IRRIGATION DEMAND AND ON-FARM WATER CONSERVATION IN ENGLAND AND WALES

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FOREWORD AND ACKNOWLEDGEMENT

Foreword

The growing demands for irrigation water in England and Wales, particularly in the drier south and east, coupled with rising domestic demand, increased environmental awareness and concern for habitat protection, have highlighted the limitations on water supply for agricultural and horticultural irrigation.

This project was initiated by MAFF in 1993, funded by the Chief Scientist's Group (Agriculture). The main objectives are summarised below. The project involved literature review, computer modelling and extensive consultation, but not practical experimentation.

1. Provide up to date information on present and future irrigation water requirements on spatial, temporal and crop sector bases, under a range of agricultural, technical, climatic and policy scenarios.

2. Provide detailed comparative reviews of the wide range of on-farm water conservation techniques that can contribute to the effective, efficient and economic conservation, storage and utilisation of irrigation water.

3. Assess the potential for each response in selected areas by comparing the effects of the on-farm water conservation techniques, the calculated irrigation water requirements and the predicted availability of surface and groundwater.

4. Provide recommendations for developing national and local policies to promote appropriate on-farm water conservation techniques and to address the overall water shortage problem in the medium and long term.

The term water conservation has been deliberately interpreted widely, to include water harvesting and winter storage reservoirs as well as agronomic changes, more efficient application methods, and better scheduling, i.e. any action the farmer can take to use water more effectively. External measures and changes to the abstraction licensing system have not been specifically discussed in this report, but their relevance to on-farm water conservation cannot be ignored. The licensing system greatly affects the farmers' needs and incentives to save water. Furthermore, farmers need reliable supplies, even if limited, before many of these on-farm conservation measures can be economically justified.

Although the work was specifically concerned with England and Wales (and some of the 1995 data sources actually only refer to England) most of the measures would be equally applicable to Scotland (and indeed other countries with supplemental irrigation). For simplicity therefore we often refer to UK irrigation.

Acknowledgements

The authors wish to thank all those individuals and organisations who provided advice and information, including the Ministry of Agriculture, Fisheries and Food (MAFF), UK Irrigation Association (UKIA), Environment Agency (EA), Edinburgh University Data Library (EDL), irrigation companies and numerous individual farmers, growers, consultants, advisers and researchers. Particular thanks are due to members of the Trickle Irrigation and On-Farm Reservoirs Workshops held at Silsoe. We would also like to thank Peter Batho, Judith Dunderdale, and Jane Mills who undertook additional research at Silsoe, and Dr. Mark Stalham (Cambridge University Farm) for his specific contributions regarding potatoes.

KEY WORDS

GIS, Irrigation, Maps, Water conservation, Water demand, England and Wales.

EXECUTIVE SUMMARY

The study confirmed that water use for agricultural irrigation is increasing, both in area irrigated and depths applied, and is increasingly concentrated on the more valuable crops. Underlying volumetric growth was 3% per annum from 1982 to 1995. On-farm reservoir capacity doubled from 1990 to 1995, but 90% of the water still came from summer abstraction in 1995, mostly from rivers and streams.

A GIS model was developed and validated to calculate and map the spatial distribution of irrigation needs (depths) and volumetric demands, by crop category and in total.

'Most likely' future demands were calculated by crop and region. The predicted annual volumetric growth rate, for a 'design' dry year, is between 2.5% and 2.8% from 1995 to 2001, and averages about 1.5% from 2001 to 2021. The GIS maps show growth is far from uniformly spread.

A financial analysis was carried out, and shows that the value of water, and the benefit *to the farmer* of conserving water, varies enormously between enterprises. This will cause a very 'patchy' uptake of on-farm water conservation measures, as already observed in practice.

Methods to reduce water use on-farm were studied. It is suggested that, very roughly, a 10% increase in water use efficiency could be sought by improving overhead irrigation methods and a further 10% by better scheduling, whilst scheduled trickle irrigation might increase efficiency by 20 to 30% in total. These gains might lead to some increased irrigation rather than all being reflected in reduced abstraction.

- Field measurements are required to justify and encourage a change to more accurate and efficient overhead systems, including booms, where water is highly valued.
- The major water saving opportunity with trickle is on potatoes. Good results can be obtained, but some problems remain to be solved . Water savings alone would not justify a change at current water charges where direct abstraction is possible.
- About 10% to 15% of irrigators now use commercial scheduling services, primarily on potatoes, soft fruit, salad and root vegetables. Many others schedule themselves. Scheduling increases irrigation effectiveness, but may increase water use. Appropriate schedules can save some water.
- Water savings are possible through promoting deeper rooting. Climate, soil and market constraints limit the savings that can be made by other agronomic changes. Water could be saved by developing potato cultivars with increased drought resistance, common scab resistance, and deeper rooting patterns, but this has not been a priority for plant breeders so far.
- The practicality of reducing irrigation water demand through the use of mulches appears limited.
- Increasing the yield of irrigated crops through other inputs also saves water per unit of produce.

Methods to increase water availability on-farm were also studied.

- A cost survey and computer analysis showed that water from on-farm reservoirs is not cheap, but reservoir construction is viable for many crops if summer sources are unavailable.
- Computer modelling confirmed that rainwater harvesting cannot compete financially with direct abstraction at present rates, but has potential for development in the UK in particular situations.
- Literature surveys suggested that direct reuse of treated effluent for agricultural irrigation is technically feasible and would create only negligible risks to users and consumers "providing the effluent has been suitably treated". However, there are public relations problems and extra costs.

A recurring observation was that water conservation measures could not compete with the present low cost of direct summer abstraction, but that they could be often be justified where water was scarce. A more flexible licensing system would help promote effective use of water and water conservation.

Recommendations are given for the promotion of on-farm water conservation.

SUMMARY OF RECOMMENDATIONS

Specific recommendations have been made at the end of each section within the report, and are brought together in summary only here:

Improving data sources

- A considerable amount of useful information is collected through the MAFF Irrigation Surveys, but only released as national statistics, or by MAFF Standard Statistical Region (SSR). For this study, county level data was specially processed. MAFF should consider ways to make the data available at local level.

- MAFF should support research to improve irrigation demand maps by incorporating remote sensed data on land use and, in the future, irrigated areas.

Improving future predictions

- MAFF should fund the periodic review and updating of ‘future irrigation demand’ forecasts, as agricultural policy (particularly CAP) develops. A GIS approach should be used to map the forecasts and produce results by catchment or aquifer.

