impact of climate change on soil moisture and irrigation demand in England and Wales. Royal Meteorological Society meeting, February 2004, London.

Weatherhead EK (2005). Farmer adaptation to water scarcity. Paper presented at UK-China workshop on Impact of Climate Change and Extreme Events in China, Beijing, August 2005.

Knox JW and Weatherhead EK (2005). Golf course irrigation: impacts of abstraction licensing, water resources and regulatory change. Four presentations to English Golf Union roadshow meetings, October/November 2005.

Weatherhead EK (2005). Climate change impacts on irrigated agriculture in eastern England. Paper presented at CIWEM (East Anglia Branch) Annual Conference, St Neots, October 2005.

Papers accepted for presentation

Knox JW (2005). Climate change impacts and adaptation in leisure (golf). Paper to be presented at the Spanish national golf course managers and greenkeepers congress, Pontevedra, Spain, November 2005.

Knox JW (2005). Climate change impacts and adaptation in turfgrass production. Paper to be presented at the UK National Turfgrass Association (TGA) annual technical conference, Peterborough, November 2005.

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- Atkinson, P, (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part B3- Coastal simulator and biodiversity - Modelling the change in wintering Twite Carduelis flavirostris populations in relation to changing saltmarsh area,** Tyndall Centre Technical Report 42B3
- Gill, J, Watkinson, A. and Sutherland, W., (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part B2- Coastal simulator and biodiversity - models of biodiversity responses to environmental change** Tyndall Centre Technical Report 42B2
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