

# The economics of irrigating wheat in a humid climate – A study in the East of England



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## ABSTRACT

In the UK, wheat is the most important cultivated cereal, grown extensively as a rainfed crop. Irrigation of wheat has previously been considered uneconomic, but increases in world wheat prices and recent droughts have led to some farmers revising their views. Widespread adoption of wheat irrigation would have major implications for wheat production, the irrigation industry and water resources in regions that are already water scarce. This study investigated the financial viability of irrigating winter wheat grown on a sandy loam soil in the East of England. Long-term climate data (1961–2011) for Silsoe (Bedfordshire) was used to drive a biophysical crop model to assess irrigation water requirements and yield response. Modelling assumed a typical irrigation schedule to maximise yield and quality, and average reported wheat prices for 2007 to 2012. Irrigation costs were calculated assuming an overhead mobile hose-reel-raingun system applying river water, abstracted either in summer and used directly, or abstracted in winter and stored in an on-farm reservoir.

The results suggest that the yield benefit would justify supplemental irrigation by farmers who have unused irrigation equipment and unused summer water, although irrigation of higher-value field vegetable crops later in the season would normally take precedence – the Added Value of Water (AVW) usefully applied to milling winter wheat under these conditions ranged between 0.24 and 0.32 £ m<sup>-3</sup>. Investment in new irrigation schemes could also be marginally viable if unused summer river water was available for direct abstraction (AVW = 0.08 £ m<sup>-3</sup>). Investments in new farm reservoirs for irrigating wheat are currently not profitable (AVW = −0.23 £ m<sup>-3</sup>). Sensitivity analysis suggests that in the longer term, the expected increase in world wheat prices and the impacts of climate change are likely to make the financial benefits stronger, particularly in the drier catchments further east and on low moisture retentive soils, but competing demands for water would still make extensive wheat irrigation unlikely.

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## 1. Introduction

Wheat production constitutes a significant component of UK agricultural land use and is a major contributor to the UK rural economy. It is an important player in Europe accounting for around 12% of total EU wheat production (Eurostat, 2013). The viability of wheat production is influenced by spatial and temporal variability in agro-climate and soils, since these influence cultivar choice, agronomic husbandry practices and the economics of production. Almost all wheat grown in the UK is rainfed due to the favourable humid climate. However, recent short, intense periods of drought have highlighted the risks to production (Kendon et al., 2013; Marsh et al., 2013). Increasing market prices and demand for high quality wheat have led to many growers re-considering the economics of cereal irrigation. Recent government and scientific studies have also

highlighted how future production is at risk due to a changing climate with increasing temperatures, greater rainfall uncertainty and more frequent extreme events (CCRA, 2012; Knox and Wade, 2012). In future, hotter drier summers, less reliable rainfall and increased drought frequency are projected to further increase the benefits of irrigation in the East of England.

Most of the wheat currently grown in the UK is termed ‘hard’ wheat, with its high protein and starchy gluten content making it suitable for bread-making (milling). Soft wheat milling varieties which have a lower protein and weak gluten content are used for biscuits and other general flour uses while lower quality wheat is used in animal feedstock and for industrial uses including biofuels and starch (Nabim, 2013; UK Agriculture, 2013; Wheat Initiative, 2013). Most wheat is planted in late autumn because the mild UK climate allows the plant to grow through the winter and produce a higher yield and hence a better return (Asby and Renwick, 2000; Spink et al., 2000), although some spring-sown wheat is also grown. It is also mostly grown on heavier soils that are not workable in the spring. In recent years UK wheat production has undergone

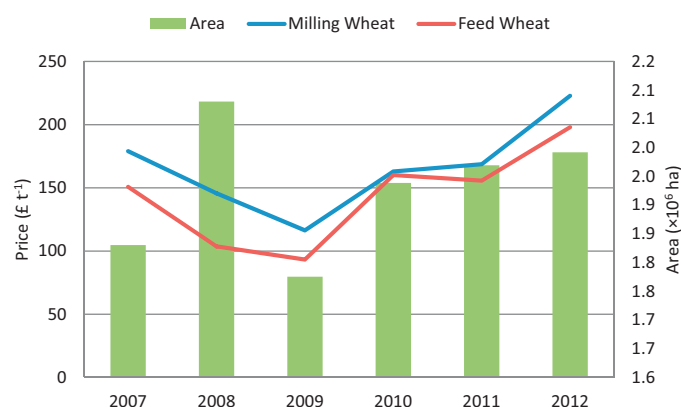
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**Table 1**  
Wheat production summary statistics for England and the East of England for 2011.

Indicator	England	East of England	East of England/ England (%)
Farmed area ( $\times 10^6$ ha)*	8.89	1.38	15.5
Wheat area ( $\times 10^6$ ha)*	1.79	0.50	28.0
Wheat yield ( $\text{t ha}^{-1}$ )	7.73	7.21	93.3
Wheat production (Mt)	13.8	3.6	26.1
Wheat output (million £)	1984.64	573.51	28.9
Total crop output (million £)	7724.42	1979.58	25.6

(Source: Defra, 2011a)

\* Area data relate to 2010.

