Royal Agricultural Society of England

Practice with Science Group

Water for Agriculture - Implications for Future Policy and Practice

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Reviewing and modelling the impacts of climate change on future food production

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Executive summary

A recent report for The Royal Agricultural Society of England (Godwin et al., 2008) indicates that agriculture faces considerable future challenges in meeting a range of demands of which water resource availability for crop and animal production, flood control and climate change are prominent.

The overall aim of this project was to examine the impacts of climate change on water availability, drought and flooding and how farmers can adapt to these impacts. This was achieved through the following objectives:

1. Review water availability and use within agriculture
2. Review flood defence policy and implications of flooding for crop and livestock production
3. Illustrate the potential impacts of climate change on future water availability, drought and flooding across England through case studies employing original hydrological modelling using different scenarios of future climate change.
4. Assess the implications of these potential changes for a range of farming practices.
5. Identify and evaluate potential options for addressing the likely changes
6. Make recommendations for future farming practice, research and policy.

There were three main phases to the research: (1) the key issues and impacts literature review (Objectives 1-2), (2) the hydrological impacts modelling (Objective 3), and (3) the implications and adaptation review and recommendations for the future (Objectives 4-6).

The review highlighted the following facts:- livestock enterprises use approximately 40% of total agricultural water use, field vegetables use another 40%, and the protected and nursery crops sector uses the remaining 20%. A significant proportion of water use by livestock occurs in the west and is fairly evenly distributed throughout the year. Most water use is for drinking, but water is also used for washing down of plant and machinery, particularly within dairy enterprises. Water use for cropping is concentrated in the east and south and occurs during the drier summer period. The dominant use of water for crop enterprises is direct abstraction for irrigation of field crops, with most water abstraction applied to potato and vegetable crops. Polytunnel crops use significant amounts of irrigation water but the process is more efficient than for field crops. In both cases, product quality and profitability are highly dependent on the timing and volume of water applied. Finally, rain fed crops, such as cereals and oilseed crops, which use water indirectly, will also influence water availability.

Seasonality and the duration of flooding are critical factors that affect the impact of flooding and waterlogging on agriculture. Short duration flooding in winter, after establishment, may have a limited impact on grassland and cereals. A flood event in summer, however, could completely destroy a crop of grass or cereals ready for harvest. The most common sources of flooding are from rivers arising as a result of heavy rainfall and in coastal locations due to high tides and stormy conditions. The impact, of heavy rainfall and whether or not flooding arises is dependent on field capacity status, soil type and geology. There is a greater risk of flooding on clay soils, which represent almost half of English soils. On agricultural land, previous cropping, drainage systems, and the presence of hedges and ditches and their status will also have an influence.

The criteria used for the selection of the case study catchments were critical to the success of the project. Catchments were chosen to reflect different broad farming types. At the same time, the catchments chosen reflect issues regarding drainage, flooding and water availability and impacts in terms of access to land, crop productivity, and water use. The four catchments were:

- Harpers Brook - covers cereal and general cropping farm types and pigs
- Medway - covers horticulture and lowland livestock (pigs, but also poultry, cattle and sheep, horses and goats)
- Teme - mixed farms, with emphasis on horticulture, pigs, poultry and sheep
- Eden - dairy and grazing livestock (upland) farm types, so cattle and sheep

The impact of climate change will be to change the availability of water in general. The impacts will be spatially and temporally variable. Changes in extremes of water shortage will lead to changes in drought frequency, magnitude and duration. Climate change will also change the magnitude, frequency, distribution (spatially and temporally) and duration of flood events and may even lead to the loss of land in coastal areas and on floodplains.

The modelling results for the four catchments suggest a general reduction in annual flows, with a large reduction in summer flows set against a proportionally smaller increase in winter flows. The Eden catchment in Cumbria has the largest winter flow increase, although this does not outweigh the reduced summer flow. Increasing temperatures and evapotranspiration at all sites also reduces soil moisture availability. Generally in all catchments there will be less water available. There is thus a greater frequency of drought risk at all sites particularly in the south and east, as indicated by the results for the Medway and Harpers Brook catchments. Conversely, there is also a greater frequency of flood/waterlogging risk at all sites, particularly in the north and west as indicated by the results for the Eden and Teme catchments. Flood risk at all sites is less likely than the drought risk.

For both policy and the agricultural industry as whole, there a number of key messages and areas of further work:

- There is a need to focus on managing both water demand and supply
- There will be less water available and demand needs to be reduced with the location of production focused on enterprises which use water more efficiently or, alternatively, moved to areas where water is more readily available
- The alternative is to move water from areas where there are fewer requirements to areas with higher demand
- The better use of excess winter rainfall and flood water through capture and storage presents an opportunity that needs investigation
- The feasibility of water re-use and what is acceptable to the consumer needs to be established
- The emphasis in plant breeding programmes should be on drought resistance

- Crop protection needs to be prepared for new weed, pest and disease pressures
- The management of grassland systems will need to adapt including the introduction/increase of alternative forages within the diet
- Investment in livestock housing, feed (conserved crops) and manure storage may be required
- There are limited opportunities to reduce livestock drinking water requirements or improve the efficiency of water use in the protected crops sector
- In the livestock sector efforts should focus on more efficient use of water for the washing of plant and machinery, particularly within dairy enterprises, through knowledge transfer initiatives regarding opportunities to capture excess winter waters and making better use of available water
- In the irrigated crops sector there is a need for knowledge transfer regarding irrigation techniques and improving application, and research into producing crops with less demand for water focusing on drought resistance and improving quality traits without water use
- Flood risk will increase and farmers should have contingency plans in place
- Land management which reduces flood risk through reducing runoff and increasing infiltration should be encouraged
- There is a need for investment in landscape features, such as hedges, ditches and ponds, to reduce flood risk
- Investment in improving existing drainage systems where appropriate is needed, with recognition that ins some areas reverting to natural floodplains may be more appropriate
- Policy, both regulation and incentives, and advice mechanisms should be in place to facilitate adaptation
- This requires appropriate frameworks within which the various stakeholders can communicate and operate and the provision of relevant guidance information

Acknowledgements

The research in this report was funded by The Royal Agricultural Society of England.

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1 Introduction

1.1 Background

A recent report for The Royal Agricultural Society of England (Godwin et al., 2008) indicates that agriculture faces considerable future challenges in meeting a range of demands of which water resource availability for crop and animal production, flood control and climate change are prominent. Climate change is expected to produce higher temperatures, drier summers and wetter winters across much of England (Charlton and Arnell, 2010). Reductions in water availability are expected as a consequence (Arnell, 2004), with implications for agriculture in England. The Environment Agency (2005) expects direct abstractions to become less reliable during the summer and more seasonal, higher intensity rainfall producing high runoff and less water able to percolate into aquifers. The potential impact of climate change on increased demand for water is expected to be high and the potential irrigation requirements could increase dramatically moving northwards and westwards (EA, 2009). The magnitude, frequency and timing of droughts and flooding may change, which in addition to the impacts of water availability (itself spatially and temporally variable), means that there is an urgent need to identify and understand the potential impacts of climate change on agriculture, assess the implications and develop options for adaption to these changes over timescales relevant to farmers.

1.2 Aims and objectives

The overall aim of this project was to produce a detailed scientific report for The Royal Agricultural Society of England's "Practice with Science" Group addressing the potential impacts of climate change on water availability, drought and flooding and how farmers can adapt to these impacts. This was achieved through the following objectives:

1. Review water availability and use within agriculture
2. Review flood defence policy and implications of flooding for crop and livestock production
3. Illustrate the potential impacts of climate change on future water availability, drought and flooding across England through case studies employing original hydrological modelling using different scenarios of future climate change
4. Assess the implications of these potential changes for a range of farming practices
5. Identify and evaluate potential options for addressing the likely changes
6. Make recommendations for future farming practice, research and policy.

1.3 Structure of the report

This final report begins with an outline of the methods used in producing the report before outlining the expected changes in climate across England to the 2050s. This information is used to develop site-specific scenarios of climate change. This is followed by a review of the potential impacts of these climate changes on agriculture with a focus on the current status and future impacts on water availability, use, drought and flooding. This review is supplemented by four case studies illustrating impacts in different agricultural sectors and geographical locations. A review of potential options for addressing the implications of these impacts is then provided before future directions are discussed in the final sections.

2 Report methodology

2.1 Overview

To satisfy the objectives requires a mix of desk research and original hydrological modelling to assess the potential impacts of climate change as outlined in the following sections. There are three main phases to the research: (1) the key issues and impacts literature review (Objectives 1-2), (2) the hydrological impacts modelling (Objective 3), and (3) the implications and adaptation review and recommendations for the future (Objectives 4-6).

2.2 Desk review, literature and data

Objectives 1-2 and 4-6 require a combination of literature review and secondary data collation. The focus is on the issues surrounding climate change, water and agriculture, drawing on our recent experience in assessing future water availability and the impacts of flooding on the agricultural sector and a number of other major research efforts. Examples are the Foresight Flooding and Coastal Defence Project, the Flood Risk Management Research Consortium, and the recent RELU project on the Integrated Management of Floodplains. The review covers a range of scales from the entirety of England to the catchment or farm level and considers timescales relevant to change in agriculture (up to the 2050s) for different agricultural uses encompassing upland and lowland livestock systems, arable and horticultural cropping. Data were collated from other sources such as the Environment Agency Catchment Abstraction Management Strategies (for example, for estimates of agricultural water use and abstraction licences in Objective 1) and UKCP09 (for estimates of change in climate variables relevant to agriculture in Objective 3). The latter was also used in the hydrological modelling.

2.3 Illustration of Hydrological Changes

Objective 3 provides illustrative examples of the impacts of climate change on water availability plus changes in drought and flood frequency (as implied from flow statistics) to support the literature review and demonstrate how state-of- the-art climate data can be used within the industry to assess these potential impacts. This approach involved the collection of data of change in climate variables to create climate change scenarios, which can then be used to provide input to a hydrological model to produce hydrological outputs and indicators for different case study catchments.

2.3.1 Study Catchments

The criteria used for the selection of the case study catchments are critical to the success of the project. After considering six catchments (see Figure 2.1), four were selected to illustrate the impacts of climate change based on the previous comprehensive and structured review of the literature, different geographical location (to capture regional differences in climate change) and different agricultural land use characteristics. Catchments were chosen to reflect different broad farming types, for example upland grazing suckler beef and sheep, lowland mixed arable and livestock farms, and lowland cropping/horticulture. At the same time, the catchments chosen reflect issues regarding drainage, flooding and water availability and impacts in terms of access to land, crop productivity, water use, for example.

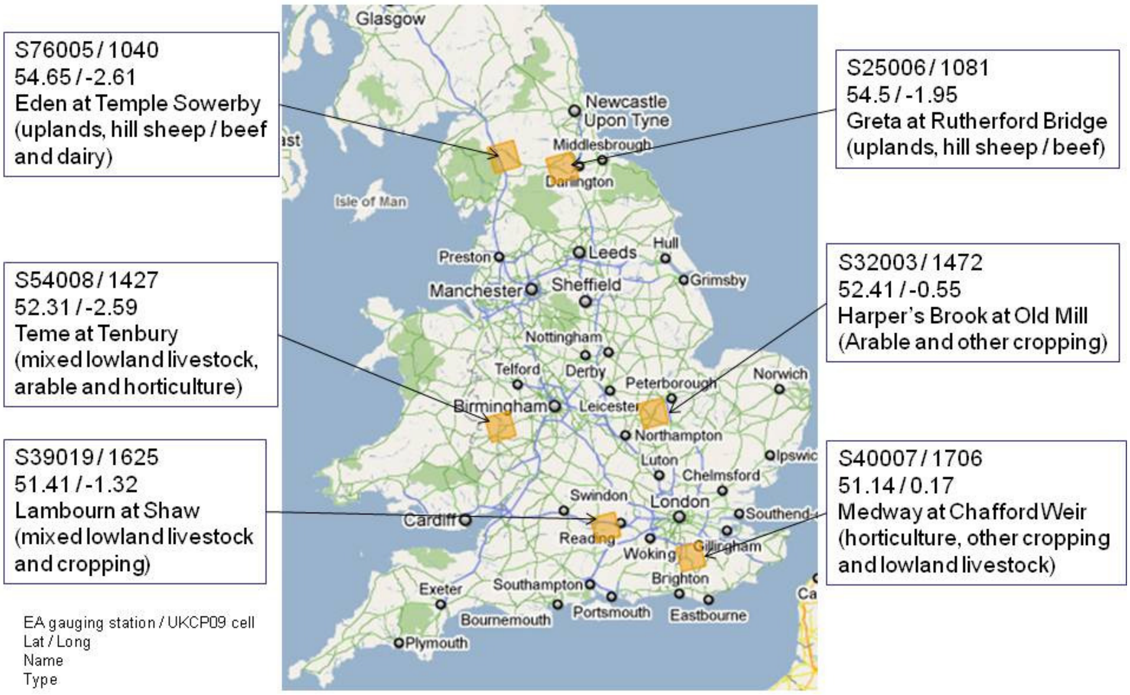


Figure 2.1 Details and locations of the six case study sites considered for this project. This figure is based on the site locator for the 25km grid squares from the UKCP09 user interface.

After reviewing Defra data (Defra, 2010a) for farm types, land use (including cropping) and livestock numbers within the counties and unitary authorities of the six original suggested sites, the following four were selected, details of which are shown in Figure 2.1 and Table 2.1:

- Harpers Brook - covers cereal and general cropping farm types and pigs
- Medway - covers horticulture and lowland livestock (pigs, but also poultry, cattle and sheep, horses and goats)
- Teme - mixed farms, with emphasis on horticulture, pigs, poultry and sheep
- Eden - dairy and grazing livestock (upland) farm types, so cattle and sheep

Baseline data is necessary for producing scenarios of change used as input to the hydrological model. This data can be downloaded from the Centre for Ecology and Hydrology Catchment Spatial Information – Index of Stations module held at http://www.nwl.ac.uk/ih/nrfa/spatialinfo/Index/indexCatchmentSpatialInfo.html. Table 2.1 provides location data, catchment codes, catchment areas, UKCP09 Cell number (for the climate change scenario data) and CRU Cell number (for baseline wind data) for each site. The baseline weather data must be between 1961 and 1990; the climate scenarios represent changes relative to the 1961-1990 period. Table 2.2 summarises the calculated baseline data for each site derived after producing the scenario input files for the computer model.

Table 2.1 Study catchment locations, areas, station and cell codes.

Catchment name	Latitude	Longitude	Catchment area (m^2)	Station code	UKCP09 cell code	CRU cell code
Eden at Temple Sowerby	54.65	-2.61	616.4	76005	1040	17701445
Harpers Brook at Old Mill	52.41	-0.55	74.3	32003	1472	17901420
Medway at Chafford Weir	51.14	0.17	255.1	40007	1706	18001410
Teme at Tenbury	52.31	-2.59	1134.4	54008	1427	17701420

Table 2.2 Baseline values of mean annual temperature (T), annual precipitation (P) and annual potential evaporation (PE) for each study catchment listed by UKCP09 cell code.

Site	Harpers Brook	Medway	Teme	Eden
UKCP09 cell	1472	1706	1427	1040
Mean annual temperature (℃)	9.14	9.49	8.96	7.81
Precipitation (mma^{-1})	608.4	747.8	761.7	1145.3
Potential evapotranspiration (mma^{-1})	488.14	475.45	484.57	432.89

2.3.2 Scenario Development

This research employs the latest UKCP09 estimates of change in climate variables. To produce the climate change scenarios for use in the hydrological model, change in precipitation, temperature, relative humidity and cloud cover were downloaded from the UKCP09 User Interface website (http://ukclimateprojections-ui.defra.gov.uk/ui/start/start.php), and combined to produce climate change scenarios consisting of change in precipitation, temperature and potential evaporation, all of which have significance for water in agriculture. Monthly data were downloaded for each climate variable for the Medium emissions scenario for the 2020s and 2050s time periods for each location. Arnell and Charlton (2010) provide some specific guidance on using the interface within the context of hydrological modelling:

1. Identify the appropriate UKCP09 grid square, using the square closest to the centre of the catchment.
2. Extract the data for each relevant climate variable for the site, year and emissions scenario of interest. Each variable needs to be downloaded separately. The UKCP09 website can be entered via data source (UK probabilistic projections over land), climate variable or geographic location; the only difference is the order in which questions are asked.

3. Choose the “Sampled data” option, and “Select all” as the sampling method.
4. Then select “raw data” and choose a data download format (*.csv is the easiest to interpret). Each request for a variable will generate a data file which can be downloaded and, if necessary, reformatted. Each data file will contain data from 10,000 scenarios; the different data files have consistent scenarios.

The changes in monthly climate (from UKCP09) must then be applied to baseline data within the period 1961-1990. The easiest way is to apply the changes (absolute changes for temperature, percentage changes for precipitation, etc) directly to the daily time series. This will produce perturbed time series representing a future climate, which has the same year-to-year variability as the present climate, and the same pattern of day-to-day variability. The changes in mean monthly precipitation are applied to the catchment daily rainfall from 1961-1990 to produce a perturbed 30-year time series with a different mean. Changes in potential evaporation were calculated by applying changes in temperature, relative humidity and cloud cover to the 0.5x0.5 gridded CRU TS3 data.

2.3.3 The model

The research will use a catchment model already widely used in hydrological impacts assessments. The model was originally developed for global scale hydrological assessments (e.g. Arnell, 1999) and has subsequently been applied at a range of scales. A version of this model has been used to assess the impacts of climate change on water availability in the public water supply sector at the catchment scale (see for example Arnell and Charlton, 2009). Operating at a daily time step, the model applies climate scenarios defining change in mean monthly rainfall, potential evaporation, temperature, rain-days and the coefficient of variation (CV) of monthly rainfall (with the option of not applying changes in some of these variables). Precipitation, temperature (to determine precipitation as snow or rain) and potential evapotranspiration are used in this analysis. The model is run for each scenario and each study catchment to produce indicators of hydrological change in the future compared with current conditions. Each scenario must be run separately through the hydrological model, to produce an ensemble of 10,000 (or fewer, if a subset is used) possible future flow series.

A range of indicators (such as average river discharge, low and high flows) will be developed to illustrate the impacts of climate change on water in agriculture. The basic output is a flow time-series and the flow duration curve, which describes variability in flow over time. Probability distributions can be constructed for individual flow duration quantiles to illustrate the range of possible changes; values beyond the 10 and 90% values of the probability distribution can be ignored (Arnell and Charlton, 2010). We specifically use changes in average annual runoff and in winter (December, January, February) and summer (June, July, August) runoff. Two extreme flow indicators are also used in combination with the median flow (Q_{50}): Q_5 (an indicator of high flow and flooding) and Q_{95} (an indicator of low flows and drought).

Note that the model has been adapted to run with the new probabilistic scenarios. As Arnell and Charlton (2010) note, changes in the flow duration curve in a catchment can currently only be assessed by calculating and comparing flow duration curves from flow data simulated with a hydrological model under both current and altered conditions. Such calculated changes can subsequently be applied to a real observed flow duration curve. Furthermore, they observe that it is not appropriate to run hydrological models with climate scenarios derived directly from the UKCP09 probability distributions (because there is no objective way of combining information from distributions describing changes in different variables in different months), so it is necessary to use either the full scenario sample set (10,000 samples), or a large subset of that sample set.

2.4 Assessment of implications and recommendations

Combining the literature reviews and the modelling exercise, the implications for agriculture are assessed (Objective 4) and a review of the potential options and the limitations of these options for addressing the water issues is conducted (Objective 5). The reviews and the modelling will be synthesized in order to complete the report and make recommendations for future work and to assist farmers and their advisors in making decisions to improve their practice (Objective 6).

3 Climate change in England

3.1 Introduction

Climate change is a global phenomenon with local impacts. A considerable literature has developed over the past few decades outlining projections of expected change and current observations confirm changes that are already in progress. The science is continually evolving and considerable uncertainty is acknowledged. This section begins with a brief outline of global projections of change before considering the downscaling of these estimates to produce state-of-the-art local scenarios. The discussion focuses on the two most important climate variables for considering the impact of climate change on water in agriculture: precipitation and temperature. It also introduces estimates of change for the local case study sites for potential evapotranspiration.

3.2 Climate change – global to local

Estimates of changes in global climate variables are derived using complex Global Climate Models (GCMs) which are subsequently downscaled to produce regional and local estimates of change. There are a large number of GCMs and the climate response differs between the different models. For example, in response to the same emissions scenario (A2), the models assessed in the Third Assessment Report of the IPCC simulate global temperature rises by 2100 between 1.6℃ and 5.4℃ (Hulme et al., 2002). GCMs typically have a 100-200km grid size resolution and although recent developments allow GCMs to be run with a grid size of less than 100km, this resolution still does not permit an appropriate estimation of hydrological responses to climate change (UNECE, 2009). Thus models need to be developed at finer scales and there are two approaches for downscaling GCMs to local and/or regional scales suitable for hydrological impact studies (UNECE, 2009): dynamically simulating physical processes at sub grid level or statistically transforming coarse-scale climate projections to a smaller scale using observed relationships between climates at the two spatial resolutions. In the UK, regional estimates are based currently on the HadRM3 model.

Using these models estimates of climate variables are made for a range of emissions scenarios. Assessments in the UK often employ the scenarios developed under the UK Climate Impacts Programme, first in 1998 and revised in 2002 (see Hulme et al., 2002). The four scenarios for UKCIP02 are summarised in Table 3.1 in terms of their emissions scenarios, global temperature change and how they relate to the global Special Report on Emissions Scenarios (SRES) scenarios. The range of global warming by the year 2100 for the four UKCIP02 scenarios is between 2.1℃ and 4.8℃ higher than the 1960-1991 average (Hulme et al., 2002). The scenarios provide alternative views of the future and collectively provide a broad range of the changes that society may face indicating in general that we are likely to experience warmer, wetter winters, hotter, drier summers, more frequent summer droughts, more extreme weather events such as high summer temperatures, and more winter storms, and fewer frosts and cold winter spells (Knox et al., n.d.). The Committee on Climate Change (2008) concludes that the world needs to plan strategies for adaptation to temperature increases of at least 2℃ (above pre-industrial levels) but it should also aim to reduce to very low levels the dangers of exceeding 4℃.

Table 3.1 UKCIP02 scenarios of global temperature change and their correspondence to the IPCC-SRES.

UKCIP02 Scenario	Global Temperature Change (°C)			Corresponding IPCC-SRES Scenario
	2020s	2050s	2080s	
High	0.94	2.24	3.88	A1F1
Medium-high	0.88	1.87	3.29	A2
Medium-low	0.88	1.64	2.34	B2
Low	0.79	1.41	2.00	B1

3.3 UKCP09

Climate change impacts and adaptation assessments have traditionally adopted a scenario-based approach (New et al., 2007), as shown above, in which a number of discrete 'stories' about possible futures are used. The UKCP09 scenarios are markedly different in that they are probabilistic: they are based on calculating probability distributions of potential future climates. Probability distributions of climate change impacts allow us to move to a risk-based impact and adaptation decision making framework (New et al., 2007) in an attempt to address the uncertainty inherent in this process. Many climate change impacts on water studies have followed the traditional path (e.g. Foresight Flood and Coastal Defence Project, 2004a, 2004b) and have been codified into policy documents (e.g. the United Nations Economic Commission for Europe's 'Guidance on Water and Adaptation' (2009)) and guidance (e.g. The EA Water Resources Planning Guidelines, 2008a). Recognising weaknesses (e.g. the conclusions of any assessment depend on the scenario used) in addressing uncertainty from a limited number of 'stories', there has been a move to increase the number of scenarios using large ensembles (e.g. Dessai and Hulme, 2007). In preparation for the release of the UKCP09 scenarios, Fung et al. (2009) applied a large number of ensembles of climate change information (from ClimatePrediction.net) and for three water-related case studies in England found that the additional information contained in the climate model ensemble provides a better understanding of the possible ranges of future conditions, compared to the use of single model scenarios.

Thus the UKCP09 projections do not present climate information in the same way as the earlier UKCIP02 scenarios and are essentially based on a very large ensemble of climate change information. Probability distributions of changes in individual climate variables are then constructed from these large ensembles. The UKCP09 projections do not provide scenarios with a specific assigned likelihood but provide a framework to allow the construction of probability distributions of changes in specific indicators. The probabilities depend on the three different emissions scenarios and are best seen as relative likelihoods rather than absolute probabilities. Specific indicators for the current study include precipitation and temperature and after running the scenarios through a hydrological model includes changes in flow characteristics under the future climates.

The UKCP09 briefing report (Jenkins et al., 2009) summarises changes in temperature and precipitation across the UK by the 2080s under the medium emissions scenario as follows (central estimates of change are presented followed, in brackets, by changes which are very likely to be exceeded, and very likely not to be exceeded (10 and 90% probability levels, respectively):

- All areas of the UK warm, more so in summer than in winter. Changes in summer mean temperatures are greatest in parts of southern England (up to

4.2ºC (2.2 to 6.8ºC)) and least in the Scottish islands (just over 2.5ºC (1.2 to 4.1ºC)).

- Mean daily maximum temperatures increase everywhere. Increases in the summer average are up to 5.4ºC (2.2 to 9.5ºC) in parts of southern England and 2.8ºC (1 to 5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7 to 2.7ºC) to 2.5ºC (1.3 to 4.4ºC) across the country.
- Central estimates of annual precipitation amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
- The biggest changes in precipitation in winter, with increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
- The biggest changes in precipitation in summer, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.

It should be noted that the changes could be very different for different time periods or emissions scenarios. Figures 3.1 to 3.2 provide distribution maps of changes in mean summer and winter temperature change (℃) for the medium emissions scenario for the 2020s and 2050s. These maps were downloaded from the UKCP09 User Interface and many other example products are available. Other maps can be downloaded for presentations at: http://ukclimateprojections.defra.gov.uk/content/view/1124/499/ . Each map consists of three maps based on the 10% (very unlikely to be less than this value), 50% (the central estimate) and 90% (very unlikely to be greater than) probability levels; representing three points along the probability distribution curves. The three maps are required in order to get a sense of the range of possible future values. Average summer temperature change shows a clear gradient of decreased temperature increase towards the North of the UK in both the 2020s and 2050s, with temperature increases varying between 0-3℃ and 0-5℃, respectively. Variability is greatest in the extremes of the probability distributions. The temperature gradient is less apparent in the central estimate map indicating temperature changes up to 2℃ for the 2020s and 3℃ for the 2050s. There are starker gradients in the winter maps with lower overall temperature increases across the full probability distribution but the central estimates are similar to the summer estimates although the geographic distribution is different.