- MAFF should fund research to evaluate the impact of climate change on irrigation needs. The GIS approach described here could be used to predict and map the increased demand for the current irrigated cropping. Research is also needed to predict changes in cropping patterns, the economics of irrigation, and the location of irrigated agriculture.

Improving incentives to save water

Some farmers clearly have little financial incentive to save water, because abstraction charges are very low and because they cannot easily pass unused water to other farms under the current licensing system. Two recommendations follow from these observations:

- MAFF should consider proposals for a levy (e.g. through an increase in abstraction charges) on summer abstraction from sources where water is scarce, both increasing the incentive to save water *and* generating funds to support water conservation measures in those catchments.

- MAFF should support proposals to make the licensing system more flexible, so that water is conserved where it is cheapest to do so, and applied where it is most beneficial.

Promoting ways to reduce water use on-farm

Overhead irrigation

- MAFF should fund a scientific field study to determine actual losses from overhead irrigation systems under UK farm conditions, as a basis for justifying (or otherwise) the pressure on farmers to move away from hosereel-gun systems to more expensive but supposedly more efficient systems. The study should include micro-sprinkler and hosereel-boom systems as well as hosereel-gun systems.

- MAFF should investigate the potential for water saving by precision irrigation from booms (and linear moves) onto bed systems.

Trickle irrigation

Before promoting trickle irrigation on potatoes, research is needed on wetting patterns and on correct scheduling under UK conditions. Growers need to be confident that scab is controlled and high quality potatoes will be produced under all weather conditions. Product development is required on equipment for lifting tape without damage and without slowing the harvest.

- MAFF should fund one or more on-farm trials on potatoes, scientifically monitored and replicated and for at least 3 years, comparing different systems. The trials should be alongside normal commercial irrigated potato production, and at sufficient scale to identify labour issues during laying and retrieval. The trials should also be used as a demonstration site(s) along the lines of 'Sandlands 84' providing this does not compromise the research. Product development for the retrieval equipment should be encouraged by involving the manufacturers.

- For crops where trickle irrigation is already being adopted, MAFF should concentrate on assisting technology transfer between growers, through the promotion of farm visits, demonstration days and workshops.

- The anomaly of trickle irrigation being outside the abstraction licensing system will be increasingly questioned. MAFF should support bringing trickle under the system, but urge simultaneous changes giving more flexibility to vary licences and removing specification of the application point from licences. Otherwise there is a real danger of stopping the current growth in trickle irrigation, and hence losing the water saving benefits.

Scheduling

Seeking improvements in the effectiveness of irrigation through better scheduling should be part of water conservation strategy, in terms of making better use of water.

- MAFF should actively promote the benefits of scheduling, through conferences and publications.

- MAFF should fund research into identifying optimum scheduling for trickle irrigation in the UK.

Changing agronomic practices

- MAFF should fund research to clarify the effects of sub-soiling and other deep cultivations on yield and particularly irrigation need for potatoes.

- MAFF should urge NIAB to give a more prominent role to irrigation need when scoring varieties, and when developing new varieties, and encourage farmers to consider drought resistence and scab resistence when selecting varieties where water resources are unreliable.

Mulches

- It is recommended that MAFF fund a small experimental study to validate (or otherwise) the computer modelling of the effect of mulches on irrigation demand under UK conditions.

- MAFF should continue to research and promote ways of increasing yield (t/ha) of irrigated crops, including plant breeding, cultivations, fertiliser use, etc., as a means of reducing the irrigated area and saving water.

Promoting ways to increase water supply on-farm

Reservoirs

MAFF should continue to promote storage reservoir development where appropriate. The emphasis should be on providing better information to farmers, on identifying and removing unnecessary constraints, and on encouraging planning at group or catchment level.

To improve information available to farmers:

- MAFF should continue to support publications, conferences etc.
- MAFF should fund research to quantify reservoir costs under different site conditions.
- MAFF should fund the development of reservoir suitability maps when base data is available.
- MAFF should ask EA to clarify the availability and reliability of winter water in each sub-catchment.

To reduce constraints:

- MAFF should support current moves to reduce reservoir operating costs by amending the Reservoirs Act for reservoirs which do not present risks to life or property.
- MAFF should continue to resolve planning regulation conflicts with reservoir development.
- MAFF should encourage farmers to consider joint reservoirs. Funding should be provided for setting up local groups and undertaking preliminary studies, at least for pilot areas.

A re-introduction of construction grants for all reservoirs is not recommended. However, this should not preclude part funding winter storage reservoirs where summer abstraction has to be reduced, funding to encourage environmental benefits, or support in preliminary planning stages, particularly to encourage group reservoirs or innovative ideas.

Water harvesting

There is surprisingly limited data on the costs and feasibility of rainwater harvesting in the UK.

- MAFF should fund a small study on on-farm water harvesting, to include:

  An analysis of the financial cost benefit of existing installations.
  Development of an improved computer model for determining optimum catchment areas and storage capacity in different parts of the UK.
  An analysis of the cost and feasibility of providing artificial on-farm catchments.
  A study on the net effect on local hydrology.
  Construction of one or more trial installations.

Reuse of waste water

Reuse of waste water for agricultural irrigation appears technically feasible but there are public relations problems and extra costs.

- It is recommended that MAFF do not actively promote direct re-use of treated sewage for the irrigation of crops for human consumption at present. Indeed, we recommend that MAFF should consider banning it for spray irrigation of crops sold directly to the public.

- It is suggested MAFF maintain a watching brief on current research on re-use (e.g. by UKWIR), with a view to possible future research funding into re-use through subsurface trickle irrigation onto orchard crops and/or irrigation of crops for processing (e.g.sugar beet).