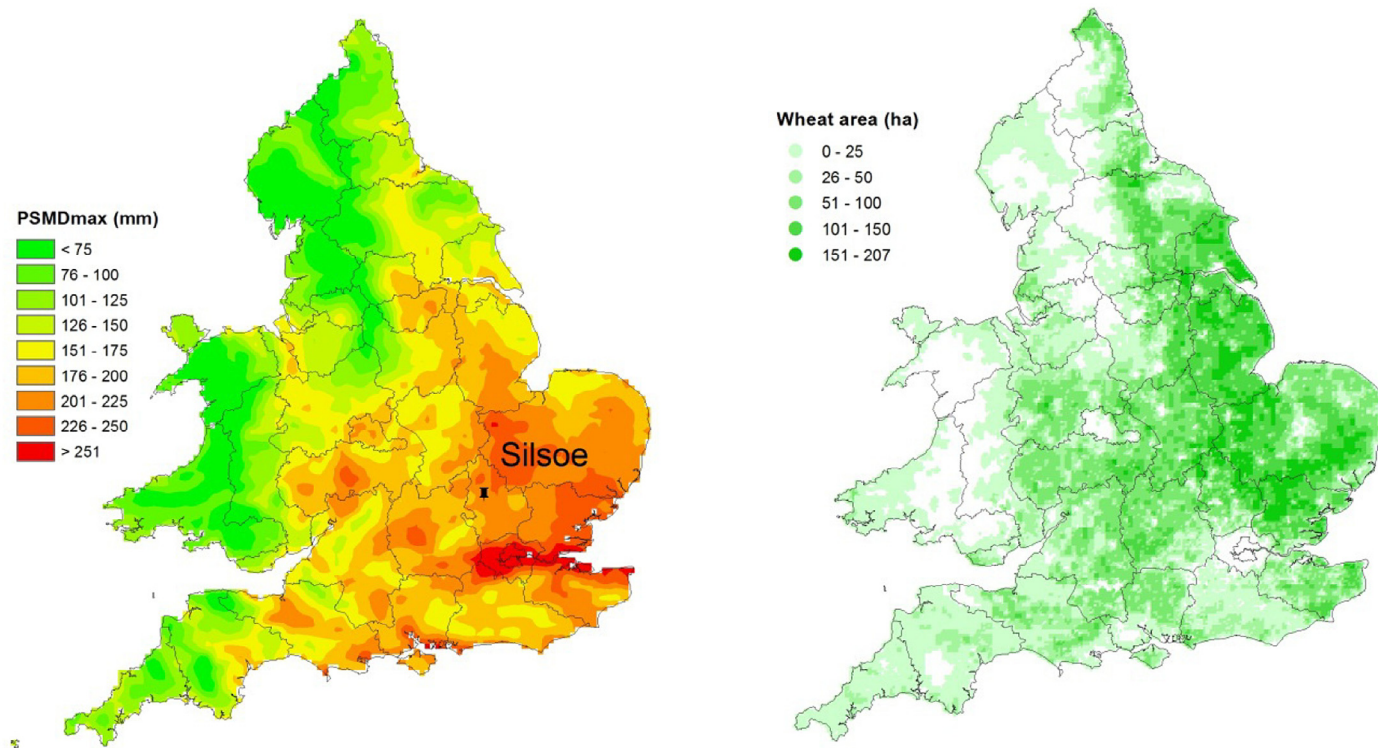


**Fig. 1.** UK wheat area ( $\times 10^6$  ha) and prices (£  $\text{t}^{-1}$ ) between 2007 and 2012 for milling and feed wheat. (Sources: areas Defra, 2012 and prices HGCA, 2013)

significant changes in cropped area as well as in the value of production, the latter essentially reflecting the changes of wheat market prices (Fig. 1). In 2012 wheat accounted for approximately 22% of the UK cropped area, around 1.9 million hectares, and harvested production equated to around 15.3 million tonnes (Defra, 2012).

The East of England is an important agricultural region with a farmed area of about 1.38 million hectares (Table 1). More than a quarter of this is used for wheat production. However yields are slightly lower than the national average (Defra, 2011a). This is also one of the driest regions in England (Fig. 2), which may be a partial explanation for the lower yield. The perceived benefits of irrigating cereals seem to have changed in recent years. Experiments in the late 1970s and 1980s suggested that irrigation did not have a significant impact on cereal yield. A series of field experiments in the East of England (1966–1976), on different barley and spring and winter wheat varieties showed that yield response would range between 0.11 and 0.42  $\text{t ha}^{-1}$  as a response to irrigation and barley up to 1.26  $\text{t ha}^{-1}$ . Research in the late 1990s confirmed that agroclimatic effects can play a considerable role in UK yields of well-managed wheat and estimated 0.29  $\text{t ha}^{-1}$  to 3.82  $\text{t ha}^{-1}$  yield loss as a response to limited soil water-holding capacity depending on soil type (Landau et al., 1998). Landau et al. (2000) assessed four effects they considered to be most important; the negative impacts of climate change on wheat yield due to increased rainfall (increasing water logging risk and increased winter frost damage), and positive effects of higher temperature and increased radiation levels.

The importance of recognising both the genetic and management approaches available to boost UK wheat yields by ameliorating water deficits was stressed by Dodd et al. (2011) who reported on how improved soil and crop management strategies coupled with the development of new genotypes could support increases in wheat yield particularly in situations where water was limiting. The



**Fig. 2.** Long term average (1961–1990) maximum potential soil moisture deficit  $\text{PSMD}_{\text{max}}$  (mm) and wheat cropped area in 2010 (ha per  $4 \text{ km}^2$  grid square) in England and Wales. ( $\text{PSMD}_{\text{max}}$  (mm) is an agroclimatic indicator used as an aridity index to assess the impact of rainfall and ET variability on irrigation demand (e.g. De Silva et al., 2007; Rodríguez Díaz et al., 2007)).

management options considered included both irrigation and growth-promoting rhizobacteria. Similar studies in different humid climates comparable to the UK evaluated the importance of genetics and management practices in a changing climate (Aurbacher et al., 2013; Dhungana et al., 2006; Dueri et al., 2007; Lehmann et al., 2013).

Many recent studies of wheat production in humid climates have focussed on the impacts of climate, but generally considered qualitative factors such as change in grain vigour and hardness, as well as protein content (Atkinson et al., 2005; Swanston et al., 2012; Weightman et al., 2008). Quantitative responses have only been tackled at an experimental level in protected lysimeters or using modelling approaches (e.g. Bacci et al., 1991; Berry and Spink, 2012; Dickin and Wright, 2008; Foulkes et al., 2002; Porter and Semenov, 2005; Richter and Semenov, 2005) to assess the effects of waterlogging and drought on yield and on plant physiological characteristics and responses to drought (e.g. number of shoots per plant, sensitivity of biomass accumulation and leaf senescence to drought, induced changes on root system architecture, and efficiency of root water extraction and extraction rates).

Many of these impacts, especially those related to increasing summer water stress, could theoretically be overcome by supplemental irrigation. However, current literature predicts a general reduction in water availability for UK agriculture as a result of climate change leading to a higher frequency of droughts with drier summers and reduced rainfall (Charlton et al., 2010). Climate change would also increase the irrigation water demand for existing irrigated crops, e.g. by 14–30% for potatoes by the 2050s (Daccache et al., 2011).

Weatherhead et al. (1997) reported that in England irrigation was economic only for high value crops, such as field vegetables and potatoes. However, the rise in wheat price that has occurred over the last few years again raises the question regarding the profitability of irrigating wheat under humid climate conditions. There is very little published evidence regarding the economic returns of irrigating cereals in England or similar humid climates. This study was therefore undertaken as a preliminary investigation into the financial viability of irrigating wheat under current conditions as a basis for further work; that could include an economic assessment under different soil conditions and irrigation systems. Indicators related to water productivity and water value are also presented.

## 2. Materials and methods

The study was divided into the following six stages:

1. Defining a typical wheat-growing farm for modelling assessment;
2. Quantifying the irrigation water requirements (depths applied) under current climate conditions;
3. Estimating the yield response and yield benefits from irrigation;
4. Calculating the costs and benefits of irrigation (assuming a typical overhead application system) and other costs related to wheat production;
5. Conducting a Financial Investment Appraisal (FIA) comparing rainfed with irrigated wheat, and calculating the Added Value of Water (AVW), and;
6. Undertaking a sensitivity analysis to assess the effects of variation in costs and market prices.

### 2.1. Defining a 'typical' farm in the East of England

Cereal farms account for 51% of the total farms number in England and 45% of the total farms number in the East of England; over three quarters (77%) are predominantly wheat-growing farms (Defra, 2011b). The average farm area is about 200 ha (Table 2). The most common method of irrigation in the UK is the mobile hoses reel

**Table 2**

Distribution of farms in England and the East of England (2010) by size (ha) and by cropping pattern.

Farm type	England		East of England	
Total number of farms	53,090		8147	
Total farmed area (ha)	8,137,898		1,592,039	
Average farm size (ha)	153.3		195.4	
Classes of farm size	Number	Percentage	Number	Percentage
<20 ha	15,120	28.5	1776	21.8
20–<50 ha	8365	15.8	883	10.8
50–<100 ha	8151	15.4	990	12.2
≥100 ha	7785	14.7	1232	15.1

(Source: Defra, 2011b).

system, fitted with either a large gun or boom. These are used to irrigate 93% of the total irrigated area. In 2010, surface and ground water provided 36 and 29 Mm<sup>3</sup> for irrigation abstraction, respectively (Defra, 2011c). Most UK irrigators still abstract water in summer for direct application, although it is increasingly common to have an on-farm reservoir because of increasing restrictions on water abstraction during dry summers. These reservoirs can be unlined (or clay lined) or artificially lined; unlined reservoirs are significantly cheaper where soil conditions allow (Weatherhead et al., 2014).