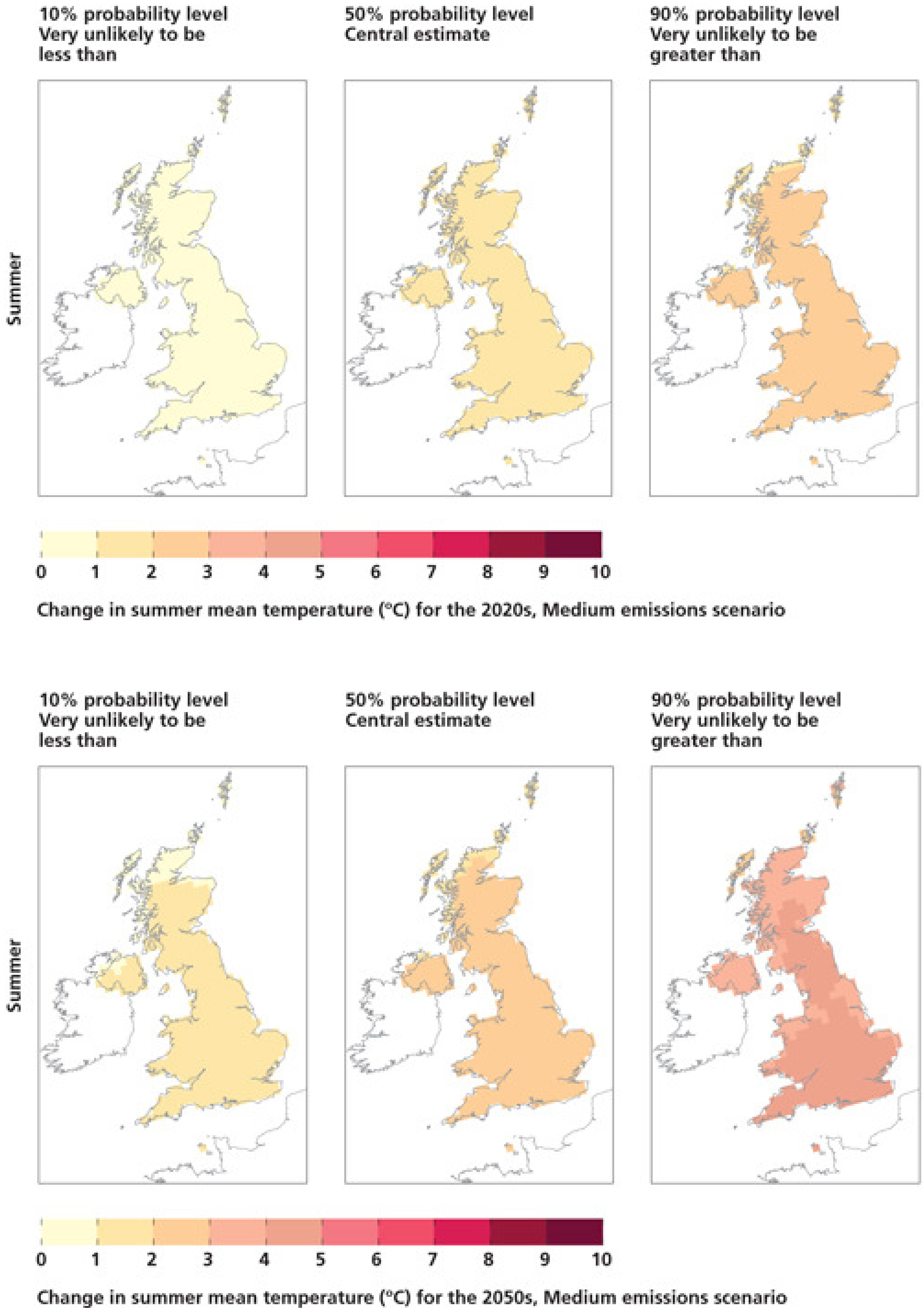
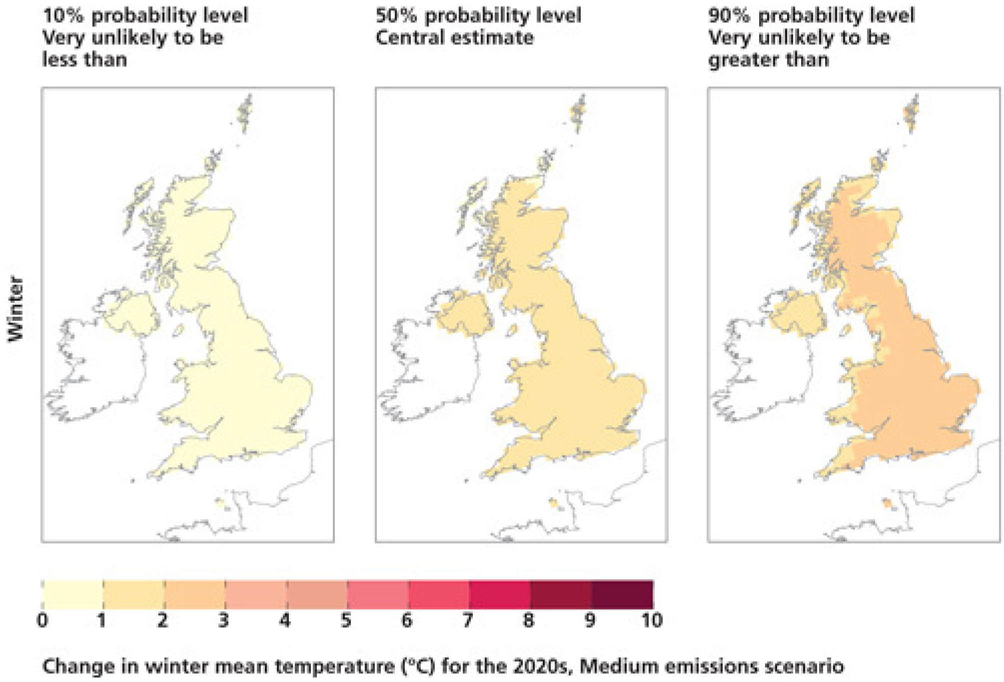


Figure 3.1 Change in summer mean temperature for the 2020s and 2050s from UKCP09.



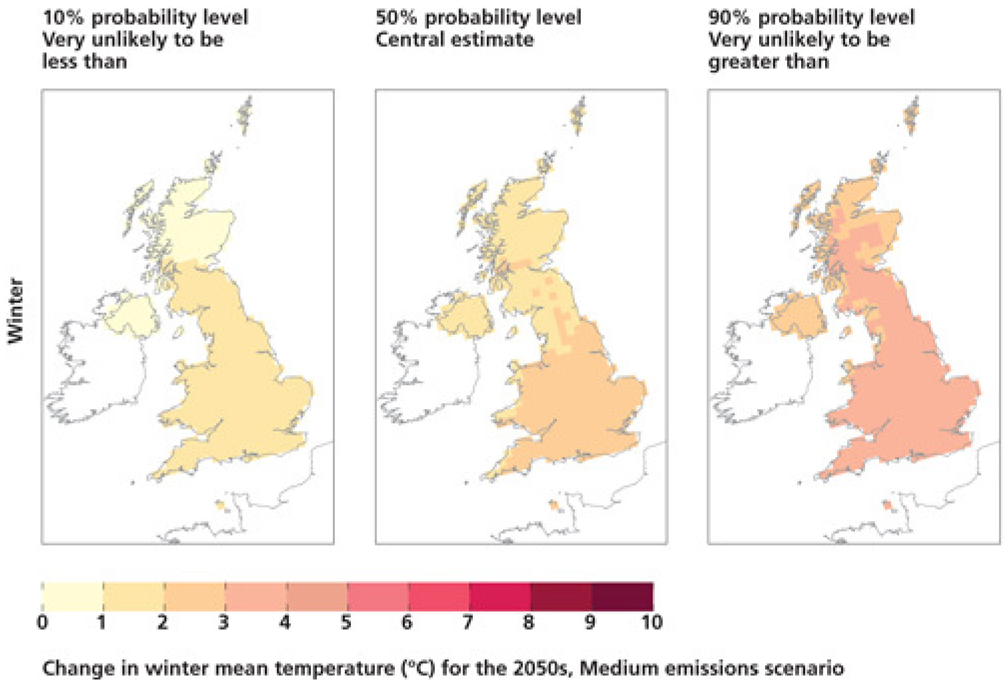


Figure 3.2 Change in winter mean temperature for the 2020s and 2050s from UKCP09.

Figures 3.3 to 3.4 provide distribution maps of changes in mean summer and winter precipitation change (%) for the medium emissions scenario for the 2020s and 2050s. In general, these show similar patterns in the north-south trend and variability at the extremes of the probability distributions. The central estimate shows summer reductions in rainfall of between 0-30 % in the 2020s and 0-40% in the 2050s with the greatest losses concentrated in the South and the smallest reductions concentrated in the extreme North. Winter shows more variability across the UK, with both reductions and increases in precipitation and a range between about -10 and +20%, with lower increases in rainfall in some upland areas.

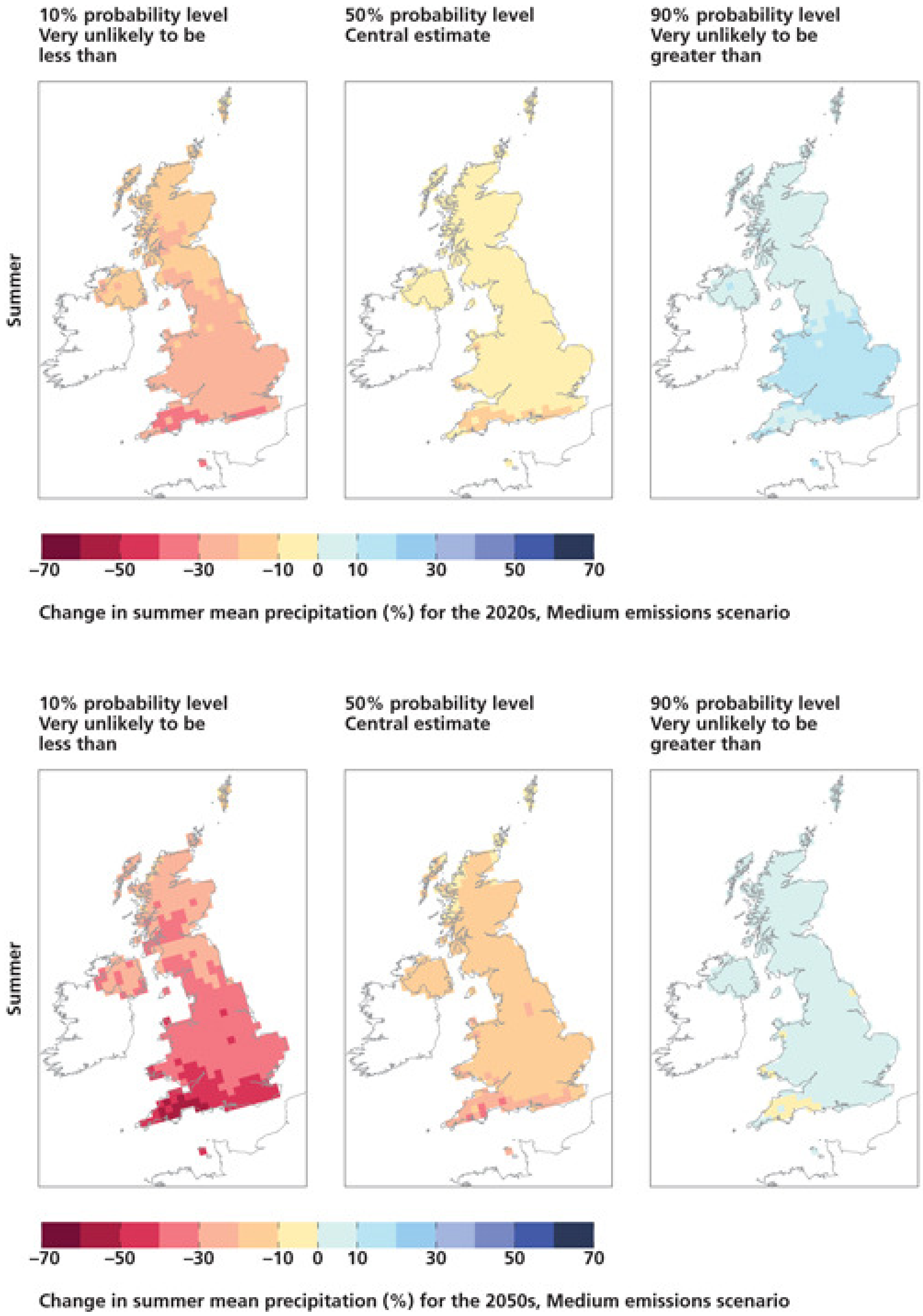


Figure 3.3 Change in summer mean precipitation for the 2020s and 2050s from UKCP09.

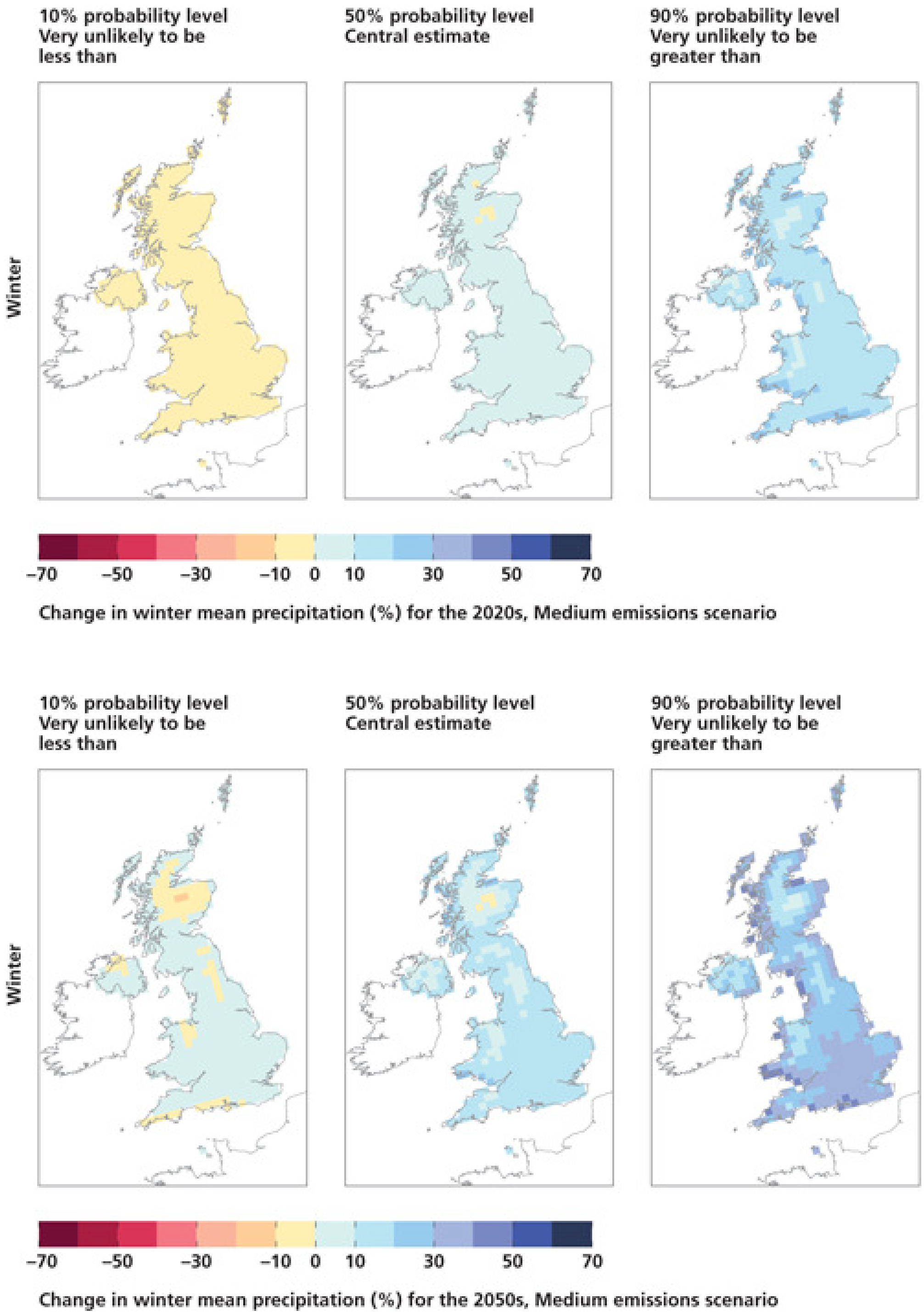


Figure 3.4 Change in winter mean temperature for the 2020s and 2050s from UKCP09.

These maps only give a very general overview of the changes in potential temperature changes and because of the 1 ℃ classes fail to show spatial and temporal contrasts clearly. Specific local differences may have a significant impact on the outcome of impacts investigations at specific locations and therefore it is necessary to look at a number of different study sites.

3.4 The project scenarios

The previous section outlined the links between global and local change and showed the latest climate change data for the UK for two agriculturally relevant variables. It showed a range of changes and a clear regional bias. These spatial differences are crucial to understanding the impacts of climate change on water in agriculture. It is therefore necessary to develop site-specific climate change scenarios, as outlined in Section 2.3.2. The scenarios for each location and year are summarised in Table 3.2.

Table 3.2 Changes in mean annual temperature (°C), total annual precipitation (%), and total potential evapotranspiration (%) estimated for each study site for the 2020s and 2050s for three probability levels.

Change in Variable	Year	Probability level	Site (UKCP09 Cell)			
			Harpers Brook (1472)	Medway (1706)	Teme (1427)	Eden (1040)
Temperature (℃)	2020	10	0.84	0.87	0.83	0.79
		50	1.41	1.48	1.41	1.35
		90	2.07	2.16	2.05	1.99
	2050	10	1.58	1.64	1.61	1.43
		50	2.41	2.52	2.41	2.24
		90	3.44	3.59	3.43	3.24
Precipitation (%)	2020	10	-5.70	-4.63	-5.21	-2.55
		50	0.62	1.05	0.38	1.64
		90	7.30	7.35	6.60	6.18
	2050	10	-8.82	-6.35	-7.45	-4.05
		50	-0.98	0.34	-0.68	1.59
		90	8.05	7.73	6.83	7.72
Potential Evapotrans-piration (%)	2020	10	4.26	3.67	3.14	4.15
		50	13.67	15.78	12.87	11.12
		90	24.38	29.52	23.75	19.10
	2050	10	11.34	11.30	10.65	9.60
		50	25.82	30.60	24.23	19.39
		90	43.20	53.60	41.53	32.14

Table 3.2 shows that temperature (T) and potential evapotranspiration (PE) increase for each site and scenario at all three probability levels but precipitation (P) does not. Temperature changes are in line with those indicated in the UKCP09 maps in the previous section. (Temperature changes are shown here largely for the climate change context; changes in P and PE (which depends on T) primarily determine the hydrological response). Annual precipitation estimates indicate a range of changes from reductions at the 10% level to increases at the 90% level. In the 2020s there are small increases in annual precipitation at all sites. However, in the 2050s these increases in annual precipitation are reduced at all sites with the two catchments in the middle of England showing small losses in annual precipitation. It should also be noted that these annual values mask seasonal variation. The scenario estimates for annual potential evapotranspiration show increases between 3-53% depending on year, location and probability level. Increases are greatest in the southern catchment and

least in the northern catchment, indicating the potential for far greater water losses in streams and in the soil for the south although the losses will still be high in the north. It is important that T and PE both show increases at all levels at all sites in all years but P does not. Patterns of flow changes will thus vary considerably making local consideration of problems and therefore solutions necessary at all times. If a small increase in PE occurs where there is a large increase in P the impacts on water availability may be reduced. However, the impacts on flooding may be significantly increased. Thus there will be a significant seasonal dimension to these balances and their impacts. Taken annually at the 50% level it appears that large increases in PE are matched against small increases in P in the 2020s and for two sites these increases in PE are set against small decreases in P by the 2050s. The annual picture is of reductions in the overall water balance by the 2020s which become worse by the 2050s. The implication is that despite seasonal differences, which may increase flood risk, there will be a reduction in water availability at each site and an increased chance of drought, although the magnitude and duration are not indicated by this work. It is also important to note that the distributions are not identical between sites so that for example at the 10% level the increase in PE is greater at Harpers Brook than at Medway but at the 50% level this pattern is reversed. The range in precipitation change is greatest at Harpers Brook for both 2020s and 2050s. It is least for the northern site – this may reflect already relatively high rainfalls in this area compared to the other sites. PE change, however, is greatest at the most southern site, relatively equal at the two middle sites and much lower at the northern most site. It is important to remember that these reported values are percentage change. A large percentage change at one site may in fact be less of a change in absolute terms when compared to the change at another site.

The implications of these changes for water in agriculture will be discussed following the application of the hydrological model in Section 4. It should be noted that the current projections are not spatially coherent although work is in progress to rectify this situation. What this means is that climate change at different locations is not strictly comparable and therefore any modelling exercise is indicative only.

3.5 Summary

This section has provided a global context for climate change and outlined different scenarios of change for the UK before outlining site-specific scenarios using the latest climate change scenarios for use in this research.

4 Climate change impacts on water for agriculture in England

4.1 Introduction

Climate change affects average temperatures and temperature extremes; timing and geographical patterns of precipitation, snowmelt, runoff, evaporation, and soil moisture; the frequency of disturbances such as drought, insect and disease outbreaks, severe storms and forest fires; atmospheric composition and air quality; and patterns of human settlement and land use change (US Climate Change Science Program (CCSP), 2008). The previous section has indicated significant change in climate variables relevant to agriculture within a hydrological context. Climate change will affect English agriculture in a large number of ways and at a range of scales. These general impacts of climate change should not be forgotten when considering the impacts of climate change on water in the agricultural context. In particular, the other impacts may be more relevant to farmers over shorter timescales and may therefore act as more significant drivers to change in agriculture than changes in hydrology. However, water is a fundamental agricultural resource that, although often taken for granted, is currently under pressure. This pressure is likely to increase under climate change with a number of direct and indirect impacts. This section discusses the key issues under two main themes:

1. Climate change will change the availability of water in general. Water availability for abstraction and in the soil will change. The impacts will be spatially and temporally variable. Changes in extremes of water shortage will lead to changes in drought frequency, magnitude and duration. Climate change will increase demand for water, particularly for irrigation, in areas already under pressure.
2. Climate change will change the magnitude, frequency, distribution (spatially and temporally) and duration of flood events. Flood waters are both destructive and rarely available for use in agriculture.

Changes in both of these aspects will have direct and indirect impacts on agriculture. The Environment Agency's (2009) water resources briefing on agriculture identified irrigation, climate change, the UK's wider footprint, food security and change of land use as the major pressures on agriculture. Climate change is one of many pressures the EA (2008b) identify with hydrological impacts including:

1. By 2050 river flows in winter may increase by 10-15% but with lower flows in most rivers from April to December.
2. River flows in late summer and early autumn could fall by over 50% and by as much as 80% in some catchments.
3. Therefore a drop in annual river flows of up to 15%.
4. Related work indicates climate change may reduce the recharge of aquifers and lead to a lowering of groundwater levels.
5. Warmer climate will mean higher demands for direct abstraction for cropping.

At a global scale, the UNECE Guidance on Water and Adaptation to Climate Change (2009) summarising work from the IPCC (2007) and a technical paper by Bates et al. (2008) provide examples of major impacts by sector, acting mainly through water. For water resources and agriculture, these impacts are summarised in Table 4.1.

Table 4.1 Summary of water-related climate change impacts on the water resources and agriculture sectors (adapted from UNECE, 2009).

Phenomenon	Water resources	Agriculture
Heavy precipitation events	• Flooding • Adverse effects on quality of surface and groundwater due to sewer overflows • Contamination of water supply • Water scarcity may be relieved	• Damage to crops • Soil erosion • Inability to cultivate land due to waterlogging of soils
Higher variability of precipitation events, including increased droughts	• Changes in runoff • More widespread water stress • Increased water pollution due to lower dissolution of sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, as well as thermal pollution • Salinization of coastal aquifers	• Land degradation • Lower yields / crop damage and failure • Increased livestock deaths • Increased risk of wildfire
Increased temperatures	• Increased water temperatures • Increase in evaporation • Earlier snow melting • Permafrost melting • Prolonged lake stratification with decreases in surface layer nutrient concentration and prolonged depletion of oxygen in deeper layers • Increased algae growth reducing dissolved oxygen	• Less water available for agriculture, more irrigation needed • Changes in growing season • Changes in species composition, organism abundance, productivity and phonological shifts

	levels in the water body which may lead to eutrophication and loss of fish • Changes in mixing patterns and self purification capacity	

There are many potential impacts of climate change on agriculture, globally. For example, higher temperatures will very likely reduce livestock production during the summer season (US CCSP, 2008) as a result of reduced feed intake, and issues associated with lack of access to drinking water and heat stress. Rosenzweig and Hillel (1995) suggest that in middle and higher latitudes, global warming will extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvesting, and the possibility of completing two or more cropping cycles during the same season. However, they also observe that in warmer, lower latitude regions, increased temperatures may accelerate the rate at which plants release CO_2 in the process of respiration, resulting in less than optimal conditions for net growth. Furthermore, when temperatures exceed the optimal for biological processes, crops often respond negatively with a steep drop in net growth and yield, and increased night time respiration may also reduce potential yields (Rosenzweig and Hillel, 1995). For grazing livestock this could mean increased yields and dry matter availability at the start of the growing season but reduced yields subsequently with a requirement for buffer feeding in-field or in-house and implications for grazing and conservation management and a potential switch to alternative forage and other crops.