GLOSSARY

AWC	Available water capacity
CAP	Common Agricultural Policy
DoE	Department of Environment
EA	Environment Agency
EPD	Environmental Protection Division (of MAFF)
ETo	Reference crop (grass) evapotranspiration
GATT	General Agreement on Tariffs and Trade
GIS	Geographical information system
IPCC	Intergovernmental Panel on Climate Change
IWR	Irrigation Water Requirements (computer program)
MAFF	Ministry of Agriculture, Fisheries and Food
NIAB	National Institute of Agricultural Botany
NRA	National Rivers Authority
PMB	Potato Marketing Board
PSMD	Potential soil moisture deficit
RSPB	Royal Society for the Protection of Birds
SI	Spray irrigation
SSLRC	Soil Survey and Land Resources Centre (Cranfield University)
UKIA	UK Irrigation Association

NOTATION

ha	hectare
ha.mm	hectare-millimetre (a volume equivalent to 1mm depth over 1 ha area)
tcm	thousand cubic metres
t	tonne

CONVERSIONS

1 tcm	1000 m^3
1Ml (equivalent to 1 tcm)	1000 m^3
1 ha	10000 m^2
1 ha.mm	10 m^3
1 acre-inch is approx 10 ha.mm	100 m^3
1m^3 km^{-2}	Equivalent to 1 mm depth over the area concerned

1. PRESENT IRRIGATION USAGE AND CURRENT TRENDS

1.1 MAFF 'Irrigation of Outdoor Crops' Surveys

Since 1955, the Ministry of Agriculture, Fisheries and Food (MAFF) has collected and published statistics on agricultural irrigation in England and Wales, through their 'Irrigation of Outdoor Crops' Surveys. These have been carried out roughly triennially, most recently in 1982, 1984, 1987, 1990, 1992 and, for England only, in 1995. With only 1% of irrigation in Wales, these last six surveys essentially provide directly comparable results.

A question in the compulsory annual MAFF 'Agricultural and Horticultural Cropping Census' asks farmers for the total area of outdoor crops they irrigated (since 1989), or whether they irrigated their outdoor crops (in 1982, 1984, 1987, and 1988). The replies are used as a trigger for addressing the irrigation surveys. For 1995, everyone registered as an irrigator in any of the three years leading up to 1995, plus all respondents to the 1992 irrigation survey, were included. Completing the irrigation survey questionnaire is voluntary, but the response rate was 77%, giving 6001 respondents of whom 4293 reported irrigating. Telephone follow up was used to clarify individual responses. The published figures are adjusted to account for the non-responses, although some error is inevitably introduced.

The national results of the MAFF 1995 Irrigation Survey were released in November 1996 (MAFF, 1996), and amended slightly in February 1997, when regional figures were published (MAFF, 1997). County level data are not officially published, but are available for selected years for research purposes.

MAFF statisticians are not permitted to release individual data. In practice, any data referring to four or fewer respondents are either aggregated or not disclosed. This is not a problem for national data, but can distort figures at county and regional level, particularly outside the main irrigation areas and for minority crops etc. For this reason, data is no longer available at parish level.

Other limitations of the MAFF data must be recognised. They exclude non-agricultural irrigation, indoor (glasshouse) irrigation and sub-irrigation by raising water tables. Because of the confidentiality restrictions, it is impossible to check the accuracy of individual returns, or to compare returns with metered abstraction. However, confidentiality also removes any incentive to deliberately provide incorrect data. The data on area irrigated is probably accurate, although it may be distorted by a single irrigation given to an essentially unirrigated crop. The volume data is probably based either on an average number of applications over those areas, or an estimated split of the total metered applications between crops; few farms seem to keep accurate records in an easily accessible form. Despite these reservations, however, it is believed that the data are broadly correct at national level, particularly in regard to trends.

1.1.1 Dry year position

Many of the surveys have asked farmers how much land they were likely to irrigate in a 'dry year assuming adequate water supply'. This gives some data on long-term trends, although the definition of a dry year is subjective, and likely to change depending on conditions at the time of each survey. Figure 1-1 clearly shows the major growth periods from 1955 to 1965, and after 1976. The slight decline recently may reflect a decline in the profitability of irrigating cereals and grass.

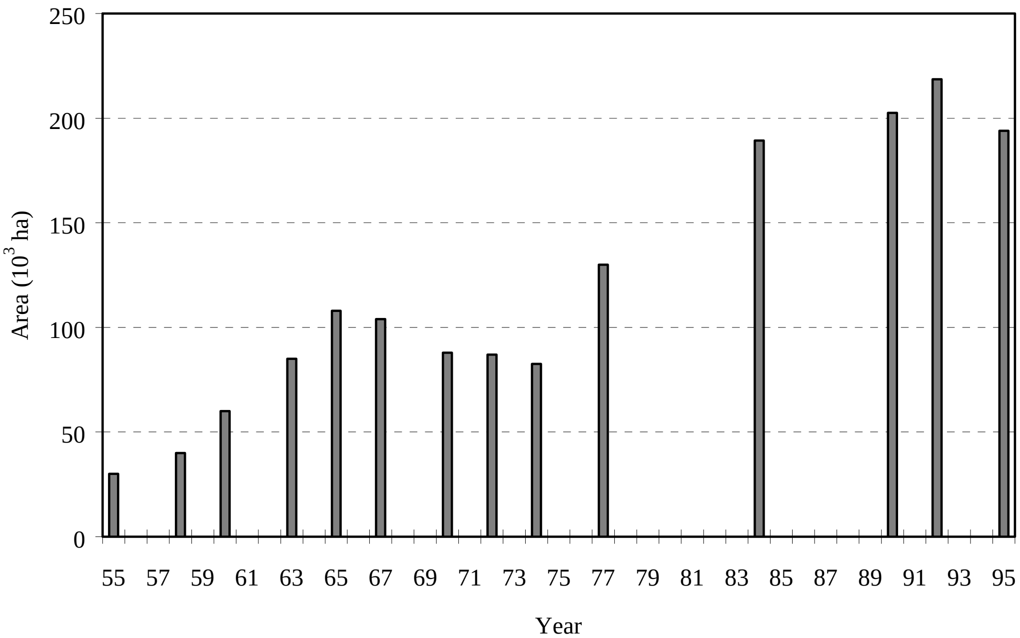

Figure 1-1. Total area 'likely to be irrigated in a dry year' in England and Wales, 1955-1995.

1.1.2 Irrigated areas and volumes

Table 1-1 and Table 1-2 list the areas irrigated and the volumes of water applied, by crop category, for the six most recent MAFF Irrigation Surveys.

Over most of England, the summer of 1995 was exceptionally warm, with the driest recorded June since 1976, the driest July since 1990 and the driest August since 1947 (Hough, 1995). At Silsoe, 1995 ranked just behind the 1990 'design dry year' in terms of irrigation need for maincrop potatoes, though still well behind the exceptional 1976. The 1995 results therefore give a good indication of the current dry year position, and can be compared with 1990 to see rough trends.

Table 1-1. MAFF reported areas irrigated (ha), by crop category, 1982-95.