The specification of the case study farm should reflect these regional farm characteristics. We assumed that the farm was 150 ha, practicing rotational agriculture with wheat occupying 50 ha annually. The on-farm irrigation system was a hoses reel fitted with a raingun using an all year abstraction licence from a nearby river, a diesel pump with an unlined farm reservoir. We modelled irrigation needs assuming a deep uniform sandy loam soil, with a soil depth of 4 m and a total available water of 120 mm/m, as irrigation in England is more likely to be used on the lighter, droughtier soils (e.g. Daccache et al., 2011); we note however that most wheat is currently grown on heavier soils where the benefits will be smaller (see methodological limitations).

### 2.2. Quantifying irrigation water requirements (IWR)

The net irrigation water requirements for winter wheat were calculated using data for the period 1961 to 2011 and the AquaCrop model, which can simulate potential yield as a function of water consumption (Steduto et al., 2009). AquaCrop assumes relative evapotranspiration is pivotal in calculating yield. It calculates transpiration and translates it into biomass using the biomass water productivity parameter normalised for atmospheric evaporative demand and air CO<sub>2</sub> concentration (Doorenbos and Kassam, 1979; Steduto et al., 2009). The choice of AquaCrop was based on a review of literature showing that it has been tested under different climate conditions (e.g. García-Vila and Fereres, 2012; Iqbal et al., 2014; Stricevic et al., 2011) and applied to winter wheat in several case studies (e.g. Mkhabela and Bullock, 2012; Singh et al., 2013). Most recently, Vanuytrecht et al. (2014) performed a global sensitivity analysis using AquaCrop for different crop types and contrasting environmental and agro-meteorological conditions, including winter wheat grown in north-western Europe (Belgium), which is not dissimilar from the East of England. Their results showed that under these conditions AquaCrop is most sensitive to soil water characteristics, root development and emergence parameters.

AquaCrop was calibrated and validated against experimental yield data obtained from the Broadbalk wheat experiment at Rothamsted Experimental Research Station (Harpenden, UK). Yield data were selected from the 'modern' period of the experiment (1968–2013), when high yielding short-straw wheat varieties were grown, with full weed and disease control. The soil was clay loam to silty



clay loam over clay-with flints. Different winter wheat varieties were grown with different management techniques (e.g. continuous wheat or rotational wheat and different fertilisation treatments). Two independent 5 year datasets of continuous winter wheat under constant management techniques were selected. For calibration, the independent dataset was from a fully fertilised treatment (Section 9 Plot 16: 288 kg N ha<sup>-1</sup> yr<sup>-1</sup> plus PKNaMg) growing “Apollo” winter wheat variety (1991–1995); the validation was performed on a dataset from a plot of ‘no fertilisation’ since 1843 (Section 9 Plot 3) growing “Hereward” winter wheat variety (2000–2004).

Under typical UK climate conditions, irrigation on wheat is not generally needed before April, and it is recommended to stop before the beginning of June with the initiation of flowering (Ashraf, 1998; Mark and Antony, 2005). Furthermore, experimental studies in the East of England in the 1990s showed that irrigation on cereals after flowering would increase the risk of lodging (Bailey, 1990). A small deficit should ideally be maintained in the rootzone to maximise the effective use for rainfall. Therefore, in this study, the irrigation schedule was defined with the following criteria:

- Irrigation period: 1 April–1 June
- Timing: irrigate at a 50 mm soil moisture deficit (SMD)
- Amount: apply 25 mm application

Climate data used in this study were daily data (1961 to 2011) from a weather station located at Silsoe, Bedfordshire (52.00 °N, 0.41 °W). Data included rainfall, reference evapotranspiration (ET<sub>0</sub>) and maximum and minimum temperature. The use of a long period is required to provide stochastic stability and ensure sufficient dry and wet years are included, but it risks including data that may no longer be relevant with climate change. However, statistical analysis (Student *t*-test) confirms that there has been no significant change in modelled irrigation requirements for the wheat crop at this site between the first and second half of this 50 year period.

### 2.3. Assessing the costs and benefits of irrigation

Cost–benefit analysis is a useful approach to assess the financial viability of a project. It has many applications in agricultural irrigation where it can identify differences, from an economic point of view, between criteria such as profit, profit/operation costs, profit/investment costs, profit/total costs and the break-even point (Layard and Glaister, 1994; Mishan and Quah, 2007; Romero et al., 2006). Financial Investment Appraisal (FIA) is a form of cost–benefit analysis that seeks to identify the costs and benefits of an investment from the point of view of a private individual or organisation.

The net benefit from wheat irrigation is taken here as the difference between the additional income and additional costs. The additional income is defined as the yield increase multiplied by the market value; any additional variable costs of harvesting, drying and storing the additional yield, as well as any reduced costs or increased benefits due for example to more uniform yield and/or higher or more consistent quality, have been ignored here for simplicity.

There are two major elements of the additional irrigation cost. The abstraction charges are calculated here based on Environment Agency charges for 2013/14 (EA, 2013). The costs of the irrigation itself, comprising investment, maintenance, labour and fuel or energy costs are based on an updated analysis of detailed irrigation costs by Ahodo (2012) and Morris et al. (2014).

The focus of this paper is on the revenue changes between rainfed and irrigated. For comparison and context only, the typical costs for all other activities and practices carried out on-farm for the production of the wheat are also presented, based on an integration of forecast figures for the 2012 harvest year from ABC (2012) and from survey data from Nix (2011). However it should be noted that

these other production costs are almost identical for rainfed and irrigated wheat production, and hence cancel out when assessing the net benefits of irrigation.

### 2.4. Sensitivity analysis

Wheat price trends for the last decade indicate very significant net price fluctuations. The cereal price index has been generally increasing since 2000 and prices by 2022 are projected to be between 12% and 27% above those of the previous decade (FAO, 2013; OECD/FAO, 2013; USDA, 2013; Willenbockel, 2011). However, oil prices are also expected to continue their upward trend, with forecasts up to a 60% rise by 2035 to reach a price of 250 US\$ per barrel (IEA, 2013); fuel price is one of the major factors influencing operating costs for irrigated crops (Amosson et al., 2011) and the capital costs for reservoir construction. Therefore, a sensitivity analysis was carried out to find out how the added value of winter wheat would respond to price fluctuations and variations in the total costs of production.

## 3. Results

This section first describes the different derived costs and benefits, divided between milling winter wheat and feed winter wheat. The results are then compared to rainfed wheat production (the counterfactual) to assess the FIA of an irrigated wheat farm.

### 3.1. Irrigation water requirements and yield estimates

The net irrigation water requirements for the 50 crop years (1961 to 2011) were modelled and ranked. The financial analysis is presented below for three different types of ‘weather year’, based on those ranked irrigation needs, plus the ‘overall mean’ values:

- ‘Wet years’, based on the means of the 25% with lowest irrigation need;
- ‘Normal years’, defined as the means of the central 50% years ranked on irrigation need;
- ‘Dry years’, based on the means of the 25% with highest irrigation need;
- ‘Overall mean’, showing the means calculated across all 50 years.