The US CCSP (2008) note that the life cycle of grain and oilseed crops will likely progress more rapidly but with rising temperatures and variable rainfall crops will begin to experience failure, especially if precipitation lessens or becomes more. Climate change will modify rainfall, evaporation, runoff, and soil moisture storage and changes in total seasonal precipitation or in its pattern of variability are both important with the occurrence of moisture stress during flowering, pollination, and grain-filling being harmful to most crops (Rosenzweig and Hillel, 1995). Increased CO_2 improves growth by enhancing photosynthesis and also tends to close stomata and slow down the rate of water loss from the leaves, meaning more food for less water consumed, but loss of water from crops (evapotranspiration) will be greater due to the warmer, sunnier weather (Thompson, 2007). Most importantly, on average there will be less rainfall during the critical growing period and crops will suffer from soil moisture deficits (Thompson, 2007). As already noted (see EA, 2009), the demand for water for irrigation is projected to rise in a warmer climate, bringing increased competition between agriculture and other sectors (Rosenzweig and Hillel, 1995).

Within the global context it is worth noting the concept of the water footprint (WF) which is defined (Chapagain and Orr, 2008) as the total virtual water content of products consumed by an individual, business, town, city or country and consists of two parts: (1) use of local resources (internal), and (2) use of global water resources (external). Chapagain and Orr (2008) indicate that the UK is the 6th largest net importer of virtual water based on the WF of agricultural products with a larger share of internal WF related to livestock production and cereal products, whereas the larger share of the external footprint is related to products originating from oil crops, cotton products, livestock products and stimulants. They also note that external WF products are not grown in UK mainly because of unsuitable agro-climatic conditions and that in addition to the direct impacts of climate change on water availability in the UK, climate change could alter water availability for imported products, altering market conditions, for example, and it could also change the nature of product that could be produced in the

UK and further afield. The global context and complexities should not be forgotten when adapting to climate change in the future.

The PESETA project (Ciscar et al., 2009) investigated climate impacts across a range of sectors and discusses the physical impacts on agriculture across Europe, which are summarised briefly here. In particular they note that the results show that agroclimatic regions will have substantial modifications as a result of climate change and that these have important implications for the evaluation of impacts on future crop productivity. Whilst the project's crop yield estimates include the direct positive effects of CO_2 on the crops, the rain-fed and irrigated simulations in each district, they did not consider restrictions in water availability for irrigation due to changes in policy. There are substantial variations in yield depending on location in Europe and time period considered, although there are generally gains in yield in 2025. By the 2080s the British Isles would have yield losses for the two less warming scenarios.

Within the UK, the implications of climate change for agriculture is a key research area for Defra under their Climate Change Impacts and Adaptations (Agriculture) (CC03) Research Programme. A useful summary of the projects commissioned from 1999 through to 2006 is the review led by IGER (Hopkins, 2005). The following paragraphs summarise some of the key research outcomes.

It is recognised that regional variations in climate have a role in determining the suitability of land for different agricultural enterprises, and rainfall and temperature is a major component in influencing the crops grown, their yield and quality. Changes in climate and climatic extremes such as droughts, storms, heavy and prolonged rainfall, and flooding are components of weather that are already experienced by farmers. It is the continued change and the increased frequency of events that presents greatest risk to farm business and requires the development of adaptation and mitigation strategies.

For livestock enterprises, longer, hotter summers will mean that the grazing season may become extended with the potential for yield increases. This is dependent on the availability of nutrients (fertiliser) and water (irrigation). If irrigation is not feasible then summer droughts may require a shift to non-grass forage, e.g. maize, as conditions may be more favourable for forage legumes. From an animal welfare perspective, there are concerns with regard to the availability of drinking water supplies and heat stress. An increased risk of wildfires on moorland and rough grazing will also be problematic. The extended grazing season also presents challenges with the risk of increased autumn rainfall leading to soil saturation such that reseeding of pastures may become difficult and poaching damage could increase if livestock remain on the land for longer periods. Finally, as the environment changes, there will be changing weed, pest and disease problems.

For arable and other crop enterprises, there are many implications of climate change primarily for sowing and harvesting dates, and rates of spring growth. Earlier sowings may be possible for some crops, with the greatest potential in summer vegetable cropping. However, the changing nature of supply has implications for crop prices particularly in niche markets. For many crops new pest and disease problems may pose potential threats. There will also be an increased drought risk for some crops, that require water for both yield and quality benefits at the time of year when the drought risk is greatest (July-August).

It is important to note that climate change is only one determinant in influencing agricultural practice in the UK. There are other, potentially more important, national and global drivers including political and socio-economic influences and technological developments. It is the interaction between these that is important for the future agricultural industry, particularly in terms of the effect of world commodity prices on the competitiveness and comparative advantage of UK agriculture.

In the following sections, the current characteristics of water use, availability, droughts, flooding and soil waterlogging are outlined in order to provide a baseline, before reviewing future changes in these characteristics and their implications for agriculture.

4.2 Water for agriculture at present.

According to annual Defra June survey data agriculture occupies over 70% of the land within England, approximately 18 million hectares, with a further 10% occupied by forestry and woodland. Of the agricultural land about 70% (11.5 million hectares) is used for grazing livestock and 25% (4.5 million hectares) for arable production. The grazing area comprises permanent grassland over five years old (32%), sole right rough grazing (25%) and temporary leys that is grassland less than five years old (6%). In terms of livestock numbers there are 10 million cattle (dairy and beef), 34 million sheep, 5 million pigs, and 168 million poultry. Water use within the livestock sectors is as soil moisture for crop growth, e.g. grass, and abstractions and mains water use for drinking water, and for plant and machinery cleaning. Value wise, milk contributes the most to the economy, followed by beef, then poultry and finally sheep. Cereals occupy the majority of the arable area, primarily wheat (40%) and barley (20%), with other crops such as oilseed rape, peas and beans, potatoes, sugar beet and horticultural crops each occupying between 5% and 10% of the remaining land. For field crops such as cereals soil moisture is the most important source of water. For potatoes, sugar beet and other field vegetable crops, abstractions for irrigation are important. Similarly, in the horticultural and protected crop sector abstractions for irrigation are also important. The most valuable crops are those within the horticultural sector that occupy the smallest areas of land. (see www.defra.gov.uk/evidence/statistics/foodfarm/index.htm)

4.2.1 Water use and availability

Agriculture is one of many users of water and, like other industry sectors, dependent on its availability. Agricultural use of water may be direct (e.g. water for livestock, irrigating crops in situ, preparation of produce, or for cleaning purposes) or indirect (e.g. water in ground for growing crops), i.e. not all water used in agriculture is abstracted (e.g. soil moisture use).

Approximately 40% of the water used within agriculture is for livestock enterprises. Direct water abstractions for livestock enterprises, particularly in the dairy sector, are comparable to direct abstractions for crop production. However, abstraction for livestock is more prominent in the west, where there is less pressure on water supplies, than the east. Most of the water abstracted is for drinking, but water is also abstracted for washing down of plant and machinery. A recent report by the Milk Development Council (MDC, 2007) lists how (and how much) water is used on dairy farms as follows:

- Livestock drinking – 50-75% of a dairy farm's water use
- Plate cooler water – up to 25%
- Collecting yard and parlour washing down – 5-17%
- Plant washing – bulk tanks and parlour plant washing – 4-10%
- General water use
- Sprayer use
- Slurry flush systems

- Irrigation
- Domestic use

The same report also briefly summarises where this water comes from:
- Mains water (charged as either metered or un-metered, including individual field trough rates)
- Abstraction, from surface water (rivers, ponds, lakes, canals) and ground water (springs and bore holes)
- Direct stock drinking from water courses, e.g., rivers, ponds, streams etc.
- Rain-water harvest, e.g., roof water collection
- Re-use, e.g., re-use of water from plate coolers, or re-use of dairy plant washings for yard wash-down or footbaths

The dominant use of water for crop enterprises is direct abstraction for irrigation of field crops, with most water abstraction applied to potato and vegetable crops. Polytunnel crops use significant amounts of irrigation water but the process is more efficient than for field crops. In both cases, product quality and profitability are highly dependent on the timing and volume of water applied. In contrast to livestock enterprises, abstraction for crop enterprises occurs predominantly in the southern and eastern regions where there is more pressure on water supplies, although abstraction for cropping also occurs in the west. It is worth remembering that although agriculture is a user of water and within this abstraction for irrigation is a significant amount (EA, 2006a), farmers use less than 1% of the total water abstracted for spray irrigation (EA, 2008b) and only 1% for both spray and trickle irrigation combined (EA, 2009).

Finally, rain fed crops, such as cereals and oilseed crops, which use water indirectly will also influence water availability, and could reduce ground and surface water resources.

A comprehensive review to establish a baseline for water use in agriculture was conducted by ADAS for Defra (ADAS, 2006), the main results of which are reproduced in Table 4.2 and indicate that the total on-farm use of abstracted water is estimated to be in excess of 300 million cubic metres a year. Significant spatial, temporal and sectoral differences were identified as summarised here (ADAS, 2006):

Livestock
- Livestock rearing is estimated to account for another 119 M m^3 of water used on farms; mainly for consumption (drinking), but also for cleaning housing and yard assembly areas.
- Livestock use is fairly evenly distributed throughout the year, with a small increase during the summer months when animals tend to drink more when temperatures are higher.
- Water use by cattle is heavily biased towards western regions.
- Sheep are also concentrated in the west, where most land is under pasture.
- Pigs and poultry are more evenly spread across the country, but with concentrations of pigs occurring in Yorkshire and Humberside and Eastern England, and poultry in Eastern England and East Midlands.

Crop irrigation
- Within the total, approaching half (128 M m^3) is reliably estimated to be used for the irrigation of field crops during the summer months only (June to August inclusive).
- Of this irrigation water, 75 M m^3 is used on the potato crop (5 M m^3 on early varieties and 70 M m^3 on maincrop), and a further 34 M m^3 on field vegetables.
- An increasing proportion, though still <10%, of irrigation is by trickle irrigation methods.

- Field crop irrigation is carried out predominantly in eastern and southern regions of England, and almost not at all in Wales.
- This distribution of irrigation use corresponds with the areas of high insolation and least summer rainfall.

Protected and nursery crops

- The third largest sector in terms of overall water use is the protected and nursery crops sector, accounting for about 53 M m^3 of water annually. This is mainly concentrated in the South East of England, but with significant use in the Midlands and Eastern England and with a presence in all regions.

Summary

- Overall across England, agriculture uses most water in the regions which are least capable of supplying it: Eastern England > East Midlands > South West > South East > West Midlands > North West > Yorkshire & Humberside > North East. In addition this supply is demanded during the driest part of the year and is abstracted almost equally from ground and surface water sources.

Table 4.2 Estimate of overall annual water use by agriculture (2006) by sector and region (GOR) throughout England ('000 m^3 a^{-1}) (Adapted from ADAS, 2006)

	Government Office Regions (GOR) in England								
	East Mids	**East**	**London & S East**	**N East**	**N West**	**S West**	**West Mids**	**Yorks & Humber**	**Total England**
Irrigation of field crops	29,415	45,554	22,533	3,344	1,019	5,248	13,025	7,955	**128,093**
Field crop spraying	551	800	363	108	75	301	269	390	**2,857**
Vegetable spraying (estimated)	40	89	10	8	9	13	14	15	**198**
Vegetable washing	28	48	19	1	18	8	73	11	**207**
Potato washing	6	8	1	1	2	2	4	3	**26**
Glasshouse use	1,250	2,560	3,400	120	1,680	1,440	1,140	1,730	**13,320**
Nursery Use	3,990	8,360	11,870	680	2,640	3,740	6,340	2,890	**40,510**
Cattle	6,826	2,378	6,557	2,425	16,402	28,246	11,909	7,255	**81,998**
Pigs	796	2261	571	143	309	884	444	2,466	**7,874**
Sheep	1,383	384	1,543	2,103	3,260	3,680	2,556	2,363	**17,272**
Poultry	2,118	3,016	1,094	184	822	1,670	1,658	1,394	**11,956**
Total Usage	**46,403**	**65,459**	**47,961**	**9,118**	**26,236**	**45,232**	**37,431**	**26,472**	**304,311**

Data on abstraction licences and water use are also available as part of the Observatory Programme. This programme involves the development of a set of indicators to help monitor agricultural change, to identify environmental risk, and to provide an evidence base for informing future policy. Water abstraction for agriculture is one of its indicators (DA5). It shows the recorded quantity of water abstracted from surface and groundwater for agricultural use (Defra, 2010b).

Table 4.3 shows the licensed use throughout agriculture between 1995 and 2007. Licences are often granted in excess of requirements but also do not reflect all abstractions.

Table 4.3 Observatory programme monitoring data for total licensed agricultural abstraction between 1995 – 2007.

													Ml per day
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total licensed abstraction for agriculture	1,114	1,217	1,233	1,332	1,358	1,365	1,334	1,307	1,285	1,275	1,163	1,151	1,162
Spray irrigation	808	846	904	954	937	947	949	936	933	931	924	911	922
Other agricultural use	306	371	330	378	421	417	385	370	352	344	239	239	241

Table 4.4 shows reported use throughout agriculture between 1995 and 2007 by region. These are reported values and may not necessarily be accurate but reflect regional and temporal variation and are more useful as a baseline for future climate impacts than the licensed values. In 2007 agriculture reportedly used 233 Mld^{-1}

Table 4.4 Observatory programme monitoring data for reported agricultural abstraction between 1995 – 2007.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total reported abstraction for agriculture	**455**	**505**	**399**	**393**	**467**	**443**	**367**	**368**	**447**	**347**	**286**	**325**	**233**
Spray irrigation	**352**	**369**	**292**	**282**	**325**	**291**	**259**	**248**	**315**	**225**	**226**	**277**	**161**
North West	6	6	2	1	3	4	13	23	26	7	8	3	2
North East	37	55	17	25	56	17	20	14	21	11	15	17	11
Midlands	97	82	49	50	60	50	54	61	64	40	50	63	33
Anglian	148	171	179	152	169	187	137	115	159	126	119	153	91
Thames	15	14	17	26	11	11	9	10	13	10	9	9	6
Southern	27	23	19	20	16	12	15	13	18	16	15	17	12
South West	11	8	5	4	4	4	5	4	8	11	4	5	3
Wales	11	10	5	4	5	4	6	9	6	6	6	11	2
Other agricultural use	**103**	**136**	**108**	**111**	**142**	**152**	**108**	**120**	**132**	**122**	**60**	**48**	**72**
North West	5	5	6	5	2	6	5	4	7	15	3	5	6
North East	11	13	9	9	37	28	12	25	11	9	6	5	5
Midlands	5	7	8	9	12	11	10	8	11	11	5	5	5
Anglian	20	17	16	24	14	27	15	15	16	14	8	7	7
Thames	6	7	6	7	12	8	12	10	15	9	8	9	8
Southern	3	27	8	8	5	18	5	5	7	5	5	5	7
South West	46	54	43	40	48	45	43	43	57	52	22	11	31
Wales	7	6	11	8	11	10	6	8	8	7	4	3	3
													Ml per day

The final source of information on water use and availability is that provided by the Environment Agency. The Environment Agency assesses the water resources that are available for abstraction through the CAMS (Catchment Abstraction Management Strategies) process. Each CAMS considers how much freshwater resource is reliably available, how much water the environment needs and the amount of water already licensed for abstraction (EA, 2008b). They recently completed the first cycle of 119 CAMS, which for the first time has provided a comprehensive baseline for all catchments in England and Wales. Each CAMS that is available can be found online at http://www.environment-agency.gov.uk/business/topics/water/119927.aspx . Figure 4.1 reproduces the water availability map constructed from this work (EA, 2008c) and shows that there are many catchments where there is no water available for abstraction at low flows and that some catchments are over-licensed or over-abstracted. The total amount of water abstracted from all sources in England and Wales in 2006/07 averaged about 60,000 Mld^{-1}, which is almost half the amount licensed for abstraction (EA, 2008b).

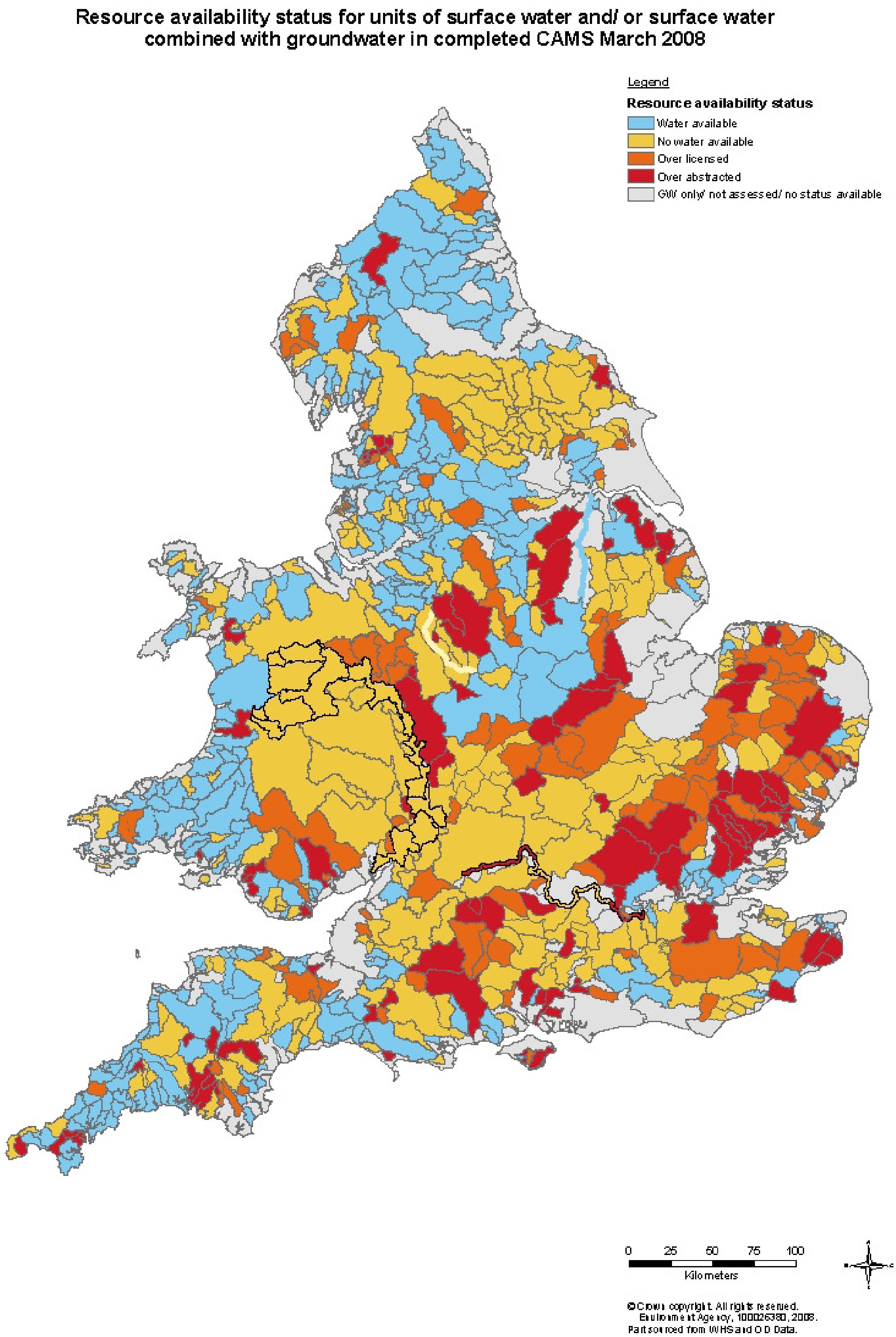


Figure 4.1 Resource availability status from available CAMS (taken from EA (2008c)).

Table 4.5 outlines licensed abstraction by total volume and surface or groundwater source and the use by each main sector for the four study catchments. This information is adapted from the CAMS for each site: Eden (EA, 2006b), Medway (EA, 2005a), Nene (EA, 2005b) for Harpers Brook, and Teme (EA, 2005c).

Table 4.5 Summary of the volumes and uses of licensed abstracted water for each of the study sites (taken from the CAMS for each site).

	Teme	Medway	Harper's Brook	Eden
Total licensed volume (m^3a^{-1})	8,303,071		186 licences	N/A
Licensed surface water volume (m^3a^{-1})	6,994,751 (84%, 113 licences)	153,204,131		N/A
Licensed groundwater volume (m^3a^{-1})	1,301,020 (16%, 9 licences)	90,958,515		N/A
SW (or SW and GW combined) uses	Public Water Supply 50% 95 licences for agriculture	Agriculture 5% Public Water Supply 93% Industry 1% Other 1%	Agriculture <0.5% Public Water Supply 92% Industry 7.6% Other <0.1%	
GW use		Agriculture 1% Public Water Supply 41% Industry 58%		
Status	No Water Available	Over-licensed / No additional water available	Over-licensed	Water Available

Some significant points from the four CAMS documents are now briefly summarised.

Whilst there is an adequate supply of surface water in the Teme during the winter period, in the summer it often experiences low flows and therefore there is a need to limit the volume of water abstracted during low flows. The main uses are public water supply and agriculture and it is an important source of water for irrigation. Fish farming and potatoes are on the increase in this catchment. Trickle irrigation is currently exempt from licensing but this will change with implementation of the Water Act of 2003. Currently 95 licences are for agricultural purposes and spray irrigation but public water supply has 50% of the licensed quantity. Flows from the Teme into the Severn are protected and therefore the resource availability assessment of this catchment is no water available.

For the Medway, the Environment Agency assesses rivers and groundwater units within the catchment as having no additional water available for abstraction during low flows (Environment Agency, 2005).

For the Nene, of which Harper's Brook is a tributary, spray irrigation is the most significant use (0.41%) for agriculture, whilst other farming is only 0.03%. During periods of low flow locally significant abstraction for spray irrigation in the lower catchment can have a major bearing upon environmental needs and other abstraction needs. Irrigation use is highly consumptive so very little is returned to the catchment. In dry summers the demands can exceed available river flow.

The Eden is covered by two units of the Eden and Esk CAMS (Upper and Lower Eden). Both are water available but 'volumes of water available for abstraction will be determined by the local assessment point relevant to the location of the abstraction'. For the Upper part specifically this means that less water is available for abstraction from the small upland tributaries than the main river. This could be significant if the modelling indicates a large reduction in flow. A large part of the area is used for agricultural purposes, dominated by animal rearing (including dairy) with lesser amounts of arable farming. Surrounding rivers are no water available, over-licensed and over-abstracted.

4.2.2 Droughts

Droughts reflect an extreme reduction in water availability. They are a natural and recurrent feature of the UK climate that can develop over short periods or several seasons and years with a wide range of consequences for the environment, water supply and agriculture (Wade et al., 2006). Rainfall droughts occur during periods of low rainfall significantly below long-term averages and, if prolonged, can develop into 'agricultural droughts' with persistently low soil moisture affecting crops, and 'hydrological droughts' reducing river flows and groundwater recharge (Wade et al., 2006). Ramamasy and Baas (2007) observe that meteorological (rainfall) and agricultural droughts are frequently, but erroneously, considered synonymous. They consider meteorological and hydrological droughts as physical events and agricultural drought as referring to the impact of the first two on agricultural production. Acknowledging that both climate variability and climate change influence such aspects as time (season, intra-season), location and length of drought occurrence, Ramamasy and Baas (2007) distinguish between these types as follows:

Meteorological drought occurs when the reduction in rainfall for a specified period (day, month, season or year) is below a specified amount – usually defined as some proportion of the long-term average. It is usually an expression of precipitation's departure from normal over some period of time. These definitions are region specific.

Hydrological drought refers to deficiencies in surface and subsurface water supplies based on measurements of stream flow and lake, reservoir and groundwater levels. When precipitation is reduced or deficient during an extended period of time, this shortage eventually will be reflected in declining surface and subsurface water levels.

Agricultural drought occurs when there is not enough soil moisture to meet the needs of a particular crop at a particular time. Agricultural drought happens after meteorological drought but before hydrological drought.

In parts of England and Wales, particularly where the Environment Agency has indicated that there is an 'unsustainable or unacceptable abstraction regime' or that there is 'no additional water available' (Environment Agency, 2001), hydrological droughts can have impacts on public water supplies, the environment, agriculture (with high soil moisture deficits, increased irrigation costs or insufficient water available for irrigation), industry, recreation and navigation and tourism (Wade et al., 2006). The vulnerability of England and Wales to drought impact has changed markedly with time, reflecting the changing balance between water supply and demand and the strategies in place to manage drought situations (Cole and Marsh, 2006).

Historically, the most notable droughts were the rainfall droughts and hot dry summers of 1976 and 2003 with limited rainfall and increased evaporation from the soil; and the hydrological droughts of 1995-98 and the mid-1980s, with warm dry summers followed by cool dry winters where water resources, including groundwater, were not replenished and reservoir water levels fell. On the Eden, one of the case study sites, three of the four most severe droughts occurred in the past two decades, the one early event being 1826 (Jones et al, 2006).

Orson (2000), in a review of the hot dry summer of 1995, illustrates the impact of drought on the agricultural sector. The key findings are summarised here:

Livestock
- Forage supply reduced with a loss in both yield and quality and consequently the need to provide more supplementary feed
- Dairying – with reduced grass growth and less silage cutting there was lower feed stocks for the following winter
- Beef and sheep – reduced forage production
- Pig and poultry – reduced feed intake due to the hot weather led to a reduced productive output

Cropping
- There was a range of impacts on crop yield dependent on species
- Shorter harvest period with longer more unsocial hours, in particular the early maturation of vining peas presented some major logistical problems
- Cereal yields and quality were high, oilseed crop yields also increased although the spring crop incurred greater growing costs than the winter sown crops
- Pea and field bean crops – reduced yields
- Potato, sugar beet and field vegetables yields and quality were reduced as irrigation facilities were overstretched with difficult conditions for weed and insect pest control and also disease issues
- Orchard fruit crop yields were reduced but eating quality in many cases improved
- Protected crops – increased demand along with increased production costs
- In some cases the reductions in yield had some benefits where shortages in supply were offset by higher prices

Farmers responded to the drought in a number of ways. In the short term this led to the earlier drilling of spring crops, and an increase in the autumn drilling of winter sown crops such as cereals, oilseed rape and field beans with a swing to early maturing varieties less susceptible to heat and drought. There was also some investment in water storage and application equipment and crop storage improvements.