Crop category	Year					
	1982	1984	1987	1990	1992	1995
Early potatoes	8050	7720	5360	8510	8180	8730
Maincrop potatoes	22810	34610	29520	43490	45290	53390
Sugar beet	15770	25500	10100	27710	10520	26820
Orchard fruit	3100	3250	1330	3320	2280	2910
Small fruit	3610	3560	2230	3470	2750	3250
Vegetables	14810	17460	11040	25250	20200	27300
Grass	16440	18940	6970	15970	7240	10690
Cereals	14800	24700	7510	28100	7160	13440
Other crops	4100	4890	2440	8650	4320	9120
Total	103490	140630	76500	164470	107940	155650

Note: Data for England & Wales, except for 1995 (England only).

Table 1-2. MAFF reported volumes of water applied (tcm), by crop category, 1982-95.

Crop category	Year					
	1982	1984	1987	1990	1992	1995
Early potatoes	4680	4920	2350	6770	5590	9345
Maincrop potatoes	15280	32730	14700	51170	38520	74460
Sugar beet	8260	17370	3430	20320	4860	21295
Orchard fruit	2180	2430	550	2930	1220	2445
Small fruit	1890	2660	970	3180	2000	4320
Vegetables	6830	11390	4640	18450	12180	25500
Grass	10030	13550	3550	13100	4280	9920
Cereals	5040	8300	2160	11830	2260	5625
Other crops	1020	4030	1270	6040	4160	11160
Total	55210	97380	33620	133790	75070	164070

Note: Data for England & Wales, except for 1995 (England only).

1.1.3 Underlying growth

In the UK, the irrigated areas and volumes applied each year vary greatly with the summer rainfall. The survey data must therefore be interpreted in relation to the weather for each particular year. Figure 1-2 shows the theoretical irrigation needs (mm) for maincrop potatoes grown at Silsoe (Bedfordshire) for 1975-95. Broadly, in irrigation terms, 1982 and 1984 were average and dryish years, 1987 was wet, 1990 was a typical ‘1 in 5’ design dry year, 1992 was wet again, and as described above 1995 represented another dry year.

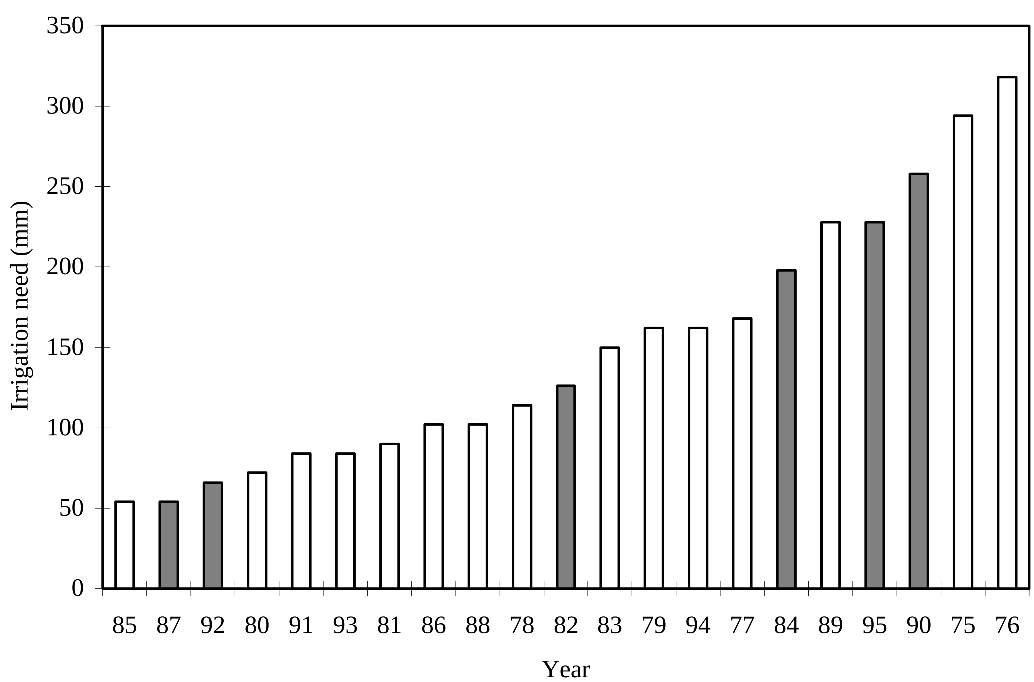

Figure 1-2. Theoretical irrigation needs (mm) for maincrop potatoes grown on a medium AWC soil at Silsoe (Bedfordshire), 1975-1995. Shaded columns represent MAFF Irrigation Survey years.

Weatherhead et al. (1994) analysed the underlying growth across four surveys (1982, 1984, 1987 and 1990) using the theoretical irrigation need (mm) for each crop as the climatic variable in a multiple linear regression analysis. This procedure has now been repeated incorporating data for 1992 and 1995. Using 6 years data, and with two dry years, the statistical reliability is much improved. The underlying growth rates for each crop category, as a percentage of the 1995 value, are shown in Table 1-3. The results confirm earlier findings that irrigation is increasingly concentrated on the more valuable crops, and that those crops that are irrigated are being given more water.

The underlying growth in the total volume applied, from 1982 to 1995, was 3% per annum. This is higher than the previous estimate of 2% per annum for 1982 to 1990.

Table 1-3. Underlying growth rates in area irrigated, average depth and total volume applied, 1982-95.

Crop category	% change per annum on 1995 value		
	Area	Average Depth	Volume
Early potatoes	+1	+4	+4
Maincrop potatoes	+4	+2	+5
Sugar beet	-2	0	-1
Orchard fruit	-3	0	-4
Small fruit	-1	+4	+3
Vegetables	+3	+2	+4
Grass	-7	+2	-4
Cereals	-5	+1	-3
Other crops	+3	-1	+2
Overall	**+1**	**+2**	**+3**

1.1.4 Composition of area irrigated

The split between crop categories, by area and volume of water applied, is shown in Table 1-4. In 1995, potatoes accounted for 40% of all irrigation by area, and 51% by volume of water applied, compared to 31% and 43% respectively in 1990. In contrast, cereal irrigation had fallen to 9% and 3% respectively in 1995, down from 17% and 9% in 1990. This reflects the relative financial benefits, discussed in Chapter 4.