The irrigation water requirements (IWR) and the rainfed and irrigated yields (t ha<sup>-1</sup>) for each of these climate years and the overall mean are shown in Table 3. There is a marked difference in rainfed yield between wet and dry years; the differences are substantially removed when irrigation is practiced. The small difference in the simulated yield between wet and normal years with irrigation (which should remove most of the water stress) could be related to the sensitivity of AquaCrop to canopy and phenological development parameters and to temperature stress, as noted by Vanuytrecht et al. (2014), in particular the “period from sowing to emergence”, the “total length of crop cycle from sowing to maturity”, and the

**Table 3**

Summary of irrigation water requirements (IWR) (mm) and modelled yield (t ha<sup>-1</sup>) for rainfed and irrigated winter wheat grown on a sandy loam soil at Silsoe, (1961–2011).

Weather year	IWR (mm)	Wheat yield (t ha <sup>-1</sup> )	
		Rainfed	Irrigated
Wet years	16.7	7.8	8.0
Normal years	58.7	7.2	8.2
Dry years	112.5	2.1	7.8
Overall mean	61.5	5.8	7.7

“minimum growing degrees for full biomass production” all of which are directly affected by temperature.

The results of the correlation for the calibration and the validation process showed that the shape of simulated yield matched the shape of the observed yield data with reasonable accuracy (Fig. 3); the goodness of fit represented by  $R^2$  was 0.81 for calibration and 0.54 for validation.

### 3.2. Irrigation abstraction charges

The abstraction charges (Table 4) have been calculated taking into consideration the annual abstraction charge Eq. (1), as set by the Environment Agency for the irrigation season 2013/14 for spray irrigation in the Anglian Region (EA, 2013).

$$\text{Annual Abstraction Charge} = \text{Standard Charge} + \text{Compensation Charge} \quad (1)$$

The standard charge is calculated under a ‘two part’ tariff; half is based on the authorised maximum annual volume specified in the licence, and the other half is based on the volume actually abstracted in that year. The authorised maximum annual quantity has been taken here (for costing purposes only) as the average water requirement in a dry year (i.e. 1125 m<sup>3</sup>). The compensation charge is an amount currently added to the standard charge by the regulator for the recovery of compensation costs associated with the revocation or variation of abstraction licences. The annual abstraction charge is related to weather years due to the change in irrigation need. However, most importantly it is also affected by the abstraction season as it increases tenfold between winter and summer (irrigation season) abstraction periods.

**Table 4**

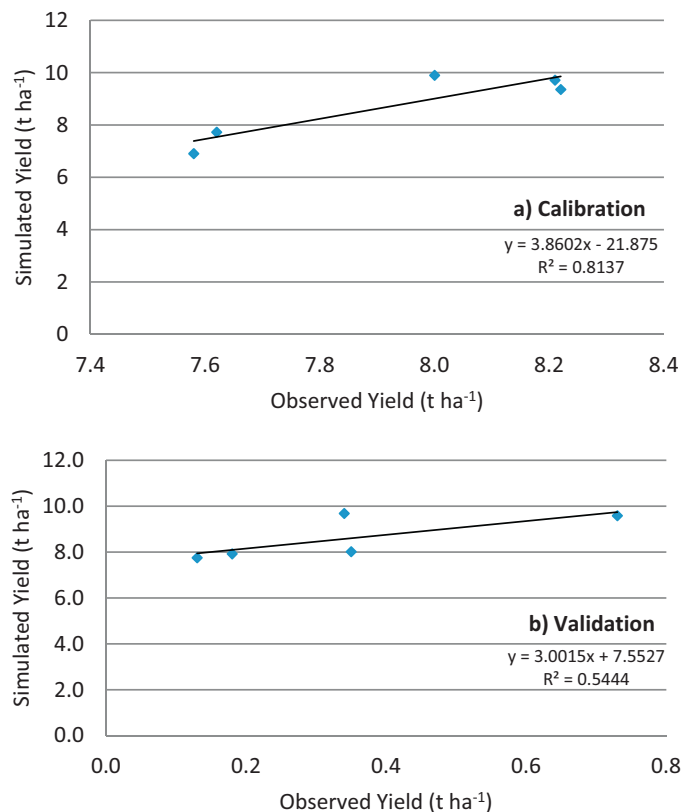
Estimated abstraction charges for irrigating winter wheat grown on a sandy loam soil at Silsoe (Beds), for summer and winter abstraction periods.

Summer abstraction	Wet years	Normal years	Dry years	Overall mean
IWR (m <sup>3</sup> ha <sup>-1</sup> )	167	587	1,125	615
Annual charge (£ m <sup>-3</sup> )	0.044	0.044	0.044	0.044
Part 1 tariff (£ ha <sup>-1</sup> )	24.8	24.8	24.8	24.8
Part 2 tariff (£ ha <sup>-1</sup> )	3.7	12.9	24.8	13.5
Compensation charge (£ ha <sup>-1</sup> )	24.7	24.7	24.7	24.7
<b>Annual abstraction charge (£ ha<sup>-1</sup>)</b>	<b>53.1</b>	<b>62.4</b>	<b>74.2</b>	<b>63.0</b>
Winter abstraction	Wet years	Normal years	Dry years	Overall mean
IWR (m <sup>3</sup> ha <sup>-1</sup> )	167	587	1,125	615
Annual charge (£ m <sup>-3</sup> )	0.007	0.007	0.007	0.007
Part 1 tariff (£ ha <sup>-1</sup> )	2.5	2.5	2.5	2.5
Part 2 tariff (£ ha <sup>-1</sup> )	0.4	1.3	2.5	1.4
Compensation charge (£ ha <sup>-1</sup> )	2.5	2.5	2.5	2.5
<b>Annual abstraction charge (£ ha<sup>-1</sup>)</b>	<b>5.3</b>	<b>6.2</b>	<b>7.4</b>	<b>6.3</b>

Bold values = products or totals.

### 3.3. Irrigation costs

The vast majority (93%) of irrigation applied in England is via hose-reel irrigators. These are the most cost-efficient for the farming system and location (where seasonal depths applied are relatively low), and would certainly be the systems used for any wheat irrigation in the UK. There are only a few centre pivots, and drip irrigation would be quite unsuitable; either method would be more expensive, and even less likely to be financially viable. We therefore base



**Fig. 3.** Calibration (a) and validation (b) outputs from the AquaCrop wheat yield simulations.

the cost analysis on the typical hose-reel irrigation systems used in England and northern Europe.

Drawing on a study of farm irrigation practices on potatoes, Ahodo (2012) calculated the typical UK irrigation costs. We used these data to calculate the costs for irrigating wheat. The fixed costs are the amortised capital costs of the in-field irrigation system, the pump and the mainline pipe, assuming a real interest rate of 6% (Eq. (2)) and a useful lifespan of 15 years for machinery (irrigation system, pumps) and 20 years for irrigation infrastructure (reservoir construction). Insurance and maintenance costs of 1% were assumed and included in the fixed costs. We considered that the system would need 1500 m of underground mainline pipe.

The variable costs are labour, the running costs of the tractor for moving the irrigator between pulls, and energy consumption at the pump; these all depend on the total amount of water applied. We assumed the pumping system generates 11 kW per hour per litre of diesel at 0.725 £ L<sup>-1</sup> at 60% pump efficiency and a total pressure head of 81 m, including head losses of the pipes and the gun pressure head; thus, irrigation costs vary from a wet year to a dry year (Fig. 4).