In summary, the dry warm weather would have a number of benefits for some crops in terms of yield and quality, but will also be detrimental to others. Increased evaporation rates result in soil moisture deficits and there are also implications for river flows, reservoirs and groundwater resources, with consequent water quality deterioration. In the worst case, reduced water availability could lead to restrictions on spray irrigation and crop failure for both irrigated and rainfed crops. Further, the lifting of root crops in the autumn becomes difficult as moist soil protects the crop from bruising. Subsequent cultivation and crop establishment could also prove difficult, in some cases resulting in autumn crop establishment failure and subsequent impacts for crop production in the following year.

4.2.3 Flooding and soil waterlogging

The Foresight Flood and Coastal Defence Project (Evans et al., 2004a) viewed agricultural impacts as a receptor not as a driver of flooding and defined flooding as the impact of flooding and associated high water tables on farm and forestry land and associated managed habitats. Seasonality and the duration of flooding are critical factors that affect the impact of flooding and waterlogging on agriculture and forestry (Evans et al., 2004a).

The most common sources of flooding are from rivers arising as a result of heavy rainfall and in coastal locations due to high tides and stormy conditions. The impact of heavy rainfall and whether or not flooding arises is dependent on field capacity status, soil type and geology. There is a greater risk of flooding on clay soils, which represent almost half of English soils. On agricultural land, previous cropping, drainage systems, and the presence of hedges and ditches and their status will also have an influence, the latter having been lost to create larger, better shaped fields.

Further, intense short duration rainfall can lead to local flooding and surface runoff, where rainfall exceeds the soil infiltration rate, land and watercourse capacity. In livestock enterprises, grassland management has moved towards more permanent species and increased yield and dry matter content. This has led to increased stocking densities and can lead to soil compaction and damage through poaching and thus increased surface water runoff caused by lack of infiltration of water into the soil. In arable enterprises, surface runoff has been exacerbated by the switch from spring to winter sown crops, with (i) the fine seedbeds of autumn drilling meaning that the interception potential of over-wintered stubbles has been lost, and (ii) cultivation by heavy machinery causing degradation of the soil structure and compacted soil.

These changes in cropping have been facilitated by the advent of field drainage, providing an outlet for excess water, lowering the level of saturation and reducing waterlogging (see, for example, Bradbury and Kirby, 2006). These authors state that better drainage improves access to fields and allows an increased length of time in the year when heavy machinery can be used on the land, soils can also be cultivated with greater ease thereby reducing cultivation costs, more effective fertiliser and manure use is also facilitated, and better drainage encourages better plant development via better rooting, thus reducing susceptibility to disease and ultimately leading to higher crop yields for both arable and grass. On grassland the length of the growing season is also increased.

The implications of surface runoff, flooding and waterlogging include a reduction in the value of crop and livestock outputs due to damages or productivity losses, increased costs to mitigate or defend against the risk of flood and waterlogging, and ultimately a loss in value-added associated with a switch to less intensive, flood tolerant land uses, for example, from arable to grassland, or from intensive grassland to less productive extensive grassland systems. Additionally, more erratic rainfall events exacerbate the risk of soil erosion and nutrient loss particularly in the autumn when these are not being taken up by the growing crop.

There have been an increasing number of flood events over the last 10 years, most usually in the autumn and winter months. The autumn months of 2000 are some of the wettest on record, with further events occurring in 2002, 2004, 2005, 2008 and 2009. Flooding can also occur in the summer months, the most notable recent event during the summer of 2007.

Crops are sensitive to excess water and anaerobic soil conditions during critical growth periods with consequences for yield, quality and value. The impact of flooding varies considerably according to tolerance of the particular crop to excess water and the seasonality, frequency, duration and depth of the event (Morris and Hess, 1988).

Reviews of the wet autumn of 2000 (ADAS, 2001a) and the summer floods of 2007 (Posthumus et al., 2009; see also Rural Economy and Land Use, 2010) are summarised here to illustrate the impact of these two different, but similar, events on the agricultural sector:

The impact of heavy autumn/winter rainfall depends on the underlying soil type. On sandy soils the impact may be small but workability can be affected leading to an increased risk of surface compaction, soil erosion and poor soil management conditions. On clay soils the impact is more severe with an early return to field capacity, high winter water tables, and exceptionally poor soil working conditions. The flood risk is also greatest on clay soils, exacerbated by poorly maintained old permanent underground pipe drainage systems and the trend towards longer time intervals between renewal of secondary drainage systems (i.e. mole drainage, subsoiling).

In the review of the wet autumn of 2000 the key issues highlighted by ADAS included implications for grazing for livestock, harvesting vegetable and root crops, ploughing and cultivations, and sowing of winter crops.

Where rainfall is high, grazing livestock can cause damage (poaching) of grassland, leading to poor utilisation and consumption of grass, and damage to the underlying sward, and also a lower quality of herbage used for silage making. Both low quality grazing and poor winter forage quality affect livestock performance. High rainfall may also mean that animals need to be housed earlier, with implications for feed and bedding and extra costs incurred.

The impact on the individual livestock enterprises as a result of the wet autumn meant the following:

- Cattle (grazing) – herds were brought indoors earlier, and there was an increase in feed costs
- Sheep – autumn lamb production was reduced
- Pig – for indoor systems there were difficulties in spreading slurry, outdoor systems were also affected by the wet weather
- Poultry – it was suggested that free range birds were reluctant to leave housing, which could potentially mean poorer bird hygiene and also poorer egg quality

For crop enterprises there were implications for harvesting and the establishment of subsequent crops.

In terms of harvest the following impacts were noted:

- Cereals – increased drying costs
- Spring oilseed rape – high drying costs made the crop unprofitable
- Vegetable quality – reduced
- Field peas – disrupted harvest in the north (later harvesting than southern regions) led to poor yields
- Winter and spring beans – more resistant to weather damage than peas
- Sugar beet – very difficult conditions for harvesting with increased costs primarily associated with lifting the crop
- Potato – disrupted harvest, including increased costs with some of the crop downgraded, dumped or sold for cattle feed, and some of the crop not lifted and abandoned
- Field vegetables, brassicas – yields were depressed, with some crops not harvested because of flooding, quality was also affected, partly because wet weather limited pesticide application opportunities
- Field vegetables, roots – crops were lost due to flooding (e.g. carrots), or not harvested due to continuing wet weather (e.g. onions), and overall costs of harvesting and market preparation increased

- Top fruit – benefited from an improvement in volume but harvesting was slow, expensive and prolonged, e.g. conditions meant that cider fruit normally machine harvested had to be hand harvested
- Soft fruit crops – those grown in the open were unmarketable and harvesting was impossible due to poor fruit quality, high levels of disease and extensive mud; under polythene quality deteriorated because of high humidity
- Protected crops under glass – there were lower yields, extra fuel costs, increased disease levels, reduction of demand for produce, and localised effects of flooding and storm damage
- Container grown nursery stock – disruption to autumn spray programmes, nutrient leaching, lack of acclimatisation for cold winter, and reduced consumer demand

The subsequent establishment of winter sown crops was hindered by the few opportunities for field operations. Additionally, the damaged soil structure as a result of working on wet soil led to the requirement to plough rather than minimally cultivate as the wet weather continued. This increased the risk of soil erosion with localised in-field losses during heavy rainfall periods, and the associated loss of phosphorus and leaching of nitrates, sulphur and pesticides.

In terms of the establishment of subsequent crops the following impacts were noted:

- There was a smaller area of winter sown crops, with an increase in the area of spring sown crops
- In the autumn, localised flooding and ponding led to patchy establishment
- In certain situations seed was broadcast rather than drilled, and there was subsequent seed loss due to waterlogging
- Early established oilseed rape unaffected, later established oilseed rape and winter cereals experienced problems but recovered due to favourable growing conditions in the following spring/summer
- Where crops were established early they were more pest and disease prone, slugs were a particular issue, aphids less so
- Spraying for disease and weed problems was made more difficult due to trafficability difficulties for the application of autumn pesticides and early spring fertilisers

As a result of the impact on livestock enterprises, harvesting difficulties, increased establishment costs, and reduced yields/output in the following year, there were also detrimental financial effects across the whole industry and as a result various adaptations, as follows, were raised:

- Alongside the need to deal with changes in mean climate conditions, there is recognition that there is a need to also consider the impact of extreme events
- Livestock farmers should conserve more forage
- Flexibility (timeliness and speed) is required for harvesting and cultivations, with the plough potentially providing more flexibility in wet conditions than minimum tillage
- Investing in new machinery systems for both harvesting and cultivations may be a possible future requirement
- Flexibility is also required in switching between autumn and spring sown crops, specifically where an autumn crop cannot be established
- Early autumn establishment and drier summers facilitate earlier harvest, however, there will be an increased need for spring crops to break the grass weed cycle; conditions may be warm enough for sunflowers and maize but there are questions as to whether they can be successfully sown and harvested with wetter spring and autumn conditions
- Wetter autumns, and difficulties of harvesting on heavier soils, force potato and sugar beet production onto lighter soils, however, drier summers mean an increased need to irrigate which raises the question of the availability and viability of water for winter storage
- In certain areas there is a need to recondition field drainage systems

- Cropping systems which minimise bare or compacted soil in the autumn should be encouraged
- Fertiliser and spray policy with regard to P, N, sulphur and pesticides losses and, for example, an increase in the slug population needs careful consideration

Short duration flooding in winter, after establishment, may have a limited impact on grassland and cereals. A flood event in summer, however, could completely destroy a crop of grass or cereals ready for harvest.

In the summer floods of 2007, at the sites reviewed by Posthumus et al. (2009), water stayed on farmland for around 2-3 weeks and land remained waterlogged for a further month. The most frequently reported impacts were loss of income from livestock, crop damage and yield loss, and debris clearing. For a minority there was also damage to buildings, equipment, drainage and field boundaries. Non-farming income activities were also disrupted.

In the livestock sector, there was lost summer grazing and a reduction in conserved grass (hay, silage) for subsequent winter feeding leading to the extra purchase of feed and increased feed costs. Costs were also incurred as a result of moving livestock, providing additional housing, increased treatment costs, increased need for slurry disposal, and additional labour. Investment was also required for reseeding of pastures and repairs to fences, gates and hedges. In the dairy sector milk production was reduced and across all enterprises livestock were lost.

The largest losses, in terms of area, were on general cropping farms, with the lowest losses occurring on mixed farms and for improved grassland. However, the highest overall financial losses were incurred in the horticultural sector due to the high value nature of the crop although a smaller area, in comparison to the acreage of general cropping, was affected. The main impacts on the arable sector were crop loss, yield and quality reduction from flooding and waterlogging of fields, increased costs associated with the use of additional inputs, delayed harvesting and increased harvesting costs, delays to other field operations and costs associated with land reinstatement. In some areas, it was not possible to sow winter crops or plant crops in the spring as these areas were still waterlogged. In these and other areas, it is suggested that soil compaction and a reduction in the worm population would suppress yields for a number of years after the event.

More generally, across all enterprises, repairs to farm infrastructure were required and there was a general need to remove debris. This included repairs and removal of buildings and their contents, machinery, farm tracks, field boundaries, field drainage, ditches and culverts, and irrigation equipment.

Adaptations considered, and in some cases adopted, as a result of the summer flood included:

- Improvement/restoration of drainage and/or flood defence
- Securing a sufficient stock of forage as a buffer for livestock feed
- Reduction in herd size
- Converting arable land to grassland
- Replacing crops susceptible to flooding
- A move away from winter cereals and potatoes
- Entrance into an agri-environment scheme

In summary, the heavy rainfall and associated flooding and waterlogging of soil have implications for both livestock and cropped enterprises. Generally, there are reduced yields with implications for productivity and quality of produce. The extent of the impact, however, depends upon soil type, the nature of the enterprise and the time at and duration over which the event occurs and, as with the impact of drought given in the previous section, the implications go beyond the immediate impact to have an influence on the productivity of future livestock enterprises and cropping systems.

4.2.4 Spatial and temporal variability

In addition to comments made in the previous sections, it is important to observe that significant spatial and temporal differences exist across England.

As stated previously, approximately 40% of the water abstracted for agriculture is for livestock enterprises (ADAS, 2006), however, this is in the western regions of England where there is less pressure on water supplies than in the east. Furthermore, abstraction generally occurs consistently across the year. Nevertheless, there is an increasing need to reduce and make more efficient use of water supplies and there may be opportunities to store water at times of excess for use in drier periods.

Another 40% of the water abstracted for agriculture is for field vegetables. For example the biggest demand for spray irrigation is in East Anglia, where abstraction can average 20% of total for all uses over a typical summer (EA, 2008b). Indeed irrigation is needed at times of low rainfall when abstraction can exacerbate already low flows (EA, 2006a). The demand for irrigation is concentrated when water resources are most scarce and are often concentrated where further opportunities to abstract water are limited (E.Anglia, E.Midlands) (EA, 2009). Even in a dry year such as 2003, only 1-2% of total water abstraction in England and Wales was for irrigation of outdoor crops, which, although almost negligible in volumetric terms, it is a consumptive use, concentrated in the drier catchments in the driest months, and can be the largest abstractor in some catchments in dry summers (Knox et al., n.d.).

In general, spatial and temporal differences notwithstanding, climate change could have a double impact on average water availability – decreased availability for abstraction (and indirect moisture availability) and increased demand for water. Irrigated horticulture represents only 1% of water use nationally but during times of drought, irrigated production is last in line when it comes to water with other users – domestic, industrial, and the environment – all given preference (Knox et al., n.d.).

4.2.5 Summary

Agriculture occupies 70% of the land within England, with three quarters used for grazing livestock and one quarter for cropping. Within the livestock and cropping sectors, the most valuable enterprises currently are dairying and milk production and horticultural crops respectively, the latter occupying the smallest area of land. In terms of water use, abstractions are approximately 40% for livestock enterprises, 40% for field vegetables and 20% for protected and nursery crops. Abstractions for livestock occur in the west and are fairly evenly distributed throughout the year. Abstractions for cropping are concentred in the east and south and occur during the drier summer period. In order to abstract water, users require an abstraction licence. Data on licences suggests that the amount of water currently abstracted is less than the number of and volume granted under the current licence system. However, the Environment Agency has recently completed an assessment of water availability through the CAMS process. This suggests that in many catchments there is limited water availability and in some cases catchments are over-licensed or over-abstracted. Thus, although abstractions in a number of areas may be less than the licences allow they may still be greater than the available water resource. In the four case study sites chosen for this study, three do not have water available during periods of low flow and demand may exceed supply.

Climatic extremes such as the hot dry summer of 1995 exacerbate water availability problems. This can lead to problems in both livestock and cropping enterprises. For livestock, forage production is reduced and alternative feed may need to be found even though livestock naturally reduce their feed intake. Demand for drinking water also increases. Overall, productive output falls. The impact on the cropped sector depends upon the type of crop, for some there may be yield and quality benefits, for others reduced water availability can lead to crop failure or reduced quality products. The establishment of subsequent crops may also be problematic.

At the other extreme, flooding and waterlogged soils can also reduce productivity in the agricultural sector. The extent of the impact depends upon the soil type, with a greater degree of risk on clay soils, the tolerance of the particular crop to excess water, and the seasonality, frequency, duration and depth of the event. Later autumn and winter flooding can have implications for grazing livestock with increased housing and feeding costs and a reduction in autumn lamb production. For cropping, problems arise with the harvesting of vegetable and root crops with reductions in both yield and quality, and the establishment of winter sown crops leading to soil damage and, in subsequent years, yield and output reductions. However, short duration flooding in the later winter may have only a limited impact on already well-established grassland and cereals. Summer flooding can have more major impacts. It will reduce livestock output through lost summer grazing and forage conservation giving rise to additional housing and feed costs. For crop enterprises there are losses in yield and quality as well as the possibility of complete crop failure.

4.3 Impacts of climate change

This section provides a review of the potential impacts of climate change on water for agriculture. It begins by assessing changes in water availability and use, and then goes on to consider implications in terms of droughts and flooding.

4.3.1 Projected changes in water availability

The changes in temperature, precipitation and potential evaporation discussed in Section 3 were used to run the hydrological model to produce probability distributions of potential river flows in the future under conditions of climate change. Interpretation of these changes in flow characteristics allows us to infer changes in water availability and the occurrence of drought and flooding. The probability distributions of climate variables indicated that under the UKCP09 climate scenarios there was a very broad range of potential changes, with low to high increases in temperature and potential evaporation, and a range of decreases and increases in precipitation. These changes varied with location, season and time period which may produce potentially complex flow responses. Figure 4.2 shows the probability distribution curves for annual runoff, winter runoff and summer runoff for all four study sites for the 2020s and 2050s. Figure 4.3 shows the probability distribution curves for Q_5, Q_{50} and Q_{95} for all four study sites for the 2020s and 2050s.. A Q_{95} flow is the flow equalled or exceeded 95% of the time and therefore indicates a low flow rate. Q_5 is only equalled or exceeded 5% of the time and indicates high flow rates. A Q_{50} flow is a flow that is equalled or exceeded 50% of the time and indicates an average flow condition. Table 4.6 summarises the distributions for the four study sites. Throughout this discussion, it should be remembered that the primary indicator is the 50% probability level. However, given the considerable uncertainty in climate estimates, to fully interpret the results it is necessary to consider the 10% level (change is very unlikely to be less than this) and the 90% level (change is very unlikely to be more than this).

2020s 2050s

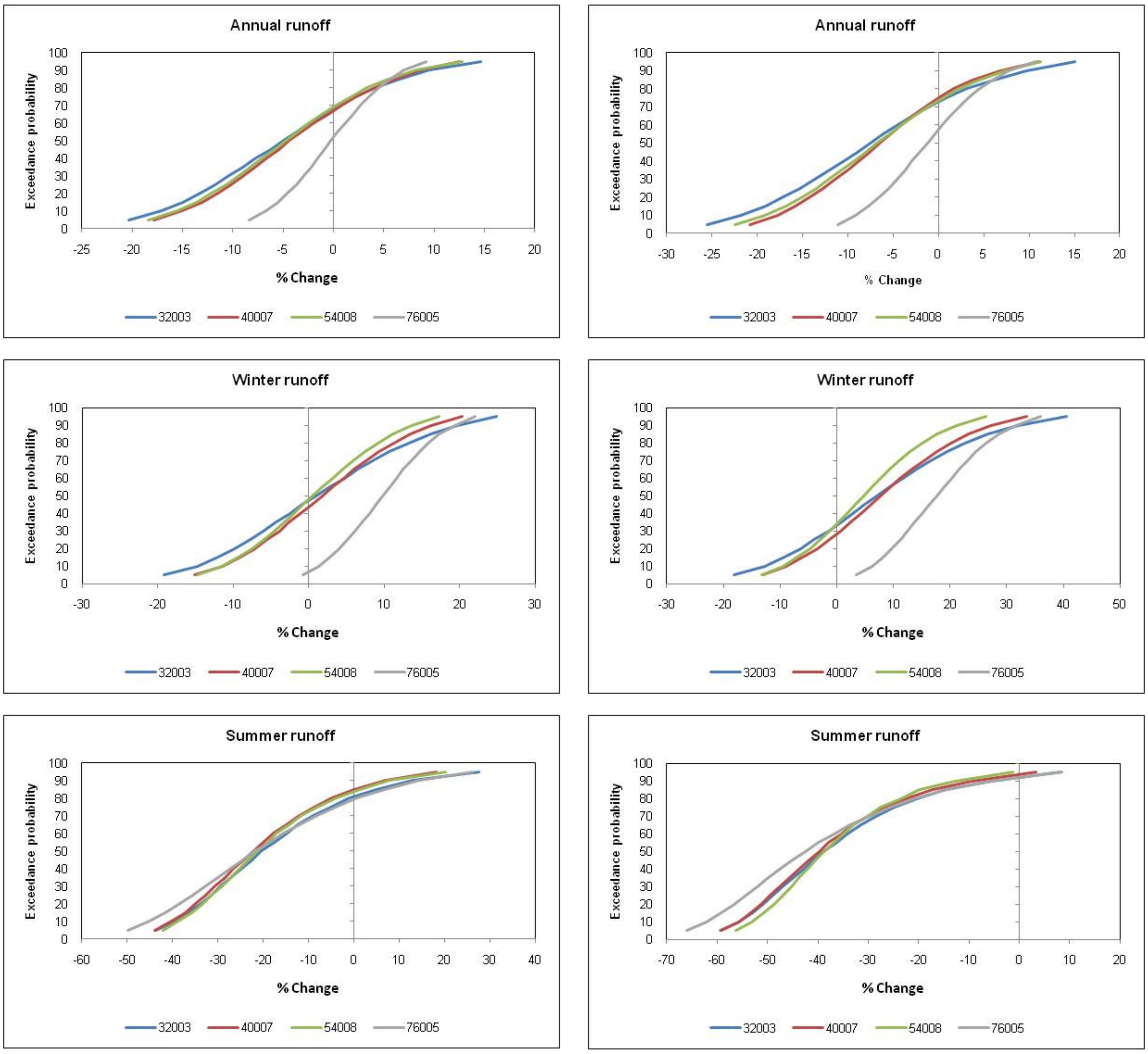


Figure 4.2 Probability distribution of change in annual and seasonal runoff characteristics for the four sites for the 2020s and 2050s relative to baseline.

2020s 2050s

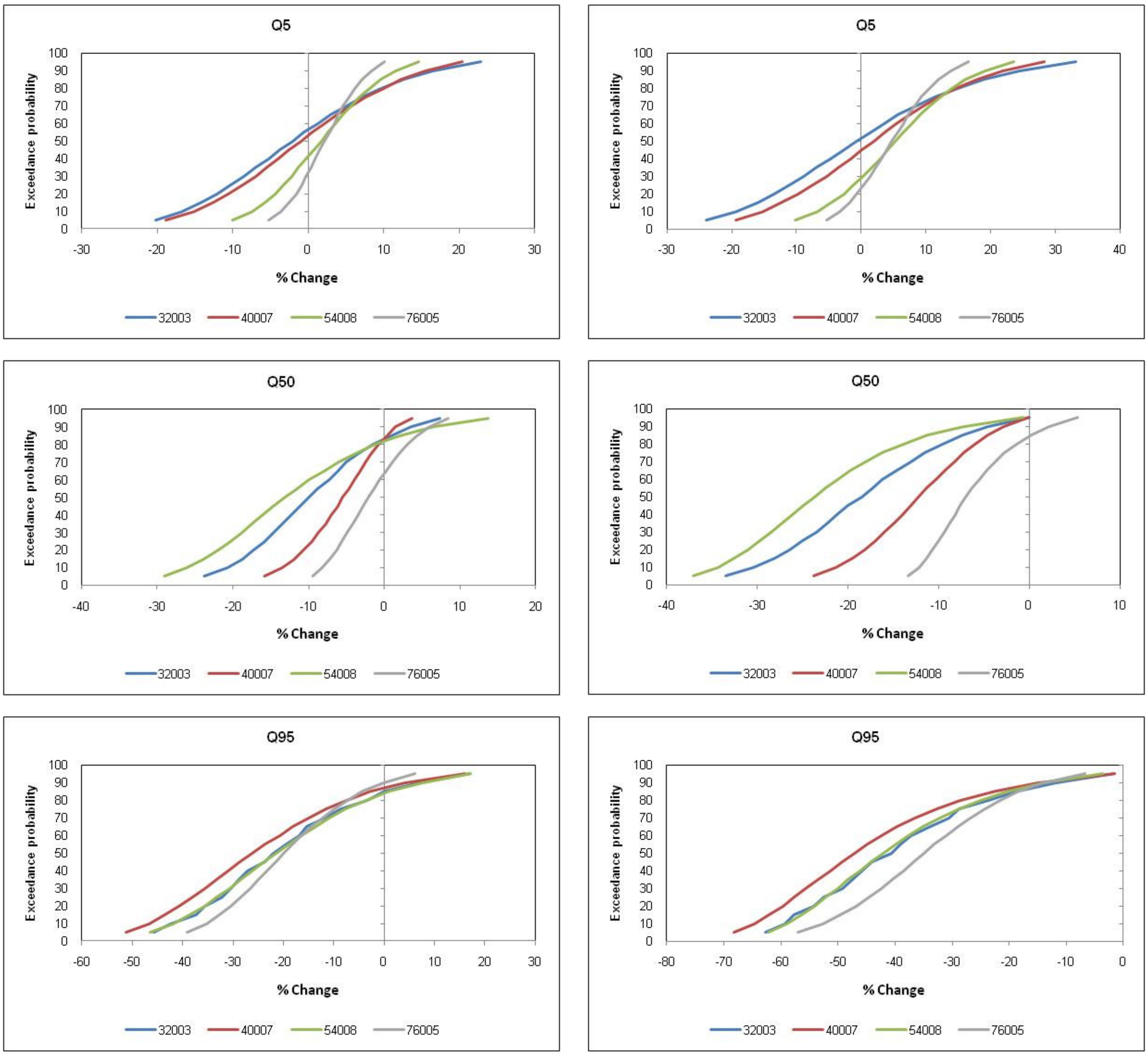


Figure 4.3 Probability distribution of change in flow statistics (Q5, Q50 and Q95) for the four sites for the 2020s and 2050s relative to baseline.

Table 4.6 Summary of changes in flow characteristics for the four study sites.