Table 1-5 shows the proportion of the whole crop area that was irrigated in 1990 and 1995, for each crop category. The proportion of the potato area irrigated continues to rise, with 65% of earlies and 44% of maincrop irrigated by 1995. By crop volume, these percentages would be even higher. There was also growth in the proportions of small fruit and vegetables irrigated, and a major drop for cereals.

1.1.5 Water source

The MAFF Irrigation Surveys also provide information on water sources, on-farm water storage and irrigation application methods (Table 1-6). There has been relatively little change between 1990 and 1995. Most irrigation water is abstracted from rivers and streams.

Since 1990, with increased demands from farmers for more reliable water sources, coupled with increased overall pressure on available summer water resources, there has been a rapid increase in the total number of on-farm reservoirs (2580 in 1990, 3220 in 1995) and a doubling in the total storage capacity. However, 90% of the water used in 1995 still came from summer abstraction.

Table 1-4. Split between crop categories, by area and volume of water applied.

Crop category)	Irrigated area (%)		Volume applied (%)	
	1990	1995	1990	1995
Early potatoes	5	6	5	6
Maincrop potatoes	26	34	38	45
Sugar beet	17	17	15	13
Orchard fruit	2	2	2	1
Small fruit	2	2	2	3
Vegetables	15	18	14	16
Grass	10	7	10	6
Cereals	17	9	9	3
Other crops	5	6	5	7
Total	100	100	100	100

Table 1-5. Proportion of each crop irrigated in 1990 and 1995.

Crop category	Proportion of whole crop irrigated (%)	
	1990	1995
Potatoes (total)	38	48
Sugar beet	14	14
Orchard Fruit	10	12
Small fruit	27	34
Vegetables	20	24
Grass	0.4	0.3
Cereals	0.9	0.5
Other crops	20	11

Table 1-6. Volume of irrigation water (%) applied by source.

Source	Volume of irrigation water (%)	
	1990	1995
River, stream or other water course	47	46
Spring rising on holding	4	2
Well	2	3
Deep borehole	31	33
Pond or lake	7	7
Gravel or clay working	2	1
Public mains supply	3	2
Other source	4	4

1.2 Licensed and actual abstractions

Data on the licensed and actual abstractions for irrigation purposes are available directly from the Environment Agency, and published by Department of Environment (e.g. DoE, 1994; 1996).

Note that this data defines irrigation differently to the MAFF Irrigation Surveys, so the numbers are not expected to agree mathematically. For example, the EA data excludes mains supply and trickle irrigation, but can include indoor spray irrigation and spray irrigation for landscape and leisure e.g. golf courses. Confidentiality constraints again restrict checking of this data. Aggregated local data can sometimes be obtained from the EA. The licensed quantities (but not actual abstractions) are theoretically in the public domain, but are not yet in a format readily available for analysis.

Figure 1-3 shows this data nationally, and for EA Anglian Region where most irrigation occurs. The trends support the results obtained using MAFF data as described above. Interestingly, the total amount licensed in EA Anglian Region has recently declined, partly due to expired licences not being renewed and partly because new licences are not being issued in many areas due to water resources being fully committed.

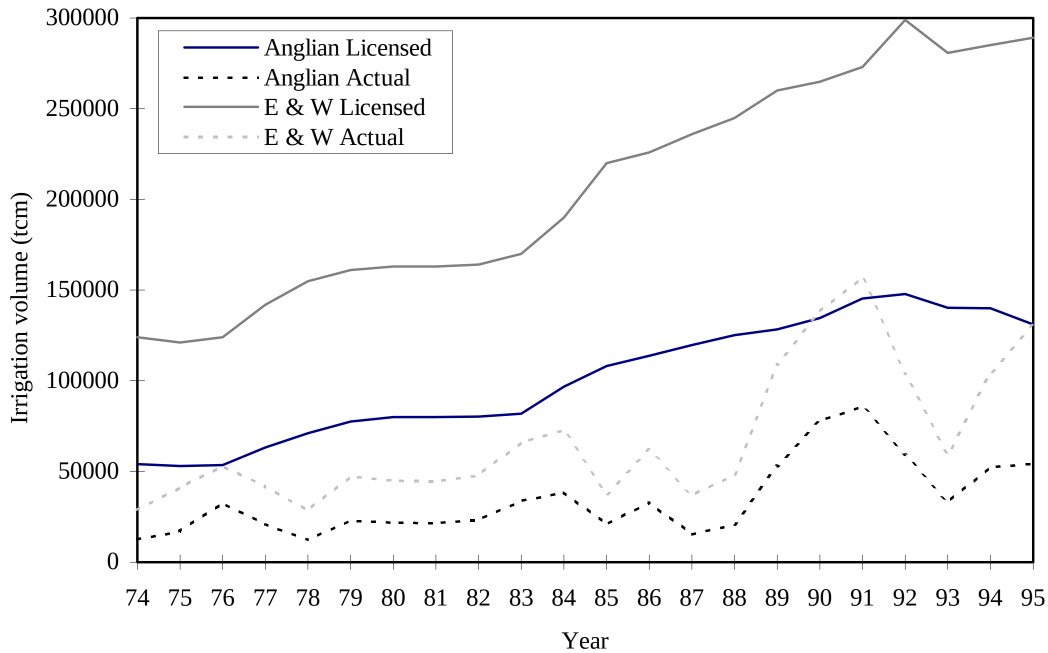

Figure 1-3. Licensed and abstracted volumes of water, for England and Wales and for EA Anglian Region.

1.3 Summary

The underlying growth in the total volume applied, from 1982 to 1995, was 3% per annum. Irrigation is increasingly concentrated on the more valuable crops, and those crops that are irrigated are being given more water. In 1995, potatoes accounted for 40% of all irrigation by area, and 51% by volume of water applied, with 65% of earlies and 44% of maincrop irrigated. There has been relatively little change in water source between 1990 and 1995, with most abstracted from rivers and streams. There has been a doubling in the on-farm reservoir capacity, but 90% of the water used in 1995 still came from summer abstraction.

2. PRESENT THEORETICAL DRY YEAR DEMANDS

Theoretical irrigation demands have been defined as the volumes required for applying the *optimum* water application on those crop areas that are *irrigated* (Weatherhead et al., 1994). The optimum is defined here in terms of recommended schedules based on current agronomic and irrigation practice, and financial return, and is not necessarily fixed.

The concept has proved useful previously when considering maximum unconstrained demand, and for this study has been used as a basis for mapping volumetric irrigation demand.