The variable costs of the hose-reel-raingun system vary three-fold from a wet year to a dry year due to the change in the IWR. Yet, this only affects the total system cost by approximately 10% as a mean because variable costs represent only 7–21% of the total irrigation system cost. In the UK, many growers already have an irrigation system for vegetable and root crops (e.g. potatoes) which is not fully utilised until the beginning of June and could be used to irrigate cereals during April and May. In this case, irrigation costs would be substantially lower (and reduced to just the variable costs if all the fixed costs were carried by the vegetable crops). Growers may also need to invest in on-farm winter storage (reservoir), depending on their local water resource availability and reliability of summer abstraction. Reservoir construction costs were calculated here based on Ahodo (2012), assuming an unlined reservoir, i.e. one without a plastic liner. These are typically constructed in clay soils, and so have very low leakage losses. Ahodo (2012) used industry survey data to correlate the capital cost of the reservoirs to the total storage capacity (Eq. (3)). A capacity of 68,960 m<sup>3</sup> was assumed corresponding to the IWR for 50 ha wheat in a dry year. An interest rate of 6% and insurance and maintenance costs of 1% were used as before to calculate fixed costs (Fig. 5). The additional variable costs of using the reservoir shown are the additional pumping cost from the sources to the reservoir assuming the same pump characteristics as previously and 1500 m of additional pipeline to link the river to the reservoir and the irrigated area; the cost of pumping from either the river or the reservoir to the field was included in the irrigation costs.

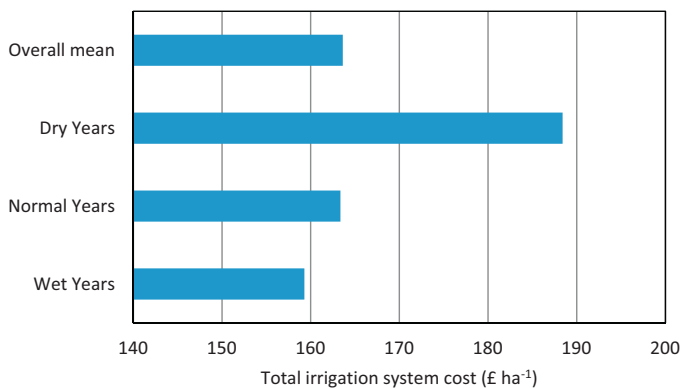


Fig. 4. Total irrigation costs (£ ha<sup>-1</sup>) for a hose-reel-raingun irrigation system, excluded water supply.

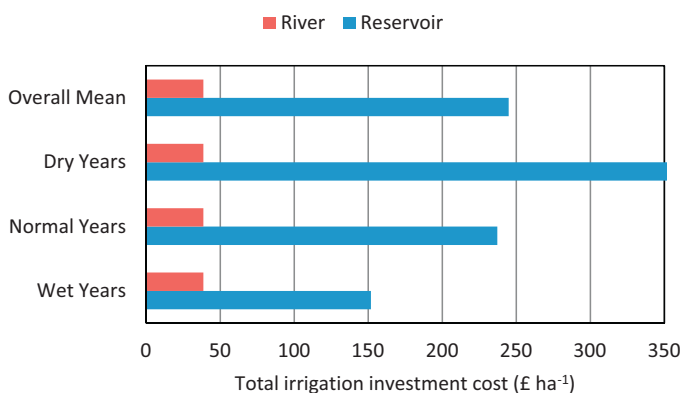


Fig. 5. Estimated total costs (£ ha<sup>-1</sup>) of the investment in water supply from river abstraction (winter river abstraction via a reservoir versus direct summer river abstraction).

$$\text{Amortisation} = \text{Capital Cost} \times \left[ \frac{i \times (1+i)^n}{(1+i)^n - 1} \right] \quad (2)$$

$$\begin{aligned} \text{Unlined Reservoir Cost (£)} \\ = (0.9071 \times \text{Volume of Water (m}^3\text{)} + 17938 \end{aligned} \quad (3)$$

### 3.4. Benefits of wheat production

The estimated benefit deriving from wheat production, expressed in terms of net margin, depends on yields, prices and cost components (Eq. (4)):

$$\begin{aligned} \text{Net Margin (£)} = [\text{Yield (t)} \times \text{Price (£ t}^{-1}\text{)}] \\ - [\text{Production Cost (£)} + \text{Irrigation Cost (£)}] \end{aligned} \quad (4)$$

The UK market wheat prices for both milling and feed wheat have fluctuated over the last six years in response to the world volatility of wheat prices due to the increase of demand and the reduction of the world production (Thompson et al., 2012). For this research, we consider the six-year average price (2007–2012) reported by HGCA (2013) at 165.9 £ t<sup>-1</sup> for milling winter wheat and 143.6 £ t<sup>-1</sup> for feed winter wheat.

### 3.5. Financial investment appraisal

We considered four cases depending on the level of investment required, including investing in a new irrigation system with (1) and without (2) a new reservoir, and using an existing irrigation system with (3) and without (4) an existing reservoir. Development without a reservoir is only feasible where farmers have access to unused summer water, i.e. a reliable surface or groundwater supply with a summer abstraction licence. For each case, we considered whether irrigation is viable at current prices, and then used a sensitivity analysis to assess how changes in irrigation costs and wheat prices might affect the outcome.

For each case, the financial investment appraisal (FIA) is based on the extra net benefit, which is the difference between the net rainfed and irrigated benefits per hectare. The added value of the water applied (AVW) (£ m<sup>-3</sup>) is then calculated from the extra net benefits (£ ha<sup>-1</sup>) divided by the amount of irrigation water (m<sup>3</sup> ha<sup>-1</sup>). The sensitivity analysis, calculated on the overall mean values and shown here only for milling winter wheat, then considers how this value changes as total production costs (including irrigation costs and abstraction charges) and wheat prices vary by an arbitrary ±20% and ±40%.

**Table 5**

FIA for irrigated wheat versus rainfed wheat, with investment in a new irrigation system and a new reservoir (Case 1).

Crop	Wet years		Normal years		Dry years		Overall mean	
	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.
Milling winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	165.9	165.9	165.9	165.9	165.9	165.9	165.9	165.9
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1294.3</b>	<b>1327.4</b>	<b>1194.7</b>	<b>1360.6</b>	<b>348.5</b>	<b>1294.3</b>	<b>962.4</b>	<b>1277.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	5.3	–	6.2	–	7.4	–	6.3
Irrigation cost (£ ha <sup>-1</sup> )	–	159.3	–	163.4	–	188.4	–	163.6
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	151.8	–	237.2	–	383.1	–	244.8
Production costs (£ ha <sup>-1</sup> )	802.7	802.7	802.7	802.7	802.7	802.7	802.7	802.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>802.7</b>	<b>1173.7</b>	<b>802.7</b>	<b>1248.1</b>	<b>802.7</b>	<b>1420.3</b>	<b>802.7</b>	<b>1256.0</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>491.5</b>	<b>153.7</b>	<b>392.0</b>	<b>112.5</b>	<b>–454.3</b>	<b>–126.0</b>	<b>159.7</b>	<b>21.6</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–337.8</b>		<b>–279.5</b>		<b>328.2</b>		<b>–138.1</b>
Feed winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1120.1</b>	<b>1148.8</b>	<b>1033.9</b>	<b>1177.5</b>	<b>301.6</b>	<b>1120.1</b>	<b>832.9</b>	<b>1105.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	5.3	–	6.2	–	7.4	–	6.3
Irrigation cost (£ ha <sup>-1</sup> )	–	159.3	–	163.4	–	188.4	–	163.6
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	151.8	–	237.2	–	383.1	–	244.8
Production costs (£ ha <sup>-1</sup> )	763.7	763.7	763.7	763.7	763.7	763.7	763.7	763.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>763.7</b>	<b>1134.7</b>	<b>763.7</b>	<b>1209.1</b>	<b>763.7</b>	<b>1381.3</b>	<b>763.7</b>	<b>1217.0</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>356.4</b>	<b>14.1</b>	<b>270.2</b>	<b>–31.6</b>	<b>–462.2</b>	<b>–261.2</b>	<b>69.2</b>	<b>–111.3</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–342.3</b>		<b>–301.8</b>		<b>201.0</b>		<b>–180.5</b>

Bold values = products or totals.