Change in Variable	Year	Probability Level	Harpers Brook (1472)	Medway (1706)	Teme (1427)	Eden (1040)
Runoff	2020	10	-17.1	-15.1	-15.5	-6.7
		50	-5	-4.4	-4.7	-0.3
		90	9.5	8.6	8.2	7
	2050	10	-21.8	-17.8	-19.2	-9.2
		50	-7.5	-6.5	-6.8	-1.2
		90	9.6	6.8	7.3	7.7
Rainfall	2020	10	-5.5	-4.5	-5.1	-2.1
		50	0.8	1.2	0.5	1.9
		90	7.4	7.4	6.6	6.3
	2050	10	-8.3	-6.1	-7.2	-3.4
		50	-0.6	0.6	-0.5	2.2

		90	8.3	7.9	7.0	8.3
Winter runoff (DJF)	2020	10	-14.8	-11.5	-11.6	1.3
		50	0.9	1.8	0.5	9.8
		90	19.6	16.1	13.6	19.3
	2050	10	-12.8	-8.9	-9.5	6.2
		50	7	7.7	4.7	17.6
		90	31.9	27.1	21.1	31.5
Summer runoff (JJA)	2020	10	-39.5	-40.3	-38.8	-45.1
		50	-20.5	-22.1	-21.3	-21.8
		90	12.9	6.9	7.8	14.2
	2050	10	-55.7	-55.8	-53.1	-62.2
		50	-39	-39.8	-38.8	-42.5
		90	-5.7	-9.6	-12.8	-5.8
Q5	2020	10	-16.8	-15.2	-7.5	-3.6
		50	-2.1	-1	1.7	2.1
		90	16.4	15.5	11.5	8.3
	2050	10	-19.4	-15.2	-6.8	-3.3
		50	-0.8	1.9	5.3	4.7
		90	24.4	21.9	19.1	13.8
Q50	2020	10	-20.8	-13.5	-26.1	-8.2
		50	-10	-5.5	-13.1	-2.1
		90	3.5	1.5	6.5	6
	2050	10	-30.4	-21.3	-34.3	-12.1
		50	-18.5	-12.2	-23.7	-7
		90	-4.6	-2.8	-7.2	2.2
Q95	2020	10	-42.4	-46.7	-41.8	-35.2
		50	-22	-26.2	-21.4	-19.9
		90	6.8	4.1	7.6	-0.1
	2050	10	-59.3	-64.6	-59	-52.7
		50	-40.7	-47.2	-42.1	-35
		90	-11.9	-15	-14	-14.1

The distributions show three aspects:

1. A general reduction in flows.
2. An apparent increase in flood magnitude / likelihood / risk.
3. At the other extreme a much larger increase in drought magnitude / likelihood / risk.

In general, annual runoff decreases for all sites and all years at the 10 and 50% levels, but increases at 90%. At the 50% level, all sites show an overall annual reduction in runoff of about 5% by the 2020s, with the exception of Eden which remains virtually unaffected by a change in annual runoff. This site is the northernmost of the four sites and as such already receives much more rainfall than the other sites. The probability distributions all show generally the same range with this increasing from the 2020s to the 2050s as a result of larger reductions in annual flow (and therefore moisture availability). Although the distributions for each site begin to differentiate in the 2050s Eden demonstrates a much narrower range than the other sites and a much steeper distribution. Such estimates of flow changes are consistent with previous work. For example, Arnell and Charlton (2009) modelled the impact of UKCIP02 scenarios on Medway flows in the 2020s. Climate scenarios characterising change in mean monthly rainfall, temperature and potential evaporation were created from the UKCIP02 scenarios (Hulme et al., 2002) and five additional climate models (ECHAM4/OPYC, CGCM2, CSIRO MKII, GFDC_R30 and CCSR/NIES2). By the 2020s, average annual runoff in the Medway catchment is reduced by between 11% and 13% under the UKCIP02 scenarios; under the other scenarios, the change in average annual runoff varies from a decrease of 18% to an increase of 14%. For the current work estimates for Medway range from a reduction of about 15% to an increase of about 9% suggesting that the UKCP09 scenarios capture much of the uncertainty suggested by using a broad range of climate models. However, at the 50% level under UKCP09, the loss is only 5.5% and results using the UKCIP02 scenarios correspond more closely to the 10% level with a reduction of 13.5%. Thus the newer scenarios would appear to be less severe in their losses and the UKCIP02 scenarios would seem to be at the drier end of the UKCP09. However, the newer scenarios facilitate greater understanding of the potential range of impact. Arnell and Charlton (2010) came to a similar conclusion regarding the comparison of the UKCIP02 and UKCP09 scenarios in a case study conducted for the Environment Agency using Harpers Brook.

The differentiation in the curves is not manifested in the summer runoff. During this season, Eden shows the greatest range in possible reductions in water flow (up to 62% reduction by 2050s). At the 50% probability level flows can be expected to be reduced by about 20-22% for all sites by the 2020s and by about 39-43% by the 2050s. Increases (of between 6-14%) in summer runoff are possible at the 90% level in the 2020s, indicating the large range of uncertainty associated with these estimates. Conversely, the differentiation is exaggerated in winter, with this northernmost site consistently showing increases in winter runoff, compared to the other three sites which all show a range of reduced to increased runoff in winter. Thus, the annual pattern for Eden masks the more extreme seasonal shift at this site, indicating greater potential for winter flooding and summer droughts. The range of winter runoff change is between a reduction of about 15% to an increase of about 32% depending on the site, time period and probability level. This is a smaller range than for summer runoff. At the 50% level winter runoff increases very little by the 2020s for all sites, whilst summer runoff decreases significantly for each site.

The implications of these results is that there will be an overall reduction in river flow and water availability at each site throughout the year but this is a consequence of small increases in winter runoff and large decreases in summer runoff. These results are consistent with most findings suggesting decreases in annual flows but with significant seasonal differences. This is itself consistent with the changes in seasonal rainfall and potential evaporation characteristics. However, to be able to imply an increased chance of high or low river flows we need to look at the other flow characteristics, which can be summarised as:

- Q5 in general shows small increases. By the 2020s high flows change between a reduction of 2.1% and an increase of 2.1%, with variation between sites. It is possible to see substantial increases in Q5 (up to 16.4 %) and these appear greater in the mid- and southern catchments. In the northern catchment the increase is only 8.3%, perhaps because it already experiences considerable high flows.
- Q50 shows reductions although there are some site differences. Furthermore, this average flow condition increases in 2020s at 90%.
- Q95 shows significant reductions except in 2020s at 90%. Reductions can be up to 47% in the 2020s and the difference between sites can be considerable.

The magnitude of change in Q95, is perhaps more worrying, given that it consistently shows significant reductions in both 2020s and 2050s except at the 90% level in 2020s. Reductions in Q95 imply two impacts that are important for agriculture. First, the amount of water flowing in a river at the indicator low flow is getting significantly less. Thus there will be much less water available for all users. Second, the change in the flow duration curve towards such reductions also means that flows in general will be reduced. The confusing picture for high flows implies that the flow duration curve at some sites will become stretched. In some cases the indicator flow will increase in volume and so too will other high flows. In other cases there will be a reduction. In other words, there is the potential for increased flooding or waterlogging at Teme and Eden (at the 50% level).

It is important to note that the distributions are not consistent at the different sites, as was shown for the annual and seasonal runoff characteristics. Again it is the Eden which appears to be the most different, with a different pattern most often. For the sites chosen there appears to be a tendency towards more significant ‘drying’ than ‘flooding’ throughout a year. Overall the results indicate that there will be less water available. There will be less available for direct abstractions and also for indirect uses. Soil moisture will be affected as a direct consequence of reduced rainfall and increased evapotranspiration as indicated by the reduced flows. The pressure to irrigate may increase but the amount of water available for irrigation may actually decrease, especially during the summer when irrigation demand is greatest but the water availability will be least. Furthermore, with reduced flows, other abstractors of water will come under increasing pressure. In particular, water companies, who provide the mains water used on farms, will be significantly affected. For example, Charlton and Arnell (2010) show that water companies estimate reductions in deployable output of greater than 50% over the next planning period (to 2034/35). This may most dramatically affect dairy farms, who rely heavily on mains water (see earlier discussion). Likely consequences may include increased restrictions on use and increased water prices. One major implication of the results is increased chance of abstraction restrictions (as a result of more low flows); these restrictions can have very high financial impacts (Knox et al., n.d.).

These problems will be exacerbated by the seasonal patterns observed. Median values indicate very small increases in winter rainfall (runoff?) in 2020s, increasing into the 2050s but much larger decreases in summer rainfall (runoff?) that almost double between the 2020s and 2050s. Thus drought may be a bigger problem. The results show significantly less water available in the summer because summer rainfall is so much more dramatically reduced than winter is increased. Thus the limitations discussed above will be acutely realised during the summer. Whilst the literature is heavily focused on flood defence issues (see later), it would appear that drought may be a more significant problem. As such, solutions for flooding that may increase water availability (through storage?) may be indicated as preferred. Furthermore, a drive to reduce demand and water use efficiency may be necessary in order to more effectively use reducing water supplies. These changes are not in themselves small but if added to existing extremes severity may be significantly increased. For example, Knox et al. (n.d.) suggest that average years in the future will become much more extreme, and more typical of our current “very dry” years.

The flow characteristics discussed above do not directly give us an indication of one very important aspect of agricultural water availability, soil moisture. River flow is based upon the interaction of the supplied water (rainfall), its losses (evaporation, abstractions etc) and its storage so that lower river flows can be taken to indicate less soil moisture. In this context, the modelling results not only generally indicate less water available for abstraction (and irrigation), but also less water available for land-based storage and less water available in the soil, particularly during the summer months. An alternative way to view this information is through the soil moisture deficit. Using the UKCIP02 scenarios, Knox et al. (n.d.) produced agroclimate maps that show how potential soil moisture deficits (PSMD) may change in the future. PSMD is the potential accumulated soil moisture deficit that builds up through the summer months and reflects the daily balance between summer rainfall and evapotranspiration, which are the main drivers of irrigation demand (Knox et al., n.d.). Figure 4.4 reproduces the Knox et al. (n.d.) agroclimatic maps for their baseline condition and for the 2020s and 2050s. They show how the drier zones generally increase in area and spread from the south and east towards the north and west, with the most critical zones where irrigation needs are greatest including parts of Suffolk, Kent, areas in West Midlands, Nottinghamshire, and the south coast. Knox et al. (n.d.) show that these changes are likely to have serious impacts on outdoor horticultural crop production; particularly those sectors dependent on water for irrigation. Another important aspect of the work is that the years in which the PSMD are highest correspond to drought years in which irrigation demands were highest (e.g. 1975-76, 1989-90, 1995-96 and 2003) (Knox et al., n.d.). Their overall conclusion is consistent with our modelling work that in the future we are likely to experience more frequent summer droughts and hence an increase in irrigation demand as a result of higher summer temperatures, lower summer rainfall, and higher evaporation. However, they view the prediction of wetter winters as a positive sign because they may increase the opportunities for storing water when stream flows are high (Knox et al., n.d.). However, there are two further points. First, the modelling results indicate that one consequence of the higher winter rainfall may be increased flooding. This will depend on local site conditions including soil and land use and existing methods for addressing flooding issues. Second, these maps were produced using the UKCIP02 scenarios and whilst there is some consistency between these and the UKCP09 scenarios, there is a far greater range of possible change in the latter. It is therefore necessary to conduct further studies on changes in agroclimates using the latest climate scenarios.

Baseline | **2020s High Scenario (UKCIP02)** | **2050s High Scenario (UKCIP02)**

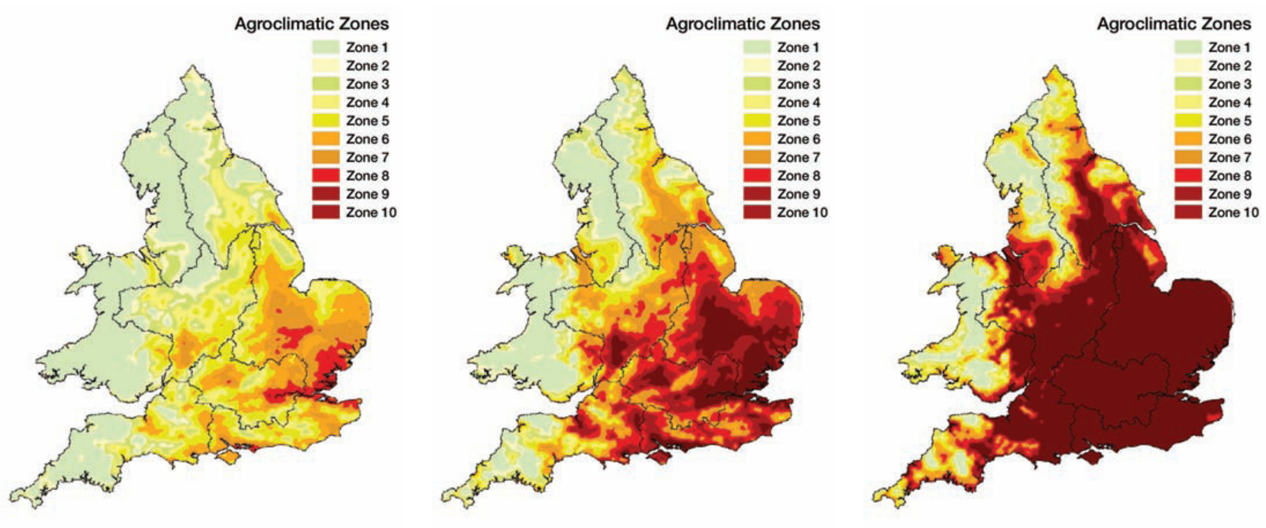


Figure 4.4 Predicted changes in summer agroclimate from the baseline to the 2020s and 2050s using the UKCIP02 High-emissions scenario (taken from Knox et al. (n.d.)).

4.3.2 Implications for agriculture in general

The modelling results, as with other climate change work, indicate a tendency for increased temperatures and evapotranspiration at all four case study catchments, with increase in precipitation by the 2050s for the Medway and Eden catchments but reductions for the Harper's Brook and Teme catchments, however at all catchments in any one year the reverse could be true.

The review of outputs from Defra's climate change research programme (Hopkins, 2005) suggests that most farmers will be able to maintain their existing crop and livestock enterprises. Research by IGER (2003) for example suggests that there will be no change in the relative suitability of areas for livestock enterprises, although there will be some change in ruminant livestock distribution. However, climatic extremes, such as droughts and wet weather (heavy rainfall and flooding) will increase in frequency and present greater risks but these are within the experience of most farmers. New opportunities will also be presented. Thus, the impact of changing weather is recognised but is not yet at a frequency to require significant change (Hughes et al., 2008).

Results for the four catchments suggest a tendency for more drying than flooding. There is thus an increased chance of drought but also an increased flood risk. In more detail, runoff is generally reduced at all sites, and this is particularly the case for summer runoff. The winter runoff results indicate slight increases at three of the catchments with a greater increase at the Eden catchment, but this does not outweigh the summer reductions. Overall, this indicates a tendency towards reduced river flows and water availability, including soil moisture and therefore a greater risk of drought at all sites. Similarly, all catchments have the potential for increased flooding or waterlogging, but this is particularly the case for the Eden catchment and also the Teme catchment.

Previous research on the impacts of climate change on the grazing livestock sector suggest that warmer wetter springs will mean that grass growth will start earlier and continue for longer (ADAS, 2001b; IGER, 2003; SAC Commercial Ltd, 2009) with associated changes in sward botanical composition and productivity across the country (Topp and Doyle, 1996a, 1996b). Higher stocking rates may be a possibility as yields and dry matter will increase (SAC Commercial Ltd, 2009) particularly in western areas of Britain, such as the Eden catchment, where dairying is predominant (IGER, 2003). However, this increase in grass growth will occur earlier on in the growing season, with lower yields later on (IGER, 2003; SAC Commercial Ltd, 2009) particularly in the summer in the south and east on lighter soils (ADAS 2001b) such as occurs in the Medway catchment. The extent of yield increase/declines will be dependent on available nitrogen and water resources (SAC Commercial Ltd, 2009). As a result of these changes in growth period there are implications for seasonal and total feed availability, and also quality. Animals could be outside for longer; allowing a reduction in the need for housing and access to conserved forages, but wet springs and autumns could in practice reduce the number of grazing days (SAC Commercial Ltd, 2009). This would certainly be the case for the Eden catchment and also possibly the Medway catchment. Thus, extended grazing may not be possible as a result of both limited growth in the latter part of the growing season and wetter autumns increasing the risk of poaching damage. There may also be problems with diffuse pollution (SAC Commercial Ltd, 2009). With a reduction in the number of grazing days at the end of the season, there may be a need to conserve more forage for indoor feeding throughout the autumn and winter period. Additional forage may also be required for outdoor supplementation at pasture in the latter part of the summer, particularly for example at the Medway catchment, although this will be the case for both upland, i.e. Eden catchment, and lowland, i.e. Medway catchment, cattle and sheep grazing systems. In short, changes will be required in both forage conservation and grazing management. Wetter autumns also present difficulties for reseeding of grass leys, and it will be a challenge to find grass species and varieties that can tolerate both wet winters and waterlogged conditions and dry summers (ADAS, 2001c). The type and balance of forage crops grown could also change (Topp and Doyle, 1996a, 1996b) with an increase in the use of alternative forages, particularly in the drier areas of England such as the Medway catchment where the emphasis could shift to legume based silage crops (IGER, 2003). There may even be a small reduction in the requirement for concentrates (SAC Commercial Ltd, 2009). For southern livestock farmers reduced summer grass growth could mean a small move to arable production, the forage maize area will also increase (ADAS, 2001b).

SAC Commercial Ltd (2009) suggest that impacts will be greater for grassland based livestock than pigs. For pigs, economic factors will have a greater impact on production than the weather (ADAS, 2001c). This is also likely to be the case for poultry.

For all livestock sectors, the gains overall need to balanced against possible greater frequency of years with reduced production due to climate induced problems (IGER, 2003). However, it is suggested that adaptation is within the capacity of industry, requiring only increased awareness and a slight shift in attitudes (SAC Commercial Ltd, 2009).

Previous research on the impacts of climate change on crop enterprises suggests that changes will occur as a result of wetter springs, drier summers, and the need for an earlier end to autumn fieldwork (ADAS, 2001b). For crop enterprises, the review of outputs from Defra's climate change research programme (Hopkins, 2005) suggests that warmer conditions associated with increased temperatures will have implications for the length of growing season giving rise to an increase in the rate of crop growth and maturation. This would be the case for the Harper's Brook (e.g. cereal), Medway (e.g. horticulture) and Teme (e.g. root crops) catchments. There is therefore an increased yield potential for the majority of crops (ADAS, 2001b) but also potential problems and increased costs associated with the over winter survival of pests and diseases (Hughes et al, 2008), for example, fungi are favoured by humid conditions (Warwick HRI, 2008). The increased frequency of extreme events will also result in a potential reduction in the control of weeds, pests and diseases (Warwick HRI, 2008).

Research also suggests that harvest dates for some crops will become compressed, for others the harvest window may be wider; some of the problems associated with these changes can be overcome through changing varieties (Warwick HRI, 2008). There could also be opportunities for new crops.

For winter wheat there could be changes in sowing date, rate of spring growth, ripening and harvesting date (Hopkins, 2005). For example, autumn sowing could be delayed to avoid excess growth and disease issues, but then the ground could be too wet to cultivate. Whenever the crop is established, spring growth would commence earlier, and the crop would ripen earlier, with a potential bigger canopy. Harvesting could also be earlier, although an alternative might be the introduction of slower maturing varieties (ADAS, 2001c). These changes have implications for the nitrogen and soil water requirement. Breeding for drought resistance would be an important avenue for research, particularly relevant to the Harpers Brook catchment. Some changes in pest and disease management will also be required.

For potatoes there is the possibility of earlier sowings, earlier harvesting and potential for higher yields (Hopkins, 2005). There may also be an increase in areas suitable for growing early crops but with the consequence of the loss of a niche market. However, there will be an associated increase in nitrogen and water requirements (i.e. irrigation), without these yield and quality will fall (ADAS, 2001c). This could be the case at the Harpers Brook, Medway and Teme catchments, but particularly for Harpers Brook and Medway. The need for water could lead to a shift of traditional potato growing areas towards the west and higher rainfall areas, away from the Harpers Brook and Medway catchments, although this gives rise to greater risk associated with aphids, wireworm and blight.

Similarly, there may be opportunities for earlier sowing dates for sugar beet with potentially increased yield and quality as a result of the longer growing season (Hopkins, 2005). There could also be an increase in the area suitable for producing sugar beet. However, as indicated by the modelling results, drought risk will also increase leading to a greater need for irrigation, and traditional sugar beet growing areas such as those around the Harpers Brook catchment may become too drought prone to produce the crop economically (Hopkins, 2005). Aphid pressure will also increase.

Unirrigated root crops on light soils in southern locations, such as at the Medway catchment, may have a small increase in yield, but yields could also decline (ADAS, 2001b).

Warmer climates also present opportunities within summer vegetable cropping sequences (Hopkins, 2005) as the warmer winters and high summer temperatures will mean earlier planting dates for summer annual crops (Warwick HRI 2008). This could be the case for the Teme, Harpers Brook and Medway catchments. Cropping programmes for crops such as cauliflower (Harpers Brook) will need to be amended to avoid gluts (ADAS, 2001c).

There could be new opportunities in the south, such as within the Medway catchment, for grain maize, sunflowers, grapes for wine, winter lupins and peaches (Hopkins, 2005). Maize will have a higher yield potential in an extended growing season, with more choice of varieties suitable for growing and a shift to slower ripening varieties. The area of production could extend northwards, with maize for silage preferred over grass and other forage crops. Sunflowers could become increasingly viable in parts of southern England, becoming competitive with winter oilseed rape (ADAS, 2001b). The potential growing season for grapevines could also increase with an associated improvement in quality (Hopkins, 2005).

Glasshouse crops will see reduced demands for heating and an increased need for ventilation. Consumer demand could also increase. For crops such as tomato there will be difficulties with timing of irrigation and harvesting (ADAS, 2001c).

4.3.3 Implications for agriculture of future droughts

Previous research by Wade et al. (2006) states that future droughts may be more severe than those currently used for water resource and drought contingency planning. In their study, the climate change scenarios suggest a 13-18 per cent reduction in yield for one reservoir by the 2020s although the impacts of climate change on reservoir storage and yield was less than the impacts on river flow and on direct river abstractions reported in water company plans. This illustrates the potential role of storage and seasonally variable licence conditions to balance increases in winter flows with reductions in summer flows due to climate change (Wade et al., 2006). Drought stress caused by higher evapotranspiration and reduced summer rainfall will probably override any growth benefits from the higher CO_2 levels, unless irrigation can be stepped up to compensate, however new regulations in the form of the EU Water Framework Directive (WFD) could restrict increases in irrigation (Thompson, 2007). As discussed above, the modelling results suggest reductions in water availability generally for all sites. These reductions are likely to be severe in the summer months. Furthermore, low flows will become considerably lower indicating that the chances of drought will be significantly increased and the opportunity to cope with the drying conditions will be reduced (e.g. no abstractions for irrigation). Being the most southerly catchment the Medway demonstrates the greatest reductions in future low flows at the 50% level in the 2020s, with Eden being least affected. However, these changes should be set within the context of the baseline flows and the potential uses of the water. For example, Eden has a much higher annual flow than the Medway and therefore the impact of reduced flows is likely to be less. For most of the country, drought occurrence will require adaptive action to ensure water availability and to maintain agricultural practice in the near future.

For grazing livestock enterprises, such as in the Medway and Eden catchments, drought has implications for grass yields with both an early summer and late summer/early autumn drought resulting in lower yields (Hughes et al, 2008). A mid summer drought may have little impact on grazing days but could reduce quality and consistency (SAC Commercial Ltd, 2009). There are also implications for silage spoilage (Hughes et al., 2008). The review of outputs from Defra's climate change research programme (Hopkins, 2005) suggests that summer droughts will provide more favourable conditions for forage legumes than grass production. This could lead to a shift from grass to non-grass forage production, such as maize (ADAS, 2001b), particularly in the Medway catchment. There are also potential problems with existing and new weeds, pests and diseases. For example, common grassland weeds cope well with warm spells (ADAS, 2001b).

Previous research by Holman et al. (2002) examining impacts in the North West region suggests that there will be a change from grassland to arable production and therefore a reduction in the grassland area, this might also be the case for the Teme catchment. With fewer requirements for irrigation than the south east the areas of sugar beet and potatoes could increase. Other break crops (proteins and oilseeds) may also be profitable.

Drought also leads to problems with the reliability of drinking water supplies for livestock (SAC Commercial Ltd, 2009) and issues of animal welfare and heat stress. This would be more acute in the Medway rather than the Eden catchment. Less dramatic impacts are decreased animal weight gain, loss of milk production, fertility problems and costs of controlling animal house temperatures (Hughes et al., 2008). An increase in moorland wildfires may also be problematic (Hopkins, 2005).

For arable production, such as takes place in the Harpers Brook catchment, the review of outputs from Defra's climate change research programme (Hopkins, 2005) suggests that the rise in average temperature translates into a higher yield potential, although this will have to be balanced against greater evaporation from leaves and soils, a greater water demand, and a greater drought stress risk particularly for crops with a high water requirement such as potatoes and sugar beet. Yields could be reduced and harvest delayed (Hughes et al, 2008).

Long term, where crops are grown could change, variety choice will be affected, and there will be changes in the timing of sowing and harvesting (see for example IGER, CCLIF and Centre for Rural Research 2002; also Hopkins, 2005; Hossel, 2002; Jackson Environment Institute, 2000; Rothamsted Research, 2004). Warwick HRI (2008) suggest that fast developing wheat varieties will be better suited to future climate change in order to avoid summer drought.