2.1 Introduction

In the UK, a dry year in irrigation terms is characterised by low rainfall and high evapotranspiration from June to August. For irrigation design and water resource planning, the design dry year is best defined statistically in terms of the annual irrigation water requirements with a given return period. For this report, the design dry year irrigation requirements have been defined as the need equalled or exceeded in 20% of years. This is roughly equivalent to the less precise '5th driest year in 20' definition.

Various authors have tried to estimate theoretical volumetric irrigation demand for a design dry year. Bailey and Minhinick (1989) divided the country into seven agroclimatic zones, and combined 1984 MAFF irrigated area data (ha) with irrigation need (mm) predictions from a daily water balance irrigation scheduling model. They estimated the '5th driest in 20' total volumetric demand to be 109 x 10^6 m^3. Applying a similar methodology, but using 1990 data, five agroclimatic zones and more stringent irrigation schedules, Weatherhead et al. (1994) calculated a 20% exceedance demand of 220 x 10^6 m^3. Both studies had to make similar gross assumptions regarding the spatial distribution of crop types, the soil types they would be grown on, and the choice of agroclimatic area boundaries and representative weather stations. The large difference in the results is partly due to the different schedules used and the use of the lower 1984 MAFF irrigated area data by Bailey and Minhinick (1989).

The development of geographical information systems (GIS), combined with the increased availability of computerised agroclimatic, soil, and land use data, now enable volumetric demand to be modelled spatially, incorporating current land use, local soil type and local agroclimate.

The methodology, developed for this study, is described in detail by Knox et al. (1996), with reference to maincrop potatoes. It was then extended (Knox et al., 1997) to cater for the other seven crop categories considered in the MAFF surveys, and updated to include more recent land use data (1994 instead of 1987) and the improved resolution of the soil and land use datasets (1 km and 2 km respectively instead of 5 km).

2.2 Methodology

In summary, the net annual irrigation needs (mm) for eight major crop categories, grown on three texturally contrasting soils at eleven representative weather stations were determined using a daily water balance irrigation scheduling model. Using a GIS, these irrigation needs were correlated to existing national datasets on climate (using crop adjusted potential soil moisture deficit as a climatic indicator), soils (crop adjusted profile available water), current land use, and the proportion of each crop irrigated in a design dry year. For each crop category, the net volumetric (m^3) irrigation water demand in a design dry year (20% exceedance) were calculated and mapped at 2 km resolution. By summing these individual maps, a total net volumetric demand map was produced.

These steps are described briefly below, and explained in detail by Knox et al. (1996, 1997).

2.2.1 Modelling irrigation needs (mm)

Annual irrigation needs were calculated using the Irrigation Water Requirements (IWR) model, developed by Hess (1997a). The model has been described in detail by Hess (1997a) and Knox et al. (1996), but a brief summary is given in Box 2.

Box 2. Irrigation Water Requirements Model (IWR)

The IWR model estimates the daily soil water balance for a selected crop and soil type, working from daily rainfall and reference crop (grass) evapotranspiration (ETo) data. For each year of the available weather records, the model outputs data on the crop water use, any irrigation applied and the proportional yield loss due to any water stress.

IWR uses a two layer (topsoil and subsoil) soil water balance to estimate the daily soil water storage, incorporating inputs of rainfall and irrigation and outputs of evapotranspiration and drainage. The soil is modelled for two zones, the active root zone (zone 1) and the remainder of the profile to the maximum root depth (zone 2). The boundary between the two zones moves as the roots develop. The model assumes that no drainage will occur until field capacity is exceeded, and that between field capacity and saturation, drainage from each zone will be a function of the volume water fraction (θ) of that zone. The model does not take into account possible contributions from groundwater (through upward capillary rise), and assumes zero runoff from rainfall. These assumptions are considered reasonable for most irrigated crops in dry years in the UK.

ETo, calculated from the Penman combination equation, is partitioned and modified to determine actual evapotranspiration (ETa) and soil evaporation based on the degree of crop cover, stage of growth and soil water status. Actual soil evaporation is calculated in a two stage process based on the method of Ritchie (1972).

For each site, the model requires input data relating to the crop cover development and rooting characteristics, soil water holding characteristics, and the planned irrigation schedule.

Cropping characteristics were based on typical UK irrigated cropping. Eight crops were modelled, namely; early and maincrop potatoes, sugar beet, cereals, permanent grassland, vegetables grown in the open, small fruit and orchard fruit. These categories matched those used in the MAFF Agricultural and Horticultural Cropping Censuses and MAFF Irrigation Surveys. Carrots were used to represent vegetables, strawberries for small fruit, and mature apples for orchard fruit.

Three soils, a loamy sand, a medium sandy loam and a loamy peat, were chosen to represent soils with low, medium and high available water capacities (AWC).

Modelled irrigation applications were based on schedules suggested by MAFF (1982) and typical UK practice (Bailey, 1990). Eleven sites with suitable long term daily weather data were used to represent the range of UK agroclimates (Knox et al., 1997).

The IWR model was run for each weather station/soil type/ crop category permutation, using historical daily ETo and rainfall data for the 20 year period 1973-1992. For each permutation, the estimated annual irrigation needs were ranked and probability plotted to determine the design (20% exceedance) dry year needs. The results are summarised in Table 2-1.

Table 2-1. Dry year irrigation needs (mm) estimated for each crop category on the three selected soil types at each weather station site.

Low AWC Soil;

Weather station	Early potatoes	Maincrop potatoes	Sugar beet	Orchard fruit	Small fruit	Vegetables	Grass	Cereals
Rosewarne, Cornwall	40	170	120	161	72	140	127	0
Keele, Staffordshire	53	168	115	167	58	137	124	0
Wisley, Surrey	56	211	151	237	80	177	170	0
Morley, Norfolk	53	210	162	249	93	173	173	30
Wellesbourne, Warks	61	230	166	246	87	183	184	30
Mepal, Cambridge	61	213	158	241	87	177	177	32
Shawbury, Shropshire	64	237	180	257	87	194	196	32
Silsoe, Bedford	63	250	191	270	103	208	212	52
Gatwick, W. Sussex	77	281	212	312	106	231	243	35
Wattisham, Suffolk	83	306	250	357	128	258	278	50
Cardington, Bedford	77	313	253	364	132	252	280	82

Medium AWC soil;