### 3.5.1. Investing in a new irrigation system and reservoir (Case 1)

The results (Table 5) show that there is no advantage in irrigating wheat if both a new irrigation system and a new reservoir are needed, given the very high capital investment required. The positive benefits in dry years are outweighed by the additional costs across other years. In all years the benefits are higher for milling winter wheat than feed winter wheat, but the profitability of irrigated wheat is always lower than rainfed. For the production costs and wheat prices modelled, the irrigation water has an overall mean negative added value (AVW) of  $-0.23$  £ m<sup>-3</sup> for milling winter wheat (and  $-0.29$  £ m<sup>-3</sup> for feed winter wheat). The sensitivity analysis for milling winter wheat (Table 6) shows that for the same average wheat price, the added value of water becomes positive (i.e. irrigation is beneficial) only if total production costs decrease by 20%. Similarly, at the modelled production costs, even a 40% increase in market price would not make investment viable.

### 3.5.2. Investing in a new irrigation system without a reservoir (Case 2)

In most catchments in the East of England, it is no longer possible to obtain a new licence for low-flow abstraction during the summer months. However many farmers do have unused summer abstraction licences, perhaps as a result of previous cropping pat-

terns. But even if summer water is available, investing in a new irrigation system for the purpose of irrigating the wheat would only be marginally financially justifiable (Table 7). The FIA result is positive in the dry years and for the overall mean, though negative in the wet and normal years, for both crops. The benefits are again higher for milling winter wheat than for feed winter wheat.

The sensitivity analysis for milling winter wheat (Table 8) shows how responsive the investment in this case is to wheat price and total production cost. Even a small increase in costs, or less than a 20% reduction in wheat price, would render the investment unprofitable.

### 3.5.3. Using an existing irrigation system with an existing reservoir (Case 3)

If a farmer has existing unused equipment available in April and May as well as unused reservoir water, then the additional costs will be limited to the variable cost (Table 9). In this case, irrigating milling wheat would be beneficial in all but wet years, which are easily offset by the substantial benefits in the dry years. Feed winter wheat is only profitable in dry years, but this is still sufficient for it to be profitable overall. Consequently, the sensitivity analysis for milling winter wheat shows a small positive added value of water (AVW = 0.24) (Table 10), and the investment is reasonably robust against a fall in wheat prices or a small increase in total costs.

### 3.5.4. Using an existing irrigation system without a reservoir (Case 4)

This final case considers a farmer who has existing unused equipment available for use during April and May as well as unused summer water that does not need on-farm storage. The higher abstraction charges are more than offset by the reduced variable cost of not using a reservoir, so the benefits are higher than in Case 3 (Table 11). The sensitivity analysis (Table 12) for milling wheat now shows that irrigation remains profitable even with a 40% decrease in wheat price or a 20% increase in total costs.

**Table 6**Sensitivity of AVW (£ m<sup>-3</sup>) to price and total production costs, for irrigating milling winter wheat, with investment in a new irrigation system and new reservoir (Case 1).

Cost (£ ha <sup>-1</sup> )	Price (£ t <sup>-1</sup> )				
	–40%	–20%	165	+20%	+40%
–40%	0.39	0.49	0.59	0.69	0.79
–20%	–0.02	0.08	0.18	0.28	0.39
1256	–0.43	–0.33	<b>–0.23</b>	–0.13	–0.02
+20%	–0.84	–0.74	–0.64	–0.53	–0.43
+40%	–1.25	–1.15	–1.04	–0.94	–0.84

Bold values = central values.



**Table 7**

FIA for irrigated wheat versus rainfed, with investment in a new irrigation system but no reservoir (Case 2).

Crop	Wet years		Normal years		Dry years		Overall mean	
	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.
Milling winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	165.9	165.9	165.9	165.9	165.9	165.9	165.9	165.9
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1294.3</b>	<b>1327.4</b>	<b>1194.7</b>	<b>1360.6</b>	<b>348.5</b>	<b>1294.3</b>	<b>962.4</b>	<b>1277.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	53.1	–	62.4	–	74.2	–	63.0
Irrigation cost (£ ha <sup>-1</sup> )	–	160.9	–	163.4	–	188.4	–	163.6
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	–	–	–	–	–	–	–
Production costs (£ ha <sup>-1</sup> )	802.7	802.7	802.7	802.7	802.7	802.7	802.7	802.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>802.7</b>	<b>1053.7</b>	<b>802.7</b>	<b>1067.0</b>	<b>802.7</b>	<b>1103.9</b>	<b>802.7</b>	<b>1067.9</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>491.5</b>	<b>273.7</b>	<b>392.0</b>	<b>293.6</b>	<b>–454.3</b>	<b>190.3</b>	<b>159.7</b>	<b>209.8</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–217.8</b>		<b>–98.4</b>		<b>644.6</b>		<b>50.1</b>
Feed winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1120.1</b>	<b>1148.8</b>	<b>1033.9</b>	<b>1177.5</b>	<b>301.6</b>	<b>1120.1</b>	<b>832.9</b>	<b>1105.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	53.1	–	62.4	–	74.2	–	63.0
Irrigation cost (£ ha <sup>-1</sup> )	–	160.9	–	163.4	–	188.4	–	163.6
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	–	–	–	–	–	–	–
Production costs (£ ha <sup>-1</sup> )	763.7	763.7	763.7	763.7	763.7	763.7	763.7	763.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>763.7</b>	<b>1014.7</b>	<b>763.7</b>	<b>1028.0</b>	<b>763.7</b>	<b>1064.9</b>	<b>763.7</b>	<b>1028.9</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>356.4</b>	<b>134.1</b>	<b>270.2</b>	<b>149.5</b>	<b>–462.2</b>	<b>55.2</b>	<b>69.2</b>	<b>76.8</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–222.3</b>		<b>–120.7</b>		<b>517.3</b>		<b>7.7</b>

Bold values = products or totals.

#### 4. Discussion

The financial analysis presented here suggests that the irrigation of a wheat crop grown on sandy loam soil in eastern England is only financially beneficial compared to rainfed wheat under limited combinations of crop and weather conditions (Table 13). This study suggests that at the modelled costs and wheat prices, over an average run of weather years with the recorded climate (1961–2011):

- Average irrigation water requirements would be  $\approx 62$  mm;
- Irrigation could increase average yield by  $\approx 1.9$  t ha<sup>-1</sup>, with the main benefit in dry years and in reducing inter-annual variation in yield.
- The yield benefit would justify irrigation by farmers with both unused irrigation equipment and unused summer water or (less beneficially) unused reservoir water (cases 4 and 3).
- It would marginally justify investment in a new irrigation system with available unused summer water from direct river abstraction, but not requiring a new storage reservoir; this would become more profitable if the wheat price rose relative to other costs (case 2).