Increasingly dry summers will increase the need for irrigation of root crops in the south and east (ADAS, 2001b), i.e. Harpers Brook and Medway catchments, without irrigation yields will be less predictable. For example, an earlier sowing date for sugar beet could increase yields but the risk of drought will also mean an increase in yield range (Warwick HRI, 2008). Warwick HRI (2008) also state that the continuity of supply of crops is vulnerable to extreme events, with planting and crop establishment sensitive to periods of drought. Similarly, research by the Holman et al. (2002) examining impacts in East Anglia suggests productivity increases for crops such as potato and sugar beet, but with a greater need for irrigation. Provided adequate water resources are available then specialisation in cereals and root crops would occur. However, decreased water resources are predicted so this may not be the case, particularly for the Harpers Brook and Medway catchments, but also for the Teme catchment. This has implications for the continued production of sugar beet on light textured, shallow and very sandy, less water retentive, soils where sugar beet yields will remain small and become more variable (Hopkins, 2005; Hulme et al., 2002; Rothamsted Research, 2004). Such areas may become unsuitable for sugar beet production particularly if irrigation cannot be secured. However, on better soils yields could increase, although there will still be a need to breed for drought resistance, for example, rooting systems which are effective at acquiring water.

In addition to reduced summer rainfall and the increasing irrigation demand for potatoes, sugar beet and vegetables in the drier areas, a reduced water flow, as indicated by the modelling work, will also increase problems associated with pollution, eutrophication and the suitability of water for abstraction (Downing et al., 2003).

Finally, late summer and early autumn drought and lower soil moisture could also give rise to planting issues for autumn crops leading to reduced autumn establishment (Hughes et al, 2008).

4.3.4 Implications for agriculture of future flooding and waterlogging

The Foresight Flood and Coastal Defence (FCD) project (Evans et al., 2004) observed that the agricultural impacts driver is strongly linked to climate change with its potential to modify patterns of land use as well as increase flood risk.

The foresight project was national in scope and consequently agricultural impacts were viewed as low across all of the Foresight Futures, reflecting the small proportion of GDP generated by agriculture in the UK as a whole. This is not to say that local impacts are insignificant. From the 2050s onwards, the FCD project considered uncertainty in agricultural impacts to be ‘medium’ across all scenarios, reflecting the impact of changes in the motives of land managers and changes in agricultural and rural policy.

The Foresight FCD Project (Evans et al., 2004) showed that a change in flood risk can have three main types of impact on agricultural land at farm level:

1. Reduction in the value of crop and livestock outputs due to damages or productivity losses associated with surface flooding and or waterlogging.
2. Increased costs to mitigate or defend against the risk of flood and waterlogging.
3. Loss of value-added associated with a switch to less intensive, flood tolerant land uses, for example, from arable to grassland.

The current modelling results do not give an entirely clear picture of changes in future flooding. However, it is possible that flooding will become more frequent as the high flow volume increases. This is most likely in the winter months. It is the northernmost catchment (Eden) that appears to be most susceptible to an increase in flooding and waterlogging at the 50% probability level. However, at the 90% level, the other sites would appear to be considerably more affected. If such impacts were to occur it would be necessary to adapt to flooding. This may include allowing for loss of land particularly in coastal regions or on river floodplains.

For livestock farmers, such as those in the Eden, Teme and Medway catchments, the result of wet weather is poor quality of feed and increases in feed and other costs when livestock have to be housed for longer (Hughes et al., 2008). Modelling results indicate the greatest risk for the Eden and Teme catchments. Prolonged heavy rainfall also reduces access for field operations and can lead to cold stress in wet and windy conditions (SAC Commercial Ltd., 2009), more so in upland catchments such as the Eden. Reseeding of pastures may be needed when wet weather and/or flash flooding leads to crop failure or loss (Hughes et al., 2008). Increased mortality as a result of flash flooding may also occur.

For arable farmers, such as those in the Teme, Harpers Brook and Medway catchments, wet conditions and flooding reduce crop yields and quality, increase disease levels, lead to poor harvest conditions, increase the cost of drying, and lead to poor seed quality for the following year (Hughes et al, 2008). The modelling results indicate the greatest risk for the Teme catchment. In low lying coastal areas, field vegetable crops, such as cauliflower grown in Lincolnshire, will be at risk of salt intrusion from rising sea levels (Hopkins, 2005). Flooding and, more frequently, waterlogging in the autumn will be a problem for potatoes at harvest (Warwick HRI 2008). Late establishment of crops such as winter wheat should be avoided as intense rainfall in the winter period may have implications for seedling damage and water-logging in poorly drained soils and this could reduce yields (Hopkins, 2005; Hulme et al., 2002; Rothamsted Research, 2004). If it is too wet, repeat drilling owing to crop failure may be required (Hughes et al., 2008). This would also be the case as a result of flash flooding leading to crop loss. Increased soil erosion and loss in soil quality will also occur.

Morris et al. (2008) in their work assumed certain cost impacts of winter flooding for both grassland and arable crops. On improved grassland, such as may be found in the Eden and Teme catchments, short duration flooding of 1-2 weeks in mid-winter has little impact. They suggest a cost of £15/ha. Long duration flooding of two months or so, however, is likely to kill improved ryegrass varieties and require reseeding at an approximate cost of £200/ha. Repeated relatively short duration flooding would have a similar impact. Persistent long duration flooding of more than two months would encourage a switch to lower intensity land use. For arable crops, for example in the Teme catchment, winter flooding of more than a few days would destroy the crop and this would require reseeding with a lower yielding spring crop. A cost of £450 to £500 per hectare is suggested.

Finally, although not part of this work, it is worth noting that the review of outputs from Defra's climate change research programme (Hopkins, 2005) suggests that storm frequency will increase leading to greater soil erosion risk and flash flooding, physical damage to perennial plants such as fruit trees, lodging risk in arable crops, and even implications for building design (see for example IGER, CCLIF and Centre for Rural Research 2002; also Hopkins, 2005; Hossel, 2002; Jackson Environment Institute, 2000; Rothamsted Research, 2004).

4.4 Synthesis and summary

The key implications of the modelling results were as follows:

- A drop in annual river flows, with a large reduction in summer flows set against a proportionally smaller increase in winter flows, with the Eden catchment having the largest winter flow increase
- An increase in temperature and evapotranspiration, and thus a reduction in soil moisture availability

- A greater frequency of drought risk at all sites
- Central estimates indicate precipitation reductions in the Teme and Harpers Brook catchments by the 2050s, with increased rainfall in the Medway and Eden catchments by this time
- A greater frequency of flood/waterlogging risk at all sites, but to a lesser extent than the drought risk.

For grazing livestock enterprises the implications suggest little change in enterprise distribution across the country with the emphasis on changes in grazing management and forage conservation, and a change in the balance of different forages within the diet.

Warmer wetter winter and spring periods could increase grass production at the start of the growing season, with declines in hotter, drier summers towards the latter end of the season. There will also be changes in weed, pest and disease pressures for both crops and livestock.

In periods of extreme hot, dry weather, reduced water availability and drought, there will be reduced forage production, but also reduced feed intake by livestock and thus reduced productivity. This could also lead to fertility problems. Heat stress is also a possibility. There will be a need to provide adequate shelter and continued access to drinking water.

In periods of extreme wet weather, leading to waterlogging and even floods, problems will occur with access to land, poaching of pastures leading to sward damage, lower quality forage and poor utilisation by livestock, and thus reduced production. Cold stress as a result of rain and wind may also occur. Problems will also arise as a result of lost grazing and reduced conservation of forage. Livestock may need to be moved or housed, with implications for feed, bedding and slurry disposal, and there may also be increased livestock treatment costs. Reseeding of pastures may also be difficult.

For dairy and upland livestock enterprises such as those found in the Eden catchment, there will be benefits in terms of the potential for increased forage availability, but costs associated with the need to plan for the conservation of forage for summer buffer feeding and over the winter period. For lowland livestock enterprises such as those found in the Medway catchment, reduced grass production could lead to a switch to alternative forages better suited to warmer summer conditions or, more radically, a shift into purely arable systems. Similarly, mixed enterprise businesses, such as those found in the Teme catchment, may also switch from livestock to cropping, particularly where there are water availability advantages over the drier eastern areas.

For cropping enterprises, there are impacts associated with changing temperatures, rainfall, runoff and soil erosion, evaporation and soil moisture deficits. These will affect sowing, harvesting and critical growth periods, the length of the growing season, and thus yield and quality of produce.

There are implications for crop establishment, including the timing of field operations, with wetter autumns and springs increasing the risk of poor and patchy establishment of crops. However, an increase in the length of growing season will encourage an increase in the rate of crop growth and maturation, and thus there is the potential for an increase in yield, although weed, pest and disease pressures could also increase. Additionally, hotter, drier summers and an increased risk of drought could result in reduced yields, particularly for crops which may require irrigation but where water availability is limited. As a result of the warmer, drier climate, harvesting could start earlier. However, in seasons where the summer and autumn periods are wetter, harvesting could be disrupted/delayed with increases in drying and storage costs and a reduction in yield and quality.

For arable enterprises, such as those found in the Harpers Brook catchment, the warmer climate could result in an increase in yields and quality for cereal and oilseed crops, but reduced yields for proteins and field vegetables, with a need for flexibility in the timing of operations and seasonal cropping choices. For farmers who grow potatoes, such as those found in the Harpers Brook, Medway and Teme catchments, there would be a need for increased irrigation. Of the three catchments, the Teme is the better placed area for sourcing winter water for on-farm storage for later use in the summer, but could also face problems associated with waterlogging at harvest. Farmers in both the Teme (mixed farming including root crops) and Medway (horticulture) catchments could also see increased yields and quality as a result of the warmer climate, with options for increased root and break crop production in the Teme catchment, and new crops and varieties better adapted to drought in the Medway catchment. For the production of field vegetables, cropping programmes may require change with earlier planting possible alongside an increased need for irrigation. Similarly, there will be an increased risk of drought in the eastern counties leading to an increase in the need to irrigate sugar beet. This could result in reduced production, and will certainly lead to increased fluctuations in yield and quality on an annual basis. Polytunnel and glasshouse production is less problematic given the more efficient use of water, although there will be increased irrigation demand which could, without water available, mean reduced production/ yield and quality issues.

Heavy rain, waterlogging of soils and flooding will increase surface runoff, soil erosion, loss of nutrients and pollution with impacts on soil quality and productivity, and thus crop yields. Wet weather has implications for field operations and could mean there is limited opportunity to cultivate and establish crops, and at the other end of the season undertake harvesting operations. It could also lead to crop failure, or rejection due to poor quality. If there is opportunity to harvest the rainfall or retain and store the flood waters, however, then it could contribute to relieving summer water scarcity.

Finally, for both livestock and crop enterprises extreme heavy rainfall and flooding could cause damage to farm infrastructure.

5 Implications and solutions

5.1 Introduction

Section 4 demonstrated a number of potential impacts of climate change for agriculture, which, although variable and uncertain can be summarised as a general trend towards less water, more severe droughts and increased flooding. The impacts on agriculture will be variable across England, notably with greater impacts towards the south (although there will be a northwards movement of average climate conditions). Impacts will also depend on the timeslice and agricultural land use. Different crop types, for example, will be affected differently. To maintain water availability or reduce the impacts of drought and flooding on a farm in the face of these changing conditions and potential increased variability of conditions, farmers may need to adapt their current farming practice. A range of solutions are available to preserve water, reduce water use, make more water available, reduce the direct and indirect impacts of flooding, or adapt policy and practice to the changing situation. Raising awareness of climate change, water availability and use, and extreme events such as droughts and flooding will also be a priority.

The IPCC defined adaptation as an adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts (Smit et al., 2001). Ramamasy and Baas (2007), writing about adaptation to drought in Bangladesh, note that the impact of climate variability and change on specific regions depends on their vulnerability: that is, how sensitive they are to even small changes, how exposed they are, and whether they can adapt. If climate change occurs faster than those affected can adapt, community vulnerability to the impacts of both climate variability and change will increase (Ramamasy and Baas, 2007). Adaptive capacity is generally considered to be greater in England but the reality of climate change suggests that current ad hoc responses will be inappropriate and that a more concerted effort is necessary. There is a need to adapt to the relatively small ongoing climate changes over time in both the short and long term, but also to be prepared for and have strategies to deal with the increased frequency of climatic extremes, the 'worst case scenarios'.

Focusing on adaptation to drought, Hadjigeorgalis (2008) distinguishes two approaches:

1. Top down, centralized approaches that rely on an administrative authority or entity to act for the good of a larger set of water consumers. Examples used by the author include proactive drought management strategies which focus on physical and technological solutions to drought or institutional changes.
2. Decentralized mechanisms providing an alternative approach, which empowers individual water users and takes advantage of information that is not available at a centralized level. There has been substantial research on the success of user-driven or demand-side approaches, such as water markets, for drought management.

In practice, adaptation is an ongoing process and it is possible that many of the options discussed below are already being actively used by many farmers throughout England, unaware that they are essentially adaptations to existing conditions. However, the increasing pressure that climate change may place upon food production in the future necessitates explicit consideration of current and future options. Climate change is happening and there will be changes in water availability and droughts and flooding. To avoid more damaging consequences in the future it is necessary to start preparing now. As the path of change becomes clearer it will be possible to begin altering the chosen responses. Such management requires understanding of the implications of climate change on water resources and the potential responses to both the relatively small changes in water flows, rainfall and temperature as well as the extremes of droughts and flooding. This also requires the provision of this information on change and adaptation options to the relevant stakeholders, i.e. those who both make and implement policy and the farming community. Within water management two approaches can be discerned (von Christierson et al., 2010), which are relevant to adaptation in agriculture:

1. A traditional approach based on prediction (estimate of climate impact) and control (a solution to address this impact).

2. *Adaptive water management* represents a paradigm shift from the traditional approach, by focusing on management and learning rather than prediction and control (Pahl-Wostl, 2007). Such an approach addresses uncertainty more thoroughly and focuses on developing flexible solutions.

There are many potential options to ensure adequate supplies of water for future agricultural production. In essence these can be divided into options to increase the availability of water (supply side options) or to save water by reducing its use (demand side options). These options may be local, farm-scale options or they may require community action at a larger scale or interaction with other users of water. Bindi (2007), in a presentation to the ‘Time to Adapt’ Conference in Berlin, differentiated between technological and management options, which could be short-term (adjustments) or long-term (adaptations), and policy mechanisms, relevant to adopting the various adaptation strategies. It may only be necessary to employ new technology or techniques to maintain productivity, however, in severely affected areas, it may be necessary to move production to new regions (Growcom, 2009).

Growcom (2009) observe that the best adaptation strategies will vary according to region, commodity and current practices. Every option within a strategy has its own advantages and disadvantages influencing its relevance for implementation at a given location under given conditions, themselves dependent on the path of change. Arnell and Charlton (2009) developed a conceptualisation of the potential barriers to implementation for a water supply case study using the Medway catchment as shown in Figure 5.1. The proposed conceptual framework for the characterisation of the barriers to adaptation in a particular place identifies two broad types of barrier:

1. *Generic barriers* influence the way the adaptation challenge is defined and potential adaptation responses identified and selected. They can be considered cognitive and information/knowledge barriers and affect the capacity to acknowledge or recognize the problem and the solutions.

2. *Specific barriers* relate to individual adaptation options and influence the capacity to carry out the solutions.

Such work can be used to provide an initial framework for an initial consideration of potential adaptation options.

Generic barriers *apply to the adaptation challenge*

- is the need for adaptation recognised?
- can the need for adaptation be defined?
- can potential adaptation options be identified?
- can adaptation options be evaluated?
- can an option be selected?

Specific barriers *apply to individual options*

- are there physical limitations on the performance of the option?
- are there financial constraints on the adoption of the option?
- are there socio-political constraints on its adoption?
- are there institutional factors within the organisation or its regulatory / market context that constrain the adoption of the option?

Figure 5.1 Characterisation of two types of barriers to adaptation (taken from Arnell and Charlton (2009)).

In addition to considering adaptation options at the farm level, increasing interconnectedness within the farming community may itself be a necessary adaptation, i.e. whereby depleted resources are used and shared more effectively. It should also be accepted that climate change is only one potential driver of change in agriculture and may by no means be the most significant on timescales or spatial scales relevant to agriculture. This report makes no attempt to assess the relative importance of different drivers. This is an area of necessary future investigation although a number of studies have begun this process (see for example the Defra projects under their Climate Change Impacts and Adaptations (Agriculture) (CC03) Research Programme).

The remainder of this section discusses a range of options identified in the literature ranging from short-term, small scale solutions to more radical approaches that may also address more extreme situations. The section begins with a discussion of existing and potential future policy issues before discussing individual options. The section concludes with a brief assessment of the advantages and limitations of these options and the recognition that no single option will address all potential impacts.

5.2 Agricultural policy

It is widely recognised that rural land acts as a driver of flood risk, a flood pathway and a receptor (Foresight Land Use Futures Project, 2010; Posthumus et al., 2010).

Historically, the most common land use in English floodplains was hay meadows (Posthumus et al., 2010). Flood defence, drainage and pumping permitted more land use options. Between 1945 and 1985 there was grant funded investment to protect farmland against flooding and enable land drainage (Robinson and Armstrong, 1988; Weatherhead and Howden, 2009). Under draining, the use of underground pipe systems to drain soils to improve production is a common agricultural practice and the UK is one of the most extensively under-drained countries in Europe (Wheater and Evans, 2009). The installation of field drains reduces surface and near surface runoff due to the lowering of the water table and increase in the available storage capacity of the soil. Alongside this is secondary treatment such as subsoiling or moling to improve the flow of water to the drains (Wheater and Evans, 2009). Where flood risk was low and field water levels could be controlled, intensive arable was possible (Posthumus et al., 2010). Godwin et al. (2008) note that after 1985, rather than a routine replacement of the older systems, falling commodity prices and farm incomes prevented anything but the most urgent investment. At this time, Stansfield (1987, cited in Godwin et al. (2008)) was suggesting that 50,000 ha of drainage were ceasing to function each year and that a further 2 million ha of land needed/would benefit from drainage. Currently, existing drains are maintained to varying degrees (Armstrong and Harris, 1996) with little recent reinvestment, and there is currently concern with respect to the possible impact of field drainage on peak flood flows (Godwin et al., 2008). Furthermore, the drainage of soils rich in organic matter has short and long term effects as, although lowering the water table increases the amount of storage capacity, it also increases organic matter decompositions rates and can lead to a subsequent decrease in available storage in the future (Holden et al. 2004).

Grant funding was also available for the ploughing of permanent grassland for conversion to arable use in 1918, 1940 to 1945, and 1958 to 1970 (Weatherhead and Howden, 2009). The changing agricultural land use and intensification of production has had significant impacts on soil structure and runoff processes reinforcing the degradation of soil infiltration rates and available storage capacities, increasing rapid runoff (e.g. Bronstert et al., 2002; Carroll et al., 2004; Heathwaite et al., 1990; O'Connell et al., 2007), and as a result led to an increase in the risk of flooding (e.g. Boardman et al., 1994; Burt, 2001; Holman et al., 2003; Stevens et al., 2002). In more detail, agricultural practices associated with increased stocking densities and degraded or bare arable soils decrease soil infiltration rate, porosity and hydraulic conductivity (Gifford and Hawkins, 1978; Greenwood et al., 1997; Langlands and Bennett, 1973; Nguyen et al., 1998; Rauzi and Smith, 1972; Willatt and Pullar, 1984) and increase the chance of flood generation at the local, small catchment scale (Foresight Land Use Futures Project, 2010) with trafficking by machinery and animals leading to soil compaction, structural damage (Posthumus et al., 2010) and enhanced runoff rates (Elliott et al., 2002; Heathwaite et al., 1990; James and Roulet, 2007; Nguyen et al., 1998).

Over time there has been some policy realignment (Posthumus et al., 2010) with the introduction of environmental management agreements with farmers in the 1980s and the decoupling of farm income support and commodity prices in the 1990s, alongside the recognition of the need to manage flood risk and the quantity and quality of water through policy such as the flood risk management strategy for England 'Making Space for Water' (Defra, 2004) and the Flood and Water Act and the EU Water Framework Directive (European Parliament, 2000).

Within this there is recognition that rural land management can help to mitigate flood risk by reducing run-off on hill slopes and by storing water on agricultural floodplains (Foresight Land Use Futures Project, 2010; Wheater and Evans, 2009) particularly where it is now less easy to manage field water levels and there is increasing flood risk (Posthumus et al., 2010). Additionally, it is recognised that there are other benefits to restoring natural floodplains such as ecosystem services delivered by floodplains linked to hydrology (Posthumus et al., 2010). However, the extent to which rural land management can alleviate flooding problems during extreme events is currently limited (Foresight Land Use Futures Project, 2010). Furthermore, a large proportion of the most agriculturally productive land is dependent on flood protection and land drainage, and flooding and soil waterlogging of these intensively farmed areas would result in significant losses of agricultural output (Wheater and Evans, 2009).

The policy implications are thus numerous, requiring a better understanding of relationship between land use and flood risk management, the appraisal of flood risk management options, proactive floodplain zoning and zoning of coastal floodplains, joining flood risk management with other land use objectives, and finally creating a regulatory framework to support this (Foresight Land Use Futures Project, 2010).

Alongside the need to manage flood risk is the problem of provision of water during periods when water may be least available. This is compounded by the fact that precipitation is biased towards the north and west, with consumption biased towards the south and east, and the demand for water for use in irrigation is growing (Wheater and Evans, 2009). Further, current concerns associated with food security and the emphasis on UK food production could significantly increase the demand for water further. There are also issues associated with the expansion of energy crops which could increase the rate of evapotranspiration (Weatherhead and Howden, 2009), furthering concerns in the food versus fuel debate.

As stated previously, agriculture uses water for livestock enterprises and the irrigation of field and protected crops. This is mostly by direct abstraction, under licence, and without storage. The agricultural use of water sources is relatively small compared to other industries, but the 1-2% of abstraction for the irrigation of crops is environmentally significant because it is concentrated in the drier catchments in the driest months. A third of all potatoes and a quarter of all fruit and vegetables are supplied by just 1000 agri-businesses in Eastern England and these businesses depend upon reliable water supplies to deliver continuous supplies of premium quality produce demanded by consumers (Godwin et al., 2008). Further, the volume applied has been growing, increasingly concentrated on high value crops such as potatoes, vegetables and soft fruit to ensure quality and continuity of supply (Weatherhead and Howden, 2009). Although irrigated agriculture accounts for only 1-2% of total UK water abstraction and 4% of the crop area, it accounts for 20% of the crop value (Godwin et al., 2008).

In terms of water availability, over-licensing is now conflicting with rising environmental protection standards and legislation. The problems are mainly in the south and east of England, but not exclusively, as illustrated by the case study catchments used in this work. Future problems will therefore be more widespread. The Climate Change and Demand for Water (CC:DeW) project (Downing et al., 2003), for example, suggests that the agricultural industry will be the one most affected by climate change with the greatest implications for the south and east.

However, the provision of extra water is a challenge. The combination of higher demand and reduced water resources has repercussions for land use. Small on-farm reservoirs are being actively promoted, but their implementation in the south and east is restricted by reduced winter flows (Weatherhead and Howden, 2009). Storing water in the north and west and transferring south and east is receiving serious consideration but there are issues associated with the current structure of the water industry, funding, and environmental impacts (Wheater and Evans, 2009). Guidance for planning and commissioning reservoirs exists (see for example Weatherhead et al., n.d.) and sharing of resources is suggested. Put simply, large scale long distance water transfers are feasible but less sustainable than demand management (Weatherhead and Howden, 2009). Thus more efficient water use, i.e. demand management and water saving, will also be an important policy direction (Weatherhead and Howden, 2009; Wheater and Evans, 2009). The Environment Agency (EA, 2007) also provides a simple guide to implementing a water management plan on different types of farm to enable farmers to assess whether they are making the best use of their water resources.

As indicated by Godwin et al. (2008), a recent study by Knox, Kay and Hammett (2007) to develop a water strategy for agriculture, reported that the way forward for improved irrigation water management included:

- *Working together*. Improving the dialogue between individual abstractors, the agri-food industry and regulator;
- *Making best use of available water*. Improving the security of on-farm water supplies and ensuring its wise use;
- *Developing a knowledge base*. Improving water management knowledge and skills training within the agri-food industry.

Increased competition for water, rising demands from other sectors, coupled with environmental protection and the longer-term threat of climate change, all threatened the sustainability of irrigated agriculture and the livelihoods it supports; and that it is essential that irrigation water management, therefore, receives priority support (Godwin et al., 2008).

Within this context Hadjigeorgalis (2008) presents some research on an alternative for agricultural water resource management in areas of recurrent drought: water allocation through market mechanisms. The research conducted statistical analysis of survey data from 166 farmer interviews in the Rio Grande Basin, which indicated that farmers are significantly more likely to participate in short-term water mechanisms, such as spot water markets and water banks than in permanent transfer mechanisms, particularly those that fully separate water rights from land. The research also found that the choice of market mechanism did not differ significantly between farmers based on their a priori intention to buy, sell or both buy and sell in these markets, nor did it differ among farmer types although small, lifestyle or hobby farmers clearly preferred spot water markets to other types of short-term mechanisms. Whether such an option is relevant to English agriculture is a matter for discussion between the industry and its regulators.

A final area for consideration in terms of conserving usable water resources is in the management of land. To conserve usable water resources, land uses and farming practices that cause soil erosion, runoff and flooding should be discouraged; the same is true for land uses that increase evapotranspiration (Weatherhead and Howden, 2009). Encouraging infiltration is an important policy objective, alongside maintaining good soil structure. Some of this may be achieved through cross compliance and/or agri-environment schemes (Weatherhead and Howden, 2009). Marshall et al. (2009), for example, suggest that woodland and tree shelter belts can help reduce overland flow and increase infiltration rates. Reinstating hedgerows would also prove beneficial (Wheater and Eavns, 2009). Farming practices which could improve soil structure and increase permeability include, for example, reductions in stocking density and the introduction of smaller hardier breeds (Wheater and Evans, 2009) and a revised strategy regarding winter cereal cultivations.

5.3 Individual options

5.3.1 Agricultural industry options

The potential strategies for adaptation to drier and warmer or wetter and colder weather and extremes of drought and flood are numerous and widespread. Adaptation options need to address issues of flooding and drought and water availability. Whilst these are generally separate, there is overlap in methods (e.g. winter storage, storage of flood waters).