Weather station	Early potatoes	Maincrop potatoes	Sugar beet	Orchard fruit	Small fruit	Vegetables	Grass	Cereals
Rosewarne, Cornwall	35	159	100	150	48	101	100	0
Keele, Staffordshire	43	157	89	147	50	104	96	0
Wisley, Surrey	47	185	121	233	65	143	145	0
Morley, Norfolk	49	189	119	242	64	132	143	0
Wellesbourne, Warks	56	206	130	242	75	145	159	0
Mepal, Cambridge	52	192	127	239	65	145	150	0
Shawbury, Shropshire	56	215	141	244	73	152	170	0
Silsoe, Bedford	57	235	154	262	90	164	181	0
Gatwick, W. Sussex	72	260	177	315	94	193	215	0
Wattisham, Suffolk	75	279	200	356	96	210	243	0
Cardington, Bedford	64	284	209	359	121	201	253	0

High AWC soil;

Weather station	Early potatoes	Maincrop potatoes	Sugar beet	Orchard fruit	Small fruit	Vegetables	Grass	Cereals
Rosewarne, Cornwall	23	143	0	114	*	*	22	0
Keele, Staffordshire	34	137	0	131	*	*	65	0
Wisley, Surrey	39	177	0	200	*	*	110	0
Morley, Norfolk	38	168	0	212	*	*	119	0
Wellesbourne, Warks	40	188	0	221	*	*	120	0
Mepal, Cambridge	43	173	0	219	*	*	115	0
Shawbury, Shropshire	48	189	32	225	*	*	135	0
Silsoe, Bedford	42	210	21	229	*	*	148	0
Gatwick, W. Sussex	58	239	52	282	*	*	182	0
Wattisham, Suffolk	59	255	115	323	*	*	215	0
Cardington, Bedford	60	261	151	340	*	*	222	0

AWC, available water capacity.

Where demands are zero (e.g. cereals on a high AWC soil) a '0' is shown; where the crop is not normally irrigated (e.g. vegetables and small fruit on a high AWC soil) a '*' is shown.

2.2.2 Crop, soil and climate national datasets

Computerised soil and agroclimatic datasets for England and Wales were obtained from LandIS, the Land Information System held by the Soil Survey and Land Research Centre (SSLRC). For this study, three national datasets were used:

- Soil data, derived from the 1:250 000 scale National Soil Map (Jarvis et al., 1983), showing the dominant soil association in each 1 km^2 pixel.
- 'Crop adjusted' profile available water data. (Thomasson, 1979), taking into account both the crop rooting characteristics and the water holding characteristics of the soil associations, at 1 km resolution.
- 'Crop adjusted' mean annual maximum potential soil moisture deficit (PSMD) data, at 5 km resolution.

For selected years, Edinburgh University Data Library (EDL) have computerised the MAFF Agricultural and Horticultural Cropping Censuses for England and Wales. Datasets based on the 1994 survey were used (the latest available when the work was undertaken). These list the area under each crop category at 2 km resolution. The EDL dataset refers only to total potatoes, and was split into early and maincrop potatoes using the ratio at county level in 1994 (PMB, 1995).

2.2.3 Correlation of irrigation needs with national datasets

The crop adjusted mean annual maximum potential soil moisture deficits (PSMD) were calculated for each weather station, again using IWR. Correlation between the design dry year irrigation needs (Table 2-1) and these PSMDs, for each soil AWC class, were then derived by linear regression analysis. A GIS regression driven model was developed to overlay the soil and climate (PSMD) datasets, and apply the relevant regression equation to produce an irrigation need (mm) map for each crop category, at 1 km resolution.

For each crop, the irrigation need map was multiplied by the land use dataset to produce a volumetric irrigation demand map, at 2 km resolution, assuming that all the crop is fully irrigated.

The proportion of each crop category which was actually irrigated in 1995 was calculated by comparing the 1995 MAFF Agricultural and Horticultural Cropping Census data with the 1995 MAFF Irrigation Survey data. Unfortunately, this can only be calculated down to county level due to confidentiality restrictions on the data. A small linear correction was applied to give the proportions that would have been irrigated in a 20% exceedance design dry year. Applying these county proportions, the theoretical net volumetric irrigation demand in a design dry year for the irrigated portion of each crop was calculated and mapped.

By summing the volumetric irrigation demand maps for each crop category, a total net volumetric irrigation demand map was produced at 2 km resolution. All these maps assume that the irrigated crops are grown on the dominant soil type in each 1 km pixel and irrigated according to the schedules described previously.

2.3 Results

2.3.1 Irrigation need (depth) maps

Irrigation need maps were produced for each of the eight crop categories. These maps show the net irrigation need (mm) for an irrigated crop grown on the dominant soil type, for a 'design' dry year, taking into account the spatial variation in soil AWC and climate. Figure 2-1 shows the irrigation need map for maincrop potatoes. As expected, irrigation needs are highest in the east and south, ranging from less than 100 mm in the west and north-west regions of the country, up to 250 mm on lighter soils in parts of eastern England. Note that although a calculated irrigation need may be shown, the climate and soil may not be suitable for the crop.