**Table 8**Sensitivity of AVW (£ m<sup>-3</sup>) to price and total production costs, for irrigating milling winter wheat, with investment in a new irrigation system but no reservoir (Case 2).

Costs (£ ha <sup>-1</sup> )	Prices (£ t <sup>-1</sup> )				
	–40%	–20%	165	+20%	+40%
–40%	0.57	0.67	0.77	0.88	0.98
–20%	0.22	0.32	0.43	0.53	0.63
1068	–0.13	–0.02	<b>0.08</b>	0.18	0.28
+20%	–0.47	–0.37	–0.27	–0.17	–0.06
+40%	–0.82	–0.72	–0.62	–0.51	–0.41

Bold values = central values.

- It would require very major changes in wheat prices to justify investment in a new irrigation system needing a new farm reservoir (case 1).

The net irrigation benefits are highest (and all positive) in dry years, but only farmers with existing equipment can respond in the short term. Irrigation can hence be financially viable for farmers with unused equipment and unused summer water. However, these dry years are also when water resources are scarcest, and the results for the added value of the water (£ m<sup>-3</sup>) are much lower than for most of the other crops presently irrigated, and which would therefore take priority.

Irrigation investment in new schemes with direct abstraction may be justified for some farms with cheaper than average irrigation costs, in drier areas or on lighter soils, and/or growing more responsive varieties, or where the capital costs are shared across other crops. There may also be quality benefits and benefits from a more predictable wheat yield, which we have not considered in this analysis.

In the short term we might therefore reasonably expect to see some increased water demand for irrigation of wheat by farmers with unused summer water, either employing existing (unused) irrigation system capacity or installing new systems whose capital costs are justified by other crops in the rotation. However there will be very limited investment in new facilities specifically for wheat irrigation, particularly reservoirs, unless there is a sustained major increase in the wheat price. In practice, water scarcity and its higher potential value for irrigating other crops later in the season will still limit its use on wheat.

Nevertheless, even this limited change could still have important implications for irrigation water demand. Many UK farmers have unused summer licences due to historic changes in cropping patterns, and most of these farmers are currently growing cereals. Even in a dry year, less than half the water licenced for irrigation in England and Wales is abstracted. Irrigation of wheat could therefore reawaken some so-called “sleepers” licences, with serious knock-on impacts on downstream water users and the environment.



**Table 9**

FIA for irrigated wheat versus rainfed wheat, using an existing irrigation system and reservoir (Case 3).

Crop	Wet years		Normal years		Dry years		Overall mean	
	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.
Milling winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	165.9	165.9	165.9	165.9	165.9	165.9	165.9	165.9
<b>Total Output (£ ha<sup>-1</sup>)</b>	<b>1294.3</b>	<b>1327.4</b>	<b>1194.7</b>	<b>1360.6</b>	<b>348.5</b>	<b>1294.3</b>	<b>962.4</b>	<b>1277.7</b>
Abstraction Charge (£ ha <sup>-1</sup> )	–	5.3	–	6.2	–	7.4	–	6.3
Irrigation Cost (£ ha <sup>-1</sup> )	–	11.7	–	15.8	–	40.8	–	16.0
River Abstraction Cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir Storage Cost (£ ha <sup>-1</sup> )	–	57.6	–	102.1	–	195.8	–	107.0
Production Costs (£ ha <sup>-1</sup> )	802.7	802.7	802.7	802.7	802.7	802.7	802.7	802.7
<b>Total Costs (£ ha<sup>-1</sup>)</b>	<b>802.7</b>	<b>915.9</b>	<b>802.7</b>	<b>965.4</b>	<b>802.7</b>	<b>1085.3</b>	<b>802.7</b>	<b>970.6</b>
<b>Total Benefits (£ ha<sup>-1</sup>)</b>	<b>491.5</b>	<b>411.5</b>	<b>392.0</b>	<b>395.2</b>	<b>–454.3</b>	<b>209.0</b>	<b>159.7</b>	<b>307.0</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–80.0</b>		<b>3.2</b>		<b>663.2</b>		<b>147.3</b>
Feed winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
<b>Total Output (£ ha<sup>-1</sup>)</b>	<b>1120.1</b>	<b>1148.8</b>	<b>1033.9</b>	<b>1177.5</b>	<b>301.6</b>	<b>1120.1</b>	<b>832.9</b>	<b>1105.7</b>
Abstraction Charge (£ ha <sup>-1</sup> )	–	5.3	–	6.2	–	7.4	–	6.3
Irrigation Cost (£ ha <sup>-1</sup> )	–	11.7	–	15.8	–	40.8	–	16.0
River Abstraction Cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir Storage Cost (£ ha <sup>-1</sup> )	–	57.6	–	102.1	–	195.8	–	107.0
Production Costs (£ ha <sup>-1</sup> )	763.7	763.7	763.7	763.7	763.7	763.7	763.7	763.7
<b>Total Costs (£ ha<sup>-1</sup>)</b>	<b>763.7</b>	<b>876.9</b>	<b>763.7</b>	<b>926.4</b>	<b>763.7</b>	<b>1046.3</b>	<b>763.7</b>	<b>931.6</b>
<b>Total Benefits (£ ha<sup>-1</sup>)</b>	<b>356.4</b>	<b>271.9</b>	<b>270.2</b>	<b>251.1</b>	<b>–462.2</b>	<b>73.8</b>	<b>69.2</b>	<b>174.1</b>
<b>FIA (£ ha<sup>-1</sup>)</b>		<b>–84.5</b>		<b>–19.1</b>		<b>536.0</b>		<b>104.9</b>

Bold values = products or totals.

However, it is unknown how many of these farmers still have a viable irrigation system.

In the longer term, with an expected increase in grain prices irrigation could become profitable for more farmers. A changing climate, with greater rainfall uncertainty and increased drought frequency could lead to much wider uptake of supplemental irrigation on wheat and other cereal crops in dry years in the most arid parts of the country. The benefits of irrigating barley, and particularly spring malting for the high value distilling market, could be significantly higher. These issues and their sensitivity warrant further research.

This study has importance at regional and national levels since it deals with irrigation of an economically important crop grown extensively in a water scarce region, and the issues raised have relevance internationally wherever similar conditions apply. The preliminary findings should be of relevance to policy and decision-makers and farmers. However, the results do need to be verified against grower evidence and experience. Therefore, further collaboration is required with wheat growers to gather yield data over a number of dry years to validate the crop model. Other farm data relating mainly to the different components of irrigation systems, additional costs resulting from incremental yield, and any non-yield benefits such as higher grain quality, which have currently been excluded from this study, should also be included to help increase the confidence in the modelled outputs.

**Table 10**Sensitivity of AVW (£ m<sup>-3</sup>) to price and total production costs, for irrigating milling winter wheat, using an existing irrigation system and reservoir (Case 3).

Costs (£ ha <sup>-1</sup> )	Prices (£ t <sup>-1</sup> )				
	–40%	–20%	165	+20%	+40%
–40%	0.66	0.77	0.87	0.97	1.07
–20%	0.35	0.45	0.55	0.65	0.76
971	–0.03	0.13	<b>0.24</b>	0.34	0.44
+20%	–0.28	–0.18	–0.08	0.02	0.12
+40%	–0.60	–0.50	–0.39	–0.29	–0.19

Bold values = central values.