ADAS (2001b) suggest that radical change is not necessary and that only partial change is required. In the first instance some amendments to the mix of enterprises will be required (SAC Commercial Ltd, 2009). In the south east, such as in the Medway catchment, ADAS (2001b) suggest that livestock farmers will need to shift into arable production. At the same time, there will be a need to introduce crops that require less water and are adapted to higher temperatures (Warwick HRI, 2009). Changing the mix of crops could include the introduction or increase in area of forage maize, flexibility with regard to winter versus spring sown crops (Hughes et al. 2008), for example, an increase in the area of spring barley where winter crop establishment is limited, opportunities to expand the introduction of traditionally Mediterranean crops (Warwick HRI and ADAS, 2006), and the substitution of sunflowers for oilseed rape in East Anglia. In the horticultural sector, production planning through avoiding certain areas, increased crop rotation, growing crops under cover, and the increased use of compost and green manures may be required (Hughes et al., 2008), although Weatherhead et al. (1997) suggest the use of mulches is limited.

Alongside the change in enterprise mix is the need to adapt the farming system, management and timing to the changing conditions (SAC Commercial Ltd, 2009). In the livestock sector, such as those enterprises found in the Medway, Teme and Eden catchments, this could include changes in stock feeding through dietary change and buffer feeding (Hughes et al., 2008; SAC Commercial Ltd, 2009), growing drought resistant forage and increasing the use of a mix of forages (Hughes et al., 2008) and adopting new grassland management practices (ADAS, 2001b) such as increasing the use of rotations and short term leys and the increased use of common grazing (Hughes et al., 2008). In extreme cases the introduction of indoor finishing rather than forage finishing for sheep could be a possibility (Hughes et al., 2008; SAC Commercial Ltd, 2009). For both livestock and arable enterprises, adaptation may require changes in sowing dates (Warwick HRI, 2009) and spring and autumn work days (ADAS, 2001b), developing farming practices that minimise susceptibility to new pests and diseases (Warwick HRI, 2009), through changing pesticide use and increased pest/disease surveillance (Hughes et al., 2008) and introducing more effective plant protection products (Hopkins, 2005).

To maximise the effectiveness of machinery, labour and available work days there will be a need for improvements in farm machinery increasing the range of equipment and specification (Hughes et al., 2008) to allow increased work rates (Hopkins, 2005; Warwick HRI, 2009), alongside flexibility in staffing through the use of overtime, casual and contract labour (ADAS, 2001b; Warwick HRI, 2009).

In terms of farm infrastructure, investment will be needed in livestock housing and shelter in the field to adapt to the extremes of cold and heat (SAC Commercial Ltd, 2009; Warwick HRI, 2009) and for storage of input resources including feed and water, particularly the case for the Eden and Medway catchments. For example, with increased/reduced yield potentials for different crops throughout the year, there may be a need for greater crop storage between seasons (ADAS, 2001b). Similarly, there is already recognition for the need to install or increase irrigation capacity where this is possible (Hughes et al., 2008). On-farm reservoirs to store water from rainfall and high flows in the winter for use in the summer has some potential, for both livestock and cropped enterprises. This is more feasible in the western rather than eastern catchments, i.e. the Eden and Teme catchments. Many farms already have water tanks to capture and store water from spring, field drains and watercourses although the capacity is not adequate to provide a reliable solution and above a certain level would require knowledge/consent of the appropriate authorities.

Additionally, there is a need to prepare for droughts periods and excess rainfall through developing or changing to breeds that are adapted to the changed conditions (Warwick HRI, 2009), such as growing heat tolerant/drought resistant varieties (Hughes et al., 2008). This is relevant to all catchments used in this study. Advances in both livestock and plant breeding (SAC Commercial Ltd, 2009) focused on traits related to resource use (Warwick HRI and ADAS, 2006) will also be required. For example, plant breeding could extend the geographical range of crops and improve their resistance to new pest and diseases (Hopkins, 2005). Similarly, breeding which, for example, promotes deeper rooting in potato cultivars would have benefits in terms of drought and common scab resistance (Weatherhead et al., 1997).

Drier, warmer periods and the extremes of drought will focus attention on water conservation, the benefits of which varies across enterprises (Weatherhead at al., 1997). For example, in the livestock sector, there is limited opportunity to reduce the level of drinking water for livestock with higher temperatures requiring greater provision specifically in the summer months (Warwick HRI 2009), and perhaps more so in the Medway as opposed to Eden and Teme catchments. However, there is potential for savings to be made in reducing waste from the water used for washing (Warwick HRI and ADAS 2006). Even the simplest techniques such as monitoring/auditing of water use can lead to reductions, and there is also potential through making sure that the plant distribution systems and water pressures are at their optimal levels. The emphasis within the livestock sector should be on cattle and, more specifically, dairy enterprises and how wash water is managed (Warwick HRI and ADAS 2006). This is of particular relevance to enterprises within the Eden catchment. For dairy cattle and intensive pig systems, there may also be some benefit in making use of rainwater harvesting and storage, whereas within sheep and poultry enterprises there is little scope for saving water as the majority is used for drinking, and currently it is not practical to pipe water from storage tanks to the fields (Hughes et al., 2008; Warwick HRI and ADAS 2006).

The focus of a recent Milk Development Council (MDC, 2007) report on effective use of water on dairy farms considers many options, a number of which overlap with the water industry options outlined in the next section, but set with a view to reducing costs rather than saving water per se. It is also the case that these are mainly demand side options, for example:

- Checking for water leaks
- Re-using water
- Using appropriate cleaning methods to reduce water use
- Revisiting waste water disposal

The report indicates that any water reused saves on both the cost of purchase (mains water which is typically £1/m^3) and on the waste water (typically costing £1/m^3 disposal cost).

In terms of supply-side options, the following were suggested as farm-level possibilities for a dairy farm (note options will differ depending on agricultural use):

- Rain water harvesting, e.g. roof water collection, with higher rainfall areas or large catchment areas having greater potential, although water storage can be a significant cost
- Direct stock drinking from water courses
- Alternative water sources: boreholes, springs, canals, rivers, lakes

The report observes that abstracted water will normally be cheaper than water supplied from the mains by a water company but it is not free and inefficient water use can significantly add to waste water disposal costs. Furthermore they note that test bores are not inexpensive and there is no guarantee of finding suitable quality or quantities of water and that an abstraction licence may not be needed if abstracting less than 20m^3/day.

It should also be noted that one potential physical limitation to many of these supply side schemes is that in some way or other they reduce effective rainfall. Anything that captures the rainwater before it enters the ground may deplete the soil storage, whilst excessive dependence on further abstractions, whilst potentially requiring regulation, or direct stock drinking may reduce river flows. At the same time each of these methods will be directly affected by reduced rainfall or changes in river flows themselves. Thus, it is important to consider the local conditions before choosing any single option.

In crop enterprises the focus is on irrigation capacity and the implications of altered irrigation demands across the country (ADAS, 2001b) and the need to adopt more effective use of irrigation (Warwick HRI, 2009).

There are a number of alternative irrigation systems, i.e. trickle, boom, sprinkler and intelligent rain guns; the most cost effective system depends on crop, soil type, water source and farm management requirements (Warwick HRI, 2009). Trickle irrigation is well established in the soft fruit, orchard fruit, salads and glasshouse sectors, such as those found in the Medway catchment and uses less water than overhead systems as it delivers water to the soil profile around the plant's roots. It can lead to an increase in yield and quality, although the capital investment is high. For in-field crops there needs to be a sufficient premium for the improved quality that results to justify the investment cost. Boom irrigation is popular for field scale vegetable and salad growers, such as those found in the Harpers Brook catchment, as it applies water evenly and precisely. However, this type of system requires large, flat rectangular fields to be most effective. Solid set sprinklers were originally used on permanent crops such as orchards, but are also now in use for field vegetables. The sprinkler utilises sophisticated electronic control systems to flexibly and precisely apply water. Rainguns are the most common irrigation system used, and would feature in the Medway, Harpers Brook and Teme catchments as they are robust, versatile and labour efficient, and for many farms the only viable system. Savings in water can be achieved by utilising more efficiently, setting the system at the right pressure and only using in moderate wind speeds with appropriate spacing.

Improved scheduling, the understanding of the movement of water in the soil profile and root zone, so that soil water conditions are optimised for yield and quality is also important (Warwick HRI and ADAS, 2006; Warwick HRI, 2009; Weatherhead et al., 1997). This requires water balance calculations considering the water applied (both rainfall and irrigation) and water lost (evapotranspiration) (Warwick HRI, 2009).

There are also a number of methods to increase water availability (Weatherhead et al., 1997) with particular value for the production of high quality irrigated fruit and vegetables and amenity horticulture in the drier regions of England (Warwick HRI, 2009), such as the Medway and Harpers Brook catchments. On-farm reservoirs are viable (Warwick HRI and ADAS, 2006; Weatherhead et al., 1997) but would only work in areas with high winter rainfall, more likely in the Teme catchment. Rainwater harvesting also has a role (Warwick HRI and ADAS, 2006) but cannot compete financially with the present direct low cost of abstraction (Weatherhead et al., 1997). Ramamasy and Baas (2007) also suggest mini ponds for rain water harvesting as a viable option in which the re-excavation of ponds can be undertaken in areas of extreme water scarcity and in farmlands with no irrigation source. The adoption of water reuse technology also has potential (Warwick HRI 2009) with the installation of recycling and disinfection systems (Warwick HRI and ADAS, 2006). However, although this is technically feasible, the direct reuse of treated effluent involves extra costs and there would be public relations problems (Weatherhead et al., 1997).

Within the different cropping enterprises the following adaptations are suggested by Warwick HRI and ADAS (2006):-

For cereals, oilseed rape and biomass crops such as those found in the Harpers Brook catchment and which are likely to be rainfed rather than irrigated, breeding efforts are needed to maximise yield stability in increasingly water limited environments through improving drought resistance and water use efficiency. Where soils become hardened due to hot, dry weather farmers may need to move to reduced or minimum tillage systems (Hughes et al., 2008). Irrigation to soften soils would not be cost effective or practical for combinable crops. This would reduce the cost of the cultivation and establishment operation, but is not suitable long term as it will result in a build up of weed problems.

For potatoes, Warwick HRI and ADAS (2006) suggest there is a more urgent need to breed for drought resistance and water use efficiency, particularly developing root traits to access soil water at a greater depth. Finding an alternative to irrigation to control common scab is also important, as is avoiding soil compaction and good soil management. Hughes et al. (2008) also suggest that without irrigation there will be a reduction in potato production in some areas, particularly where there is no capacity for winter abstraction and storage, such as in the Harpers Brook catchment. One adaptation would be the move of potato production to wetter areas where there is capacity for winter abstraction, more likely in the Teme catchment. Hughes et al. (2008) also notes that increasing irrigation will be required in drought conditions whatever the soil type. On heavier land, increased irrigation would be required to soften the hard ground to encourage tuber growth and prevent damage (bruising) at harvest. On light land increasing irrigation would again be required otherwise soil which would normally protect the potato during harvest would fall away and, again, damage (bruising) could occur. The decision to invest in storage will be about more than economic return as farmers will be willing to invest to improve saleable yield and quality and maintain their market contracts. This would require increasing storage capacity for irrigation water such as an on-farm reservoir and a winter fill licence for abstraction from a river. The case to relocate potato production away from the eastern counties to the west is most likely where there is no capacity for any further abstraction of water. However, Hughes et al. (2008) note that most of the infrastructure for growing, storing and processing potatoes is in the east. There are also agronomic reasons for retaining the spread of production, as the greater the area available, the easier it is to extend the rotation period, with the advantage of reducing the incidence of pest and disease and requirement for pesticide applications. Processors also source from different regions to spread risk. A concentration in the west would increase the exposure to risk of poor crop yields.

Sugar beet crops face similar issues to potatoes, although the main area of production is within the eastern regions. Whether rainfed or irrigated, and as with other crops, there is a need to improve drought resistance and water use efficiency. If irrigated, then with reduced summer abstraction and little opportunity for winter abstraction and reservoir storage, there may be a need long-term to reduce production or relocate.

For field vegetables, and of particular relevance to the Harpers Brook catchment, Warwick HRI and ADAS (2006) suggest improvements in irrigation scheduling and the understanding of crop water needs related to quality is equally important. To some extent this could be achieved through knowledge transfer and improving the uptake of existing technology. Mulching also has a role, and as with other crops, identifying genes for drought resistance or water use efficiency is also beneficial.

For orchard fruit, such as those found in the Medway catchment, improved scheduling and breeding for water use efficiency and drought resistance also plays a role. Hughes et al. (2008) suggest that drought would negatively impact on yield and quality and thus installing an irrigation system, such as a solid set sprinkler, and progressively replacing stock with more drought tolerant varieties is viable.

For hardy nursery stock, again found in the Medway catchment, Warwick HRI and ADAS (2006) suggest improvements in scheduling and irrigation methods will also be required, with investment in sub-irrigation systems and automation. Rainwater harvesting and recycling systems will have greater potential than for field scale systems and will require some effort in knowledge transfer.

For the protected crop sector, although less of a priority given the more efficient use of water, will be the adoption of closed hydroponic systems, rainwater harvesting, venting control, and breeding of root stocks.

Knox et al. (n.d.) identified a range of options within both the horticultural context and at the field level for reducing water needs and obtaining more water, and this provides a useful summary of the previous discussions. The options for reducing water needs include:

- Better irrigation equipment to increase irrigation application, uniformity and efficiency
- Better scheduling to increase irrigation application efficiency
- Use weather forecasting to avoid rainfall losses
- Encourage deeper rooting of crops
- Introduce low water use or drought tolerant varieties
- Increase shading and wind shelter
- Decrease the irrigated area
- Improve soil structure to improve water retention

The options for obtaining more water include:

- Purchase or rent land with water
- Convert to public mains water
- Obtain winter abstraction licence and build storage (individual or shared reservoir)
- Rainwater harvesting
- Re-use waste water from farm buildings
- Desalination of brackish or sea water

Wetter, colder periods and intense rainfall, waterlogged soils and flooding will focus attention on livestock and crop protection, managing soils, drainage and flood risk.

In general terms, options for flood defence take a more catchment overview. For example, in the Foresight FCD Project (Evans et al., 2004b), responses to increased flood risk related to agriculture are discussed in Response Theme 1 – managing the rural landscape – and are classified in three response groups:

1. Rural infiltration – water retention and management of infiltration into the catchment.
    - Changing tillage practice
    - Extensification
    - Field drainage (to increase storage)
    - Afforestation
    - Buffer strips and buffering zones

2. Catchment-Wide Storage – water retention through storage schemes at all scales
    - Detention ponds and bunds
    - Wetlands and washlands
    - Riparian and floodplain impoundments

3. Rural Conveyance – managing conveyance to alter the volume and timing of runoff.
    - Management of hillslope connectivity

- Drainage channel maintenance
- Drainage channel realignment

Many of these are discussed in more detail in the following discussion but it is important to note that the first and second group of options are also relevant to retaining water in the face of decreased water whilst the third group feeds into the other two groups by altering timings (and volumes). These options are of course not only specific to agriculture and, additionally, other options from other responses in the Foresight report could also be relevant to agriculture. It is important to note that any change in the system (be it the climate, the nature of the catchment, or agricultural practice, for example) produces a feedback loop in which the option may have impacts on other aspects of the system. For example, a flood defence option may benefit water availability. However, changing the water availability may also have an impact on the future flood risk in a catchment or on a farm.

For livestock enterprises there may be a need for more housing and thus investment in farm infrastructure and the restoration of features such as hedges to provide shelter and reduce soil erosion (Hopkins, 2005; SAC Commercial Ltd, 2009). Adopting suitable upland management to slow runoff and reduce peak flows will also be beneficial, as will introducing measures to secure the safety of livestock during extreme flood events (Warwick HRI, 2009).

For crop enterprises there will be a need to change traditional cultivation and harvesting timelines and practices, with a switch from winter to spring cropping when needed. Increasing ground cover, changing field design, expanding field margins and, as with livestock enterprises, the restoration of natural features to reduce soil erosion and runoff will also be required (Warwick HRI, 2009), as will improvements in drainage, ditches and the use of buffers to mitigate against flooding and waterlogging. There may also be a need to protect against low temperatures, whether overwinter or in the early spring, with the use of mulches or plastic covers, or the introduction of shelter belts (Hopkins, 2005). Reductions in intensity or changes in crop species are also possibilities.

Finally, farmers may also look to the opportunities that the wet weather presents, through the collection of excess rainwater and storage of flood waters from both the farm buildings and the field.

Within the different cropping enterprises the following adaptations to wet weather and intense rainfall are suggested by Hughes et al. (2008).

For cattle, where there may be limited access to pasture in winter, there will be a need to invest in the farm infrastructure such as increased and/or improvements in livestock housing alongside an increase in manure storage capacity as a result of both longer housing periods and decreased manure spreading days. The wet weather and intense rainfall also increases the risk of poaching, erosion, leaching of fertiliser, increased pollution incidents and flash flooding. Thus, alongside the need to house stock, there may also be a need to improve drainage systems and flood protection, and improve runoff containment.

For sheep, as with cattle, the waterlogging of pasture may require earlier housing at lambing and later turnout after lambing, and improvements in drainage systems and flood protection to reduce the risk of soil erosion.

For pigs, the waterlogging of land suitable for pigs will affect the ability to feed and bed stock with increased mud walked into farrowing arcs and issues associated with increased moulds in grain (feed) and straw (bedding). This could require moving from extensive to more intensive systems and housing stock, and/or alternatively, reducing stocking rates and at the same time increasing the availability of spare paddocks, alternating field entry/exits to avoid rutting, alternating paddock orientation to avoid 'water chutes', and the avoidance of steeply sloping land to avoid increased problems with soil erosion. Vehicles and feeding equipment may also need to be adapted for wet conditions. To avoid problems with feed there will be a need for more attention to be given to feed bin cleanliness and design and trough feeding as opposed to broadcasting feed. Straw bedding may require acid treatment to kill moulds, and there may be a need for additional bedding and out-use of straw as a doormat. More general adaptations, as with other livestock systems, will be the need for an improvement in drainage systems and flood protection, and improved runoff containment.

For poultry, the issues and adaptations that may be needed are similar to those for pigs. With the potential for increased mud in hen houses and dirty egg shells, adaptations could include concrete and/or the introduction of free draining material around the hen house, collecting eggs more often, and the more general adaptations of improving drainage systems and flood protection, and improving runoff containment, perhaps through the establishment of more persistent cover/grass species that will establish well.

For arable enterprises, wet weather will change the field conditions for field operations, which may require an increase in range of equipment and their specification to allow adaptation to the climate extremes. Farmers will also need to be flexible with regard to winter versus spring sown crops. Increased soil erosion and nutrient loss will require the adoption of soil conservation techniques including changing cultivation and establishment to minimal tillage operation, the use of cover crops and contour ploughing, where possible, to conserve soil. Some of these changes could reduce operational costs, in other cases costs will increase. Better management in terms of cultivar choice and plant nutrition may also be required. A decreased efficacy of pesticides could mean increased pesticide costs and a switch in strategy, for example using foliar rather than soil applied herbicides. At harvesting there could be an increased risk of lodging for arable crops, and difficulty harvesting root crops with reduced storage potential and yield penalty if harvested wet. For arable crops this may require a second application of growth regulator and increased drying costs; root crops may need to be grown on lighter soils. Harvest may also have to occur earlier leading to yield and quality penalties.

For horticultural enterprises wet weather could increase soil erosion and nutrient/pesticide loss and reduce the number of spray days. Adaptations to these impacts would include adopting soil conservation techniques such as the increased use of cover crops, compost and green manures and contour ploughing where possible, and more use made of weather monitoring to allow full crop protection programmes to occur. There may also be difficulties in harvesting autumn crops, with increased crop damage, loss of quality, reduced shelf life and even crop loss. This may require crops to be grown under cover and making use of artificial lighting, terminating the crop earlier, moving crops to more sheltered sites, growing on lighter soils, and/or increasing the range of equipment and its specification.

Table 5.1 presents a summary of the adaptations, their relevance to different enterprises, benefits/costs, and limitations.

In relation to all the adaptations outlined in the above, whether or not they are adopted is dependent on a number of factors. Hughes et al. (2008) in their work established that farmers would consider most adaptations, with a number of adaptations considered as standard practice (e.g. drainage systems), others dismissed as too expensive, impractical or unlikely (e.g. increase in casual labour). It is worth noting that the low costs or simple operational adaptations are already currently being used with farmers very sensitive to the cost of adaptation. They will not invest in an adaptation to an extreme if they have not experienced that extreme, particularly where adaptation might lead to another problem. However, it is worth noting that the driver for implementation is not necessarily always climate related. Adaptation is a function of the perception of climate/weather impact and market forces/regulation. Nevertheless, farmers see the provision of accurate long range weather forecasts as important, alongside information highlighting the options available and also where these have been implemented and whether or not they are working as useful.

Table 5.1 On farm options to improve water availability and reduce flooding

Option	Relevance	Benefits/costs	Limitations
WATER USE			
Enterprise change Introduction of new livestock or crop enterprise Removal of livestock or crop enterprise Relocation of traditional areas of production	Likely that most changes will be in the introduction of crops more suited to warmer drier conditions in both arable and grazing livestock systems	May only require minor change to the overall farm business May require more major change and investment in new facilities and equipment Additional infrastructure, machinery and labour resources may be required Alternatively these resources may become redundant	Dependent on suitability of location, soil type and farm infrastructure and willingness of farmer to adopt (and their knowledge) Dependent on supply chain infrastructure
Changes to management and timing of operations	Likely that most changes will occur with regard to establishment of crops, crop protection regimes and harvesting operations, with both earlier and later timings for each possible	Implications for labour and machinery requirements, particularly where the timing of operations becomes compressed, may reduce certain costs (e.g. establishment with minimum tillage), but increase others (e.g. crop protection)	Requires flexibility and availability of labour and machinery, which may not be readily available
Provision of extra ‘resources’	Investment in farm buildings, feed and crop storage, water storage, shelter, e.g. hedges, within field	Investment cost may not lead to direct economic return	May not be worthwhile financially May not be easy to incorporate additional infrastructure within existing set-up
Changes and development in breeding Replacing stock with new/alternative breeds	Relevant to both livestock and cropping	Benefits may take time to realise, breeding takes time	May require system change Takes time
Reducing wash waters in livestock enterprise	Particularly relevant to the dairy sector	Requires development and adoption of systems to optimise use	May require initial investment, but could pay off long term
Repairing old/outdated mains water systems	Particularly relevant to livestock enterprises	If leakage occurring savings may outweigh cost	May not always be easy to monitor/repair
Rainwater harvesting	Particularly relevant to the dairy sector and protected cropping sectors	Requires development and adoption of systems to harvest water	May require initial investment, but could pay off long term, more relevant in higher rainfall areas
Water reuse	Particularly relevant to the dairy sector and cropping	Requires development and adoption of systems to collect and treat water	Water re-use may face public relations problems
Irrigation system change	Irrigated crop enterprises	Investment in new equipment	Not all systems are suited to all field conditions

Irrigation system adjustment, better equipment	Irrigated crop enterprises	Investment of time and energy to set system to the optimum	Requires sufficient crop premium to justify effort
Irrigation: improved scheduling	Irrigated crop enterprises	Investment of time and money, may be worthwhile	Requires sufficient crop premium to justify effort
On- farm reservoirs	Particular value for high value crops, but also of value to livestock enterprises	High initial investment may outweigh return, but additional benefit from ability to secure market	Would only work where sufficient water available, and also that can be easily captured or abstracted
FLOODING			
Enterprise change Extensification Change from intensive to extensive grass Change from cropping to grass	Relevant to livestock and cropping	May only require minor change to the overall farm business May require more major change and investment in new facilities and equipment Additional infrastructure, machinery and labour resources may be required Alternatively these resources may become redundant Benefit from reduced input use, cost in terms of lost output	Dependent on farm system and extent of weather events
Change from winter to spring sown crops	Relevant to cropping	Costs may be associated with lost winter crops	Requires flexibility in farm system
Changes to management and timing of operations To reduce runoff and increase infiltration rates	Likely that most changes will occur with regard to establishment of crops, crop protection regimes and harvesting operations, with both earlier and later timings for each possible	Implications for labour and machinery requirements, may increase or reduce costs	Requires flexibility and availability of labour and machinery, which may not be readily available Dependent on topography and soil type
Reintroduction of natural features such as hedges and ditches, widening of buffer strips	Relevant to livestock and cropping	Investment cost and may reduce operational capacity, may have long term benefit	Dependent on topography and soil type
Field drainage improvement	Relevant to livestock and cropping	Investment cost, may have long term benefit	Dependent on topography and soil type, and extent of natural flooding
Detention ponds, washlands, floodplains	Relevant to livestock and cropping	May require initial investment, may have benefits in terms of water storage for future use	Would only work where natural features allow water to be easily captured/stored
Investment in farm buildings and infrastructure	Particularly relevant to the livestock sector	May require high initial investment cost	May not always be financially viable

5.3.2 Water supply industry options

Despite the extensive literature on potential options for adapting to changes in future water for agriculture there is currently a dearth of studies assessing the various options. Conversely, the water supply industry in England and Wales has made extensive provision for maintaining water supplies into the future through the production of their Water Resources Management Plans. Whilst these do not tend to explicitly discuss adaptation options solely for addressing climate change, there is potentially a reasonable model that could be adopted for assessing climate impacts (as conducted in this report) and feeding this into a general assessment of adaptation options. Charlton and Arnell (2010) discuss climate change impacts as derived from the plans and the implications for adaptation in more detail. The guidance for the water companies and the overall methods need refining and updating but there is a potential framework available in this work.

The water supply industry also provides another relevant position from which to understand climate change impacts on water and the implications for agriculture: there is often considerable overlap in the potential options for increasing supply or decreasing demand. Furthermore, a considerable amount of water is supplied by the water companies to agriculture, especially in the case of dairy farms. Coupled with this is the fact that ultimately both water supply companies and agriculture tend to be using the same sources of water (albeit water companies having greater potential to extract than individual farmers) and yet they are just two of the competing interests in the water environment.

In a previous study building on earlier work (e.g. Arnell and Charlton, 2008; Charlton and Arnell, 2008), Arnell and Charlton (2009) conducted an extensive review of many options for increasing supply or reducing demand for the Medway catchment, one of the study catchments in the current study. The focus of the study was on assessing the potential limitations or barriers to implementation of the options and Table 5.2 summarises the options and their limitations. These options are specific to the Medway case study but include a number of others and it is clear that many of these options could be directly used by agriculture and that a number of others could indirectly assist in addressing some of the water shortfalls that we have identified.

The preliminary assessment of the specific barriers to the identified adaptation options (taken from Arnell and Charlton, 2009), based on reviews of documents produced by local councils, water companies, the Environment Agency and some pressure groups, means it is possible to draw four key preliminary conclusions:

1. there are physical barriers to most of the supply-side options, relating partly to the constraints posed by environmental obligations and partly to uncertainty over whether there would be enough water to sustain the options (particularly filling reservoirs).
2. the physical barriers to most of the demand-side options relate to uncertainty over the magnitude of their contribution to reducing the supply-demand deficit.
3. there are significant pressure group objections to many of the supply-side options – largely on environmental grounds.
4. there are potential customer barriers to the implementation of many demand-side measures.

What is important to note is that it is necessary to have a framework for assessing appropriate solutions to the specific problem, based on a range of criteria, and that such solutions should be flexible given the potential uncertainty in climate impacts (and in the effectiveness of individual options to address these impacts).

Table 5.2 Key specific barriers to potential adaptation options in the Medway catchment (from Arnell and Charlton, 2009).

Option	Details[1]	Potential contributon[2] (Ml/d)	Physical	Financial	Socio-political	Institutional
Supply side						
Bulk transfers	Within region and from outside region (e.g. from	?	Environmental impacts Network capacity	High unit costs		Ability to strike deals

	Thames)		constraints High energy use			
Effluent re-use	Kent recycling scheme Re-use of water from Margate-Broadstairs	Up to 20	Moderate energy use	Moderate unit costs	Public acceptability	
Aquifer storage and recovery		5	Limited capacity	Moderate unit costs		
Desalination		?	Environmental impacts High energy use	High unit costs	Pressure group objections (strong)	
Local resources	Enlarge Bewl Bridge Reservoir	20	Availability of water	High unit costs	Pressure group objections (moderate)	
	New reservoir at Broadoak	40	Availability of water Environmental impacts	High unit costs	Pressure group objections (strong)	
	New reservoir at Clay Hill	18	Availability of water Environmental impacts	High unit costs	Pressure group objections (strong)	
	New groundwater sources	9	Limited capacity			
	Use of winter flood storages	?	Uncertainty over effectiveness			Multi-purpose management
Increased connectivity	Transfers between zones	15	Network capacity constraints			Ability to strike deals
Demand side						
Reduce distribution leakage	Across region	29	Uncertainty over effectiveness	High unit costs Not funded through capital streams		
Metering and tariff structures	New houses and retro-fitting	10-12% reduction in per capita demand; volume effect depends on growth rates	Uncertainty over effectiveness	Not funded through capital streams	Customer willingness to reduce usage	Political support for widespread metering
Water efficiency	New houses and retrofitting	8-21% reduction in per capita demand; volume effect depends on growth rates	Uncertainty over effectiveness	Costs incurred by customers	Customer willingness to install efficient devices	Lack of measures to encourage adoption
Licence trading	Transfer of surplus licences between organisations	?	Uncertainty over effectiveness		Abstractors willingness to sell licences	Lack of market history
Public education		?	Uncertainty over effectiveness		Customer willingness to reduce usage	
Curb population growth in the catchment		?		Impact on local economy	Local council willingness to deter growth	Mechanisms for curbing growth

[1]specific schemes where appropriate [2]increase in supply or reduction in demand

5.4 Option portfolios and research requirements

Two things are clear from the preceding discussion. First, no single option will be appropriate for every situation. Second, in general, options will not be able to save or provide enough water to address the magnitude of potential changes. Additionally, as the Medway water supply case study illustrated, the solution is to develop a range of options that address all potential impacts depending on the severity and potential direction of changes. Some options will be more appropriate than others and may be complementary and/or conflicting. It is important to recognise that a combination of different options rather than one single approach will be necessary to address climate change impacts. This requires a change in approach to adapting at the farm level and this will be driven by policy and related guidance. An important aspect of this will be to raise awareness of the different options available and then develop means to assess which options are most appropriate. Something akin to the Water Resources Management Plans could be developed and adopted so that an optimum solution can be found for a specific farm. There is thus a need for additional research into the potential benefits of individual options and a considerable need for further research into the variety of options that could be employed. Such work could focus on gains or savings of options, the various barriers or benefits of implementation, and the likely trade-offs that may exist between combined options.

In their earlier report for RASE, Godwin et al. (2008) identified a number of other important areas for further research which could feed into such adaptation assessment research. These are briefly summarised here.

For flood risk management there is a need for continuing applied research and development in many areas, probably the two most significant areas are related to in-field water management (drainage and soil erosion control) to reduce flooding and the issues related to the management of upland areas:

- The relationship between good field drainage and flood risk, including the use of the soil for water storage and detention for both lowland and upland situations, requires understanding
- Related to this is the management of uplands for increased production of food and fuel, whilst maintaining water supply and bio-diversity
- Practical adoption of internationally well tried soil conservation measures to reduce runoff and erosion that do not restrict mechanised field operations e.g. grass waterways, is also important.

For irrigation techniques, improving water use efficiency and precision are the key areas for applied research. Examples include:

- Precise and targeted specific application methods
- Appropriate low cost soil moisture sensors for water control
- Benefits of spatially variable application of water to accommodate variation in soil water holding capacities.

5.5 Synthesis and summary

Previous sections have highlighted the implications of climate change for the agricultural sector, with this section concentrating on the adaptations to the changing environment. In considering these adaptations it is worth reiterating the following points made in the preceding discussion.

Adaptation requires policy change in terms of the regulatory framework, incentives and advice provided. Thus, adaptation to some extent will be centralised and ‘top-down’. There is also a need for adaptation within individual businesses, i.e. decentralised and ‘bottom up’. Adaptation is not just about what individual businesses should do, but will also require cooperation between businesses, across both the industry and with other industries. This is relevant to both adaptations to reduced water availability as well as to increased flood risk.

In practice adaptation is an ongoing process, with many options already being actively used by farmers within England. In many cases this is short term adjustment rather than long term adaptation. Where adaptations are expensive or seen as impractical they will not be adopted. Furthermore, adaptation is based upon perception and if an impact has not been experienced, then an individual will not see the need to adapt for it. This requires raising awareness of climate change, future water availability and use, and the potential for the increased frequency and spread of extreme events such as droughts and flooding. Following recognition of the ‘problem’ will be the need to provide potential solutions, the financial implications and how they can be practically applied.

Potential adaptations fall into a range of categories as follows:

- Moving traditional areas of production, and changing the mix of enterprises
- Changing the management of individual enterprises, adopting different operations and practices and changing the timing of those operations
- Introducing new, and revisiting old, technologies, and similarly, introducing new, and revisiting old, breeding traits
- Investment in infrastructure including buildings, feed storage, manure storage, water storage
- Increased flexibility in enterprise combinations, machinery complements and specifications, and labour use

These adaptations apply equally to managing both flood risk and water availability, with options which can both manage the flood risk and increase the water available in a later time period.

Options to ensure adequate supplies of water in the future will include both options to increase the availability of water (supply side management) and options to save water by reducing its use (demand side management). Within this there should be recognition of the need to increase supply/manage demand within certain areas or, alternatively, move or reduce production. The latter may not always be appropriate or possible.

Options to manage flood risk include restoring natural floodplains, i.e. allowing flooding ‘to occur’ or managing the land in a way to reduce the risk through reduced runoff, improved infiltration and drainage systems, as well as mechanisms to capture flood waters for later use.

For livestock enterprises, the key adaptations need to focus on flexibility in the system with regard to location of livestock (indoors/outdoors) and feed requirements. In terms of water availability and use there are limited options regarding drinking water. The main area for adaptation is within the dairy sector and the washing of plant and machinery, where there are options to both manage demand and supply, partly through adaptations to flood risk management such as rainwater harvesting and winter storage of flood waters, but also in demand management through monitoring, optimising and reducing current water usage.

For cropping enterprises, the key adaptations are changes in where crops are grown, and the type of operations undertaken and their timing. In terms of irrigated cropping, the focus should be on in-field irrigation, rather than the protected crops sector. There is potential for rainwater harvest and winter storage (supply side management), but there is also a need to manage demand through adapting irrigation type/equipment, appropriate scheduling, and development of drought resistant breeds.

The water supply industry also has a role in managing supply and demand. In terms of supply it is the use of winter flood water storage, the transfer of water resources to where they are needed, and water reuse. In terms of demand, the emphasis is on the licensing and abstraction system, education of other industries including agriculture, and increasing efficiency, within both the water supply industry and the industries that it supplies.

No single option is appropriate for every situation, there is a need for a range of options to be employed at both the industry and individual farm level. Adaptation within the industry will be driven by policy, regulation and guidance. What is needed above all is guidance on climate change impacts, awareness of and understanding of potential adaptations, and a means to evaluate potential options at the field, regional and national scales with respect to their practicalities and cost, and how the different options are interlinked.

6 Summary and recommendations for further work

Agriculture occupies 70% of the land within England, with three quarters used for grazing livestock and one quarter for cropping. Within the livestock and cropping sectors, the most valuable enterprises currently are dairying and milk production and horticultural crops respectively, the latter occupying the smallest area of land. Livestock enterprises use approximately 40% of total agricultural water use, field vegetables use another 40%, and the protected and nursery crops sector uses the remaining 20%. A significant proportion of water use by livestock occurs in the west and is fairly evenly distributed throughout the year. Most water use is for drinking, but water is also used for washing down of plant and machinery, particularly within dairy enterprises. Water use for cropping is concentrated in the east and south and occurs during the drier summer period. The dominant use of water for crop enterprises is direct abstraction for irrigation of field crops, with most water abstraction applied to potato and vegetable crops. Polytunnel crops use significant amounts of irrigation water but the process is more efficient than for field crops. In both cases, product quality and profitability are highly dependent on the timing and volume of water applied. Finally, rain fed crops, such as cereals and oilseed crops, which use water indirectly, will also influence water availability.

Abstraction of water is from ground and surface water sources in almost equal amounts. It is worth noting, however, that only 1-2% of total water abstraction in England and Wales, i.e. including all industry sectors, is for the irrigation of outdoor crops. Other sources of water for the agricultural industry include mains water, direct stock drinking from water courses, rain water harvesting and re-use, primarily within the livestock sector.

In order to abstract water, users require an abstraction licence. Data on licences suggests that the amount of water currently abstracted is less than the number of and volume granted under the current licence system. However, the Environment Agency has recently completed an assessment of water availability through the CAMS process. This suggests that in many catchments there is limited water availability and in some cases catchments are over-licensed or over-abstracted. In the four case study sites chosen for this study, three do not have water available during periods of low flow and demand may exceed supply. This is the case for the Medway catchment in Kent, the Harpers Brook catchment in Northamptonshire, and the Teme catchment in the West Midlands. The Eden catchment in Cumbria is currently 'water available'. Nevertheless, there is an increasing need to reduce and make more efficient use of water supplies across all catchments and there may be opportunities, particularly in the Eden and Teme catchments, to store water at times of excess for use in drier periods.

Conversely, seasonality and the duration of flooding are critical factors that affect the impact of flooding and waterlogging on agriculture. Short duration flooding in winter, after establishment, may have a limited impact on grassland and cereals. A flood event in summer, however, could completely destroy a crop of grass or cereals ready for harvest. The most common sources of flooding are from rivers arising as a result of heavy rainfall and in coastal locations due to high tides and stormy conditions. The impact of heavy rainfall and whether or not flooding arises is dependent on field capacity status, soil type and geology. There is a greater risk of flooding on clay soils, which represent almost half of English soils. On agricultural land, previous cropping, drainage systems, and the presence of hedges and ditches and their status will also have an influence.

The impact of climate change will be to change the availability of water in general. The impacts will be spatially and temporally variable. Changes in extremes of water shortage will lead to changes in drought frequency, magnitude and duration. Climate change will increase demand for water, particularly for irrigation, in areas already under pressure. Climate change will also change the magnitude, frequency, distribution (spatially and temporally) and duration of flood events and may even lead to the loss of land in coastal areas and on floodplains. Flood waters are both destructive and rarely available for use in agriculture.

The modelling results for the four catchments suggest a general reduction in annual flows, with a large reduction in summer flows set against a proportionally smaller increase in winter flows. The Eden catchment in Cumbria has the largest winter flow increase, although this does not outweigh the reduced summer flow. Increasing temperatures and evapotranspiration at all sites also reduce soil moisture availability. Generally in all catchments there will be less water available. There is thus a greater frequency of drought risk at all sites particularly in the south and east, as indicated by the results for the Medway and Harpers Brook catchments. Conversely, there is also a greater frequency of flood/waterlogging risk at all sites, particularly in the north and west as indicated by the results for the Eden and Teme catchments. Flood risk at all sites is less likely than the drought risk.

For upland livestock and dairy enterprises such as those found in the Eden catchment changes in forage production and management will be required. A longer growing season for forage and potential increase in yield and dry matter in the early part of the season with possible reductions later on may necessitate more forage conservation early on for both summer buffer and over winter feeding. Changes may also be required in the types of forage grown, switching to crops better suited to the warmer summer conditions. This has implications for the composition of the livestock diet and thus liveweight gain. Appropriate livestock breeds for the changing conditions may need to be addressed. Contingency planning for summer drought and autumn flood risk will be important. Livestock will need access to drinking water, and provision of shelter against weather extremes of sun, rain and wind. Wetter autumns may also necessitate earlier housing of livestock with implications for manure storage as well as over winter feed. Long term, outdoor lambing may need to move indoors. The management of pastures and the surrounding landscape will be key to preventing runoff and soil erosion, helping infiltration and reducing flood risk.

Suggested future research avenues and knowledge transfer areas include grass varieties suited to both extremes of waterlogging and drought, alternative forage crops and their conservation, diet manipulation and liveweight gain, managing weed, pest and disease pressures, in particular grass weeds and disease management for housed livestock, opportunities for rainwater harvesting, and water reuse and treatment.

For lowland livestock enterprises such as those found in the Medway there will be similar issues as for upland livestock, specifically the amount and type of forage production, with a potentially greater potential for new forages and new varieties better suited to drier warmer conditions. There may also be a move away from livestock to more arable production.

In the pig and poultry sector, there are a number of issues dependent on the location of production, generally across all catchments used in this research. The key concerns will be the adequate provision of water during summer drought periods, and the management of the soil to prevent degradation and keeping housing, bedding and feed clean during the wetter periods.

For arable enterprises such as in the Harpers Brook catchment, the key change will be in the timing of operations with a need for greater flexibility in the farm business. Harvest could be compressed or extended dependent on the climate extremes with the potential for subsequent cultivations to be delayed or disrupted. This will require flexibility in crop enterprise choice, particularly decisions on winter versus spring cropping, labour use at peak times, the complement and specification of the machinery, particularly with regard to the type of cultivation carried out, and crop protection programmes. Key areas for research will be in breeding for drought resistance, the management of weed, pest and disease issues, and the viability of slower maturing varieties.

For irrigated root and vegetable crops, the continued production in the south and east, e.g. in the Harpers Brook catchment, is dependent on assuring adequate sources of water for irrigation. In all areas, there will be a need to implement existing technologies more effectively through the use of appropriate scheduling and making sure equipment is set and used to the optimum. Breeding for drought resistance is also a priority, as well as for traits which can improve quality and prevent problems, such as common scab in potatoes, without the need for irrigation. Harvesting in wetter autumns could also prove problematic. There is a balance between growing crops on lighter soils which may lead to problems in drought periods, and growing crops on heavier soils which may lead to harvesting difficulties in wetter autumns. One main area of concern is the continued production of sugar beet in its current location. As with arable crops, the management of new and increased weed, pest and disease pressures will also require further research.

In the horticulture and protected crop sectors, e.g. in the Medway catchment, there will be a need to ensure adequate resources of water within a system that is already a more efficient water user. To some extent this requires policy commitment to continued production within certain areas. In glasshouses, ensuring adequate ventilation may be a concern. Harvesting of rainwater and water re-use may also have potential.

In all sectors the long term use of excess winter rainfall and flood waters through capture and storage should be developed, although this will have implications for annual flows and soil moisture content. Alongside this is the need to review the abstraction licensing systems and the potential for water trading.

For both policy and the agricultural industry as a whole, there are a number of key messages and areas of further work:

- There is a need to focus on managing both water demand and supply
- There will be less water available and demand needs to be reduced with the location of production focused on enterprises which use water more efficiently or, alternatively, moved to areas where water is more readily available
- The alternative is to move water from areas where there are fewer requirements to areas with higher demand
- The better use of excess winter rainfall and flood water through capture and storage presents an opportunity that needs investigation
- The feasibility of water re-use and what is acceptable to the consumer needs to be established
- The emphasis in plant breeding programmes should be on drought resistance
- Crop protection needs to be prepared for new weed, pest and disease pressures

- The management of grassland systems will need to adapt including the introduction/increase of alternative forages within the diet
- Investment in livestock housing, feed (conserved crops) and manure storage may be required
- There are limited opportunities to reduce livestock drinking water requirements or improve the efficiency of water use in the protected crops sector
- In the livestock sector efforts should focus on more efficient use of water for the washing of plant and machinery, particularly within dairy enterprises, through knowledge transfer initiatives regarding opportunities to capture excess winter waters and making better use of available water
- In the irrigated crops sector there is a need for knowledge transfer regarding irrigation techniques and improving application, and research into producing crops with less demand for water focusing on drought resistance and improving quality traits without water use
- Flood risk will increase and farmers should have contingency plans in place
- Land management which reduces flood risk through reducing runoff and increasing infiltration should be encouraged
- There is a need for investment in landscape features, such as hedges, ditches and ponds, to reduce flood risk
- Investment in improving existing drainage systems where appropriate is needed, with recognition that in some areas reverting to natural floodplains may be more appropriate
- Policy, both regulation and incentives, and advice mechanisms should be in place to facilitate adaptation
- This requires appropriate frameworks within which the various stakeholders can communicate and operate and the provision of relevant guidance information.

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Annexe 1 – About the authors

This report was prepared by Dr Matthew B Charlton, Dr Alison Bailey and Prof Nigel Arnell.

Dr Matthew Charlton is a Hydrologist at the Walker Institute and was responsible for the climate impacts reviews and hydrological modelling. He has been involved in several projects concerned with the impacts of climate change on water resources, planning and management, including the Foresight Flood and Coastal Defence Project, the Tyndall Centre task 3.3 programme (limits to adaptation), and the NERC QUEST GSI programme. He is currently involved in research applying the new UKCP09 climate change data. More information on current research can be found at http://www.mbcharlton.com .

Dr Alison Bailey is a Lecturer in the School of Agriculture, Policy and Development whose research focuses on the relationship between agriculture, the environment and socio-economic criteria, and the implications for the farm business. She has particular expertise in working within multi-disciplinary teams. Her work has also covered the broad range of the economics of environmental and natural resource management and environmental policy.

Prof. Nigel Arnell was responsible for coordinating research activities and the overall delivery of research and discussions with RASE. Prof. Arnell has been involved in the IPCC process; he was author of the water chapters in the second and third reports, the Summary for Policymakers in the fourth report and of the IPCC's Technical Report on Climate Change and Water (2008). Prof. Arnell leads research across the University of Reading into improvements in the understanding of climate change processes, the prediction of future climate change, and the assessment of climate change impacts (Arnell et al.2005; 2006).

Annexe 2 – Royal Agricultural Society of England

Since 1840, the Royal Agricultural Society of England has played a leading role in the development of agriculture, the food chain it serves and the rural economy within which it operates. As the independent voice for the sector, the Society encourages innovation, the advancement of science, and effective knowledge exchange.

A thriving agricultural and land-based industry relies upon the rapid uptake of scientific advance. The Society is committed to improving the profitability and competitiveness of rural businesses by providing a link between research and production.

“Practice with Science” is the Society’s motto and still represents its core purpose today. The “Practice with Science” Advisory Group, chaired by Professor David Leaver, is tasked with identifying issues of strategic importance to agriculture, and advising the RASE Executive and Trustees accordingly.

With guidance from the “Practice with Science” Group, the work of the Society’s Agri-Science Department includes:-

- Developing strong relationships with partners working in science, technology and research;
- Commissioning reports on subjects of future strategic importance;
- Organising Seminars & Workshops on key topics.

The “Practice with Science” Group commissioned the report **“Water for Agriculture – Implications for Future Policy & Practice”** to provide more evidence of the state of future water supplies to UK agriculture and horticulture after this was highlighted as a significant concern to future output in the Society’s 2008 report “The Current Status of Soil & Water Management in England”.

The Society has also produced reports on emissions from farm livestock, soil and soil science, and the importance of applied research in agriculture.

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Annexe 3 – Research at Reading

A3.1 Research in the Walker Institute

The *Walker Institute for Climate System Research* is a leading UK research centre based at the University of Reading. The Institute was established in 2006 but integrates groups and departments with international reputation, some of them set up 40 years ago. The Institute includes a range of disciplines crucial for understanding our changing climate and its impacts, including climate and weather processes and modelling, water resources and quality, biodiversity, agriculture, soils and the urban environment. Walker Institute staff are UK leaders in the development of new climate models. Some of the projects, specifically on assessing the implications of climate scenarios for different sectors, include: NERC: QUEST-Global scale impacts of climate change; Environment Agency: Use and interpretation of UKCP09; DECC/Defra: Avoiding dangerous climate change. Walker Institute staff have been involved in all the IPCC Assessments, the Stern Review of the Economics of Climate Change, and many national and international research initiatives. More information can be found at http://www.walker-institute.ac.uk/ .

A3.2 Research in SAPD

Research in SAPD covers the natural and social sciences relating to agriculture, the food chain, rural environments and the countryside, and international development. The School houses the Departments of Agriculture, and Food Economics and Marketing, and the Graduate Institute of International Development and Applied Economics (GIIDAE).

The Department of Agriculture encompasses agricultural production and the environmental goods and services that the rural sector provides. The Department is the focus of teaching, learning and research in animal science, crop science, international development and the environment, and contributes to the University's research themes of Food Chain and Health and the Walker Institute for Climate Systems Research

The Department of Food Economics and Marketing focuses on the economic, policy and wider societal questions connected to the production and consumption of food and fibre in developed and developing countries including the impacts in policy relevant areas such as rural poverty, international development, the environment and dietary health. The Department contributes to the University's research theme of Food Chain and Health and is responsible for conducting the Farm Business Survey within the region.

GIIDAE provides postgraduate courses which explore key social, economic, environmental and political issues from an applied interdisciplinary perspective.

A3.2.1 Animal Science Research Group

The Animal Science Research Group (ASRG) was formed in early 2004 from a merger of the Nutritional Sciences Research Unit (NSRU), the Centre for Dairy Research

(CEDAR) and Biomathematics. The key research strategy of the Group is to carry out research on 'animal-derived food products in human nutrition and long-term health, produced in an environmentally and welfare friendly way while minimising production costs'. Some of this research is in association with the Department of Food and Nutritional Sciences and together they are addressing the University's research theme on food chain and health related issues.

A3.2.2 Crops Research Group

The crops research group focuses on 'temperate and tropical crop physiology from seed development, storage and germination to crop senescence and food quality for sustainable agriculture in current and future environments'. Staff are members of the Crops and Climate Group of the Walker Institute, and have access to numerous facilities including the Crops Research Unit (facilities for field crops research and experimentation) and Seed Science Laboratory (concerned with seed storage, seed vigour, ad seed dormancy).

A3.2.3 Economics Research Group

The Economics Research Group conducts research and policy analysis in a multidisciplinary setting, taking advantage of opportunities presented by new research programmes to extend research interests beyond the areas of historical strength in agriculture and food. The group now also undertake research in the areas of health, biotechnology and the rural environment. Research concerns and takes place in both developed and developing economies and has a strong policy orientation that involves interaction with national and international bodies, both private and public. The group contains a strong core of quantitative economists and also includes expertise in operational research and socio-psychology.

A3.2.4 Environment Research Group

Environmental research is undertaken under the auspices of The Centre for Agri-Environmental Research established in 2000 to build on and integrate the University's strengths in agricultural and environmental research. The focus of research is on the inter-relationships between agricultural land-use and biodiversity, with particular emphasis on agro-ecosystems.

A3.2.5 Livelihoods Research Group

Development research addresses major challenges facing the world in which we all live – poverty, inequality and social justice. The livelihoods research group comprises staff from a range of social science disciplines who study human and social dimensions of economic, institutional, environmental and technological change. They work in both rural and urban areas, and are interested in change across scales, from the individual, household and community, to organisations and national and international policy. They use a mix of quantitative, qualitative and participatory methods in their analysis and often work in collaboration with colleagues from other disciplines at Reading and elsewhere in interdisciplinary teams. Members of the group are engaged in research in over 20 countries around the world.

A3.3 Teaching in SAPD

SAPD offers a wide range of both undergraduate and postgraduate taught degree programmes as well as Higher Degrees by Research. There is a cosmopolitan student body of almost 500 UK and International students (300 undergraduates, around 100 taught postgraduates, and over 100 postgraduate research students), typically from over 40 countries. In our subject area, we are consistently ranked as having teaching of the highest quality by numerous newspaper university subject ratings and by student surveys. Our undergraduate, taught postgraduate and postgraduate research degrees have an international reputation for high quality.

We offer undergraduate degrees in Agriculture, Agricultural Business Management, Animal Science, Environmental and Countryside Management, Food Marketing and Business Economics, and Consumer Behaviour and Marketing.

GIIDAE provides postgraduate courses which explore key social, economic, environmental and political issues from an applied interdisciplinary perspective, ranging from Environment and Development to Food Economics and Marketing. The courses attract high calibre students representing a broad international mix, and include both young graduates and experienced mid-career professionals, creating a unique learning environment for all students.

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