## 5. Methodological limitations

This research has a number of inherent limitations which need to be recognised when interpreting the results. The study did not account for the additional harvest, drying and storage costs that would arise from an increase in irrigated wheat yield. About 20% of wheat production costs appear to be linked to harvest yield, excluding drying. Similarly, irrigation water losses, which will depend on local conditions, were ignored; most UK systems are relatively small and based on permanent underground mainline pipes, so conveyance losses should be minimal. On the other hand, this study also ignored any cost savings and neglected the quality and yield consistency benefits that would be expected. The study focused on irrigation on a sandy loam soil, which is likely to show the greatest response to irrigation. Most wheat in England is grown on heavier soils. The study could be extended to include different soil types. Irrigation was limited to April and May, to avoid risk of lodging. Some anecdotal sources recommend irrigation should continue later into the season. Spatial climate variability was also not considered. Climate data were used for a single site (Silsoe, Bedfordshire), but further work could investigate using a network of weather stations to capture spatial agro-climatic variability, with modelling sites then chosen to reflect areas of concentrated cereal production. Climate change has not been modelled; however, this would need to include impacts on the wheat crop versus other competitive crops and future land suitability as well as the impacts on water availability and spatial variability and uncertainty. Finally, we must emphasise the limitation in calibrating and validating the AquaCrop model. The model was validated using a clay loam soil, which is the dominant soil of the experimental field. The variability within the field between different sections and plots was not taken into account, which may have reduced the accuracy of the model to simulate yields.

## 6. Conclusions

This study confirmed that irrigation of wheat can be a financially viable practice in eastern England under certain limited combinations of soil type, existing irrigation systems, available

**Table 11**

FIA for irrigated wheat versus rainfed wheat, using an existing irrigation system with no reservoir (Case 4).

Crop	Wet years		Normal years		Dry years		Overall mean	
	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.	Rainfed	Irrig.
Milling winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	165.9	165.9	165.9	165.9	165.9	165.9	165.9	165.9
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1294.3</b>	<b>1327.4</b>	<b>1194.7</b>	<b>1360.6</b>	<b>348.5</b>	<b>1294.3</b>	<b>962.4</b>	<b>1277.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	53.1	–	62.4	–	74.2	–	63.0
Irrigation cost (£ ha <sup>-1</sup> )	–	11.7	–	15.8	–	40.8	–	16.0
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	–	–	–	–	–	–	–
Production costs (£ ha <sup>-1</sup> )	802.7	802.7	802.7	802.7	802.7	802.7	802.7	802.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>802.7</b>	<b>906.1</b>	<b>802.7</b>	<b>919.4</b>	<b>802.7</b>	<b>956.3</b>	<b>802.7</b>	<b>920.3</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>491.5</b>	<b>421.3</b>	<b>392.0</b>	<b>441.2</b>	<b>–454.3</b>	<b>337.9</b>	<b>159.7</b>	<b>357.4</b>
<b>FIA (£ ha<sup>-1</sup>)</b>	<b>–</b>	<b>–70.2</b>	<b>–</b>	<b>49.2</b>	<b>–</b>	<b>792.2</b>	<b>–</b>	<b>197.7</b>
Feed winter wheat								
IWR (m <sup>3</sup> ha <sup>-1</sup> )	–	167.0	–	587.0	–	1125.0	–	615.0
Productivity (t ha <sup>-1</sup> )	7.8	8.0	7.2	8.2	2.1	7.8	5.8	7.7
Price (£ t <sup>-1</sup> )	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
<b>Total output (£ ha<sup>-1</sup>)</b>	<b>1120.1</b>	<b>1148.8</b>	<b>1033.9</b>	<b>1177.5</b>	<b>301.6</b>	<b>1120.1</b>	<b>832.9</b>	<b>1105.7</b>
Abstraction charge (£ ha <sup>-1</sup> )	–	53.1	–	62.4	–	74.2	–	63.0
Irrigation cost (£ ha <sup>-1</sup> )	–	11.7	–	15.8	–	40.8	–	16.0
River abstraction cost (£ ha <sup>-1</sup> )	–	38.6	–	38.6	–	38.6	–	38.6
Reservoir storage cost (£ ha <sup>-1</sup> )	–	–	–	–	–	–	–	–
Production costs (£ ha <sup>-1</sup> )	763.7	763.7	763.7	763.7	763.7	763.7	763.7	763.7
<b>Total costs (£ ha<sup>-1</sup>)</b>	<b>763.7</b>	<b>867.1</b>	<b>763.7</b>	<b>880.4</b>	<b>763.7</b>	<b>917.3</b>	<b>763.7</b>	<b>881.3</b>
<b>Total benefits (£ ha<sup>-1</sup>)</b>	<b>356.4</b>	<b>281.7</b>	<b>270.2</b>	<b>297.1</b>	<b>–462.2</b>	<b>202.8</b>	<b>69.2</b>	<b>224.4</b>
<b>FIA (£ ha<sup>-1</sup>)</b>	<b>–</b>	<b>–74.7</b>	<b>–</b>	<b>26.9</b>	<b>–</b>	<b>664.9</b>	<b>–</b>	<b>155.2</b>

Bold values = products or totals.

unused summer water and weather. However it is unlikely to justify investments in new irrigation systems specifically for cereal irrigation, even if summer water is available, and it would require very significant price rises and/or cost reductions before investment in reservoir storage would be justified. We might therefore reasonably expect to see some small increased water demand for wheat irrigation by those farmers with existing systems and spare capac-

ity (unused water), particularly in the drier catchments further east, but very limited investment in new facilities specifically for wheat irrigation unless there is a sustained major increase in farm-gate wheat prices. Even this limited expansion could cause water resource problems, if so-called “sleepers” (unused) licences are reawakened. In the longer term, the expected increase in world wheat prices and the impacts of climate change are likely to make the financial benefits stronger, but conversely reduce water availability; again irrigation of other crops is likely to take precedence.

**Table 12**Sensitivity of AVW (£ m<sup>-3</sup>) to price and total production costs, for irrigating milling winter wheat, using existing an irrigation systems with no reservoir (Case 4).

Costs (£ ha <sup>-1</sup> )	Prices (£ t <sup>-1</sup> )				
	–40%	–20%	165	+20%	+40%
–40%	0.71	0.82	0.92	1.02	1.12
–20%	0.41	0.52	0.62	0.72	0.82
920	0.11	0.22	<b>0.32</b>	0.42	0.52
+20%	–0.18	–0.08	0.02	0.12	0.22
+40%	–0.48	–0.38	–0.28	–0.18	–0.08

Bold values = central values.

**Table 13**Summary of profitability (£ ha<sup>-1</sup>) of irrigated vs. rainfed wheat under different conditions.

Winter wheat (milling)	Wet years	Normal years	Dry years	Overall mean
New investments in irrigation systems and reservoir	×	×	✓	×
New investment in irrigation system with no reservoir	×	×	✓	~
Using existing irrigation systems and existing reservoir	×	✓	✓	✓
Using existing irrigation systems with no reservoir	×	✓	✓	✓
Winter wheat (feed)	Wet years	Normal years	Dry years	Overall mean
New investments in irrigation systems and reservoir	×	×	✓	×
New investment in irrigation system with no reservoir	×	×	✓	~
Using existing irrigation systems and existing reservoir	×	×	✓	✓
Using existing irrigation systems with no reservoir	×	✓	✓	✓

✓: Net benefit  
~: Marginal benefit  
×: No benefit

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