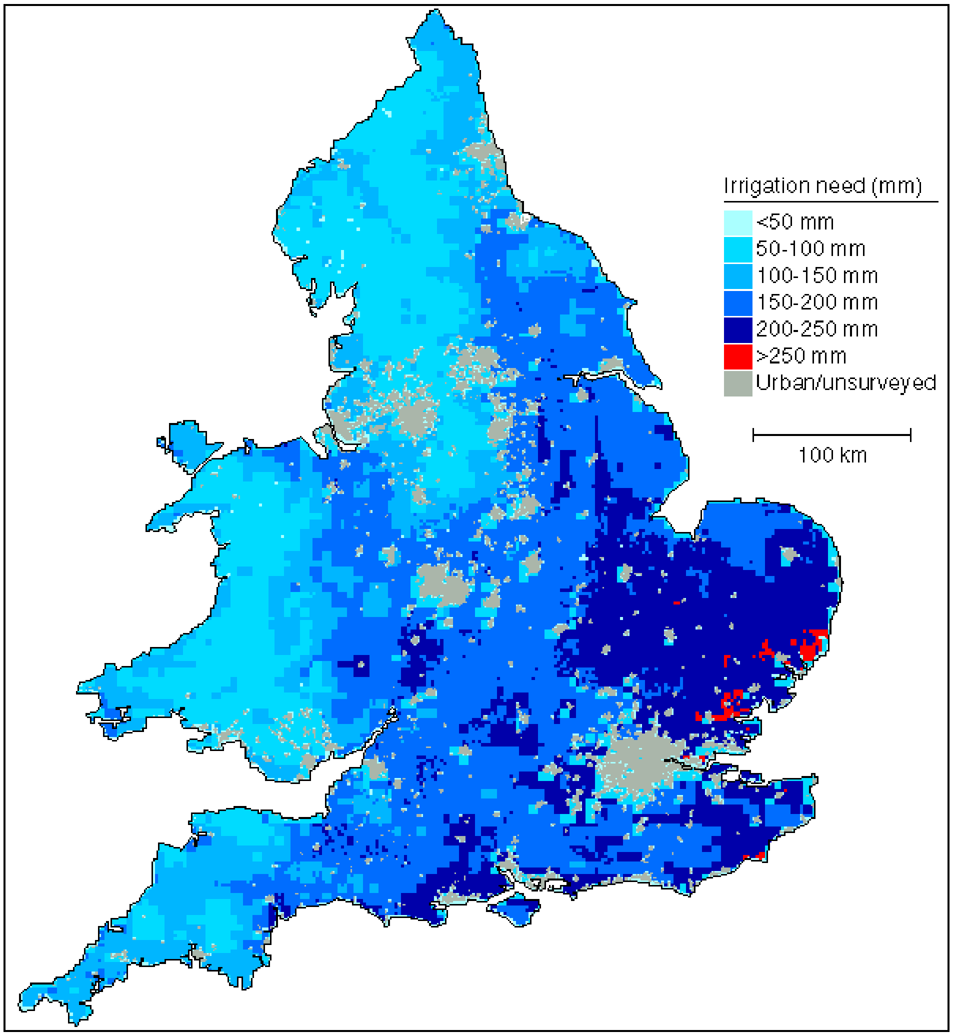

Figure 2-1. Theoretical irrigation need (mm) in a design dry year for maincrop potatoes. Note these figures should not be used for planning on a specific site, when actual data should be used.

2.3.2 Volumetric irrigation demand

Volumetric irrigation demand maps, for each crop category and in total, are shown in Figure 2-2 to 2-10 (Note that each legend is map specific for clarity).

These maps show dramatically how non-uniform volumetric irrigation demand is across the country, not only for each crop category but also in total.

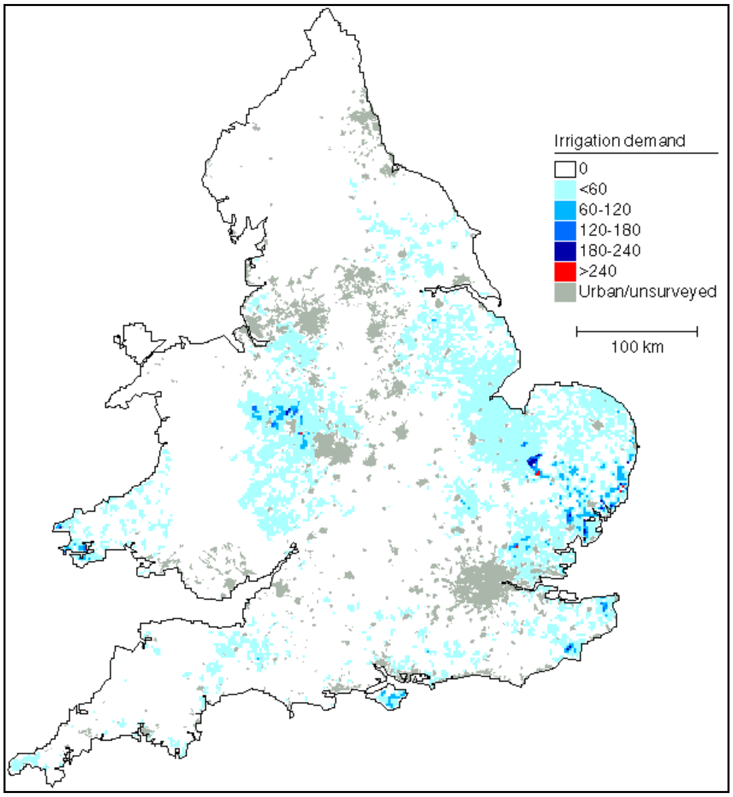

Figure 2-2. Volumetric irrigation demand (m^3 km^{-2}) in a design dry year for early potatoes.

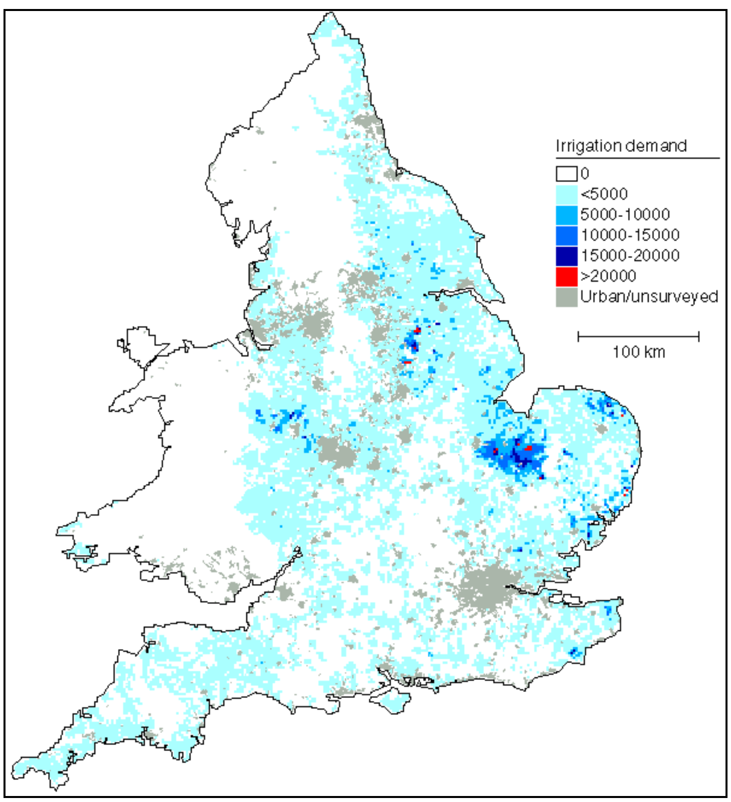

Figure 2-3. Volumetric irrigation demand (m^3 km^{-2}) in a design dry year for maincrop potatoes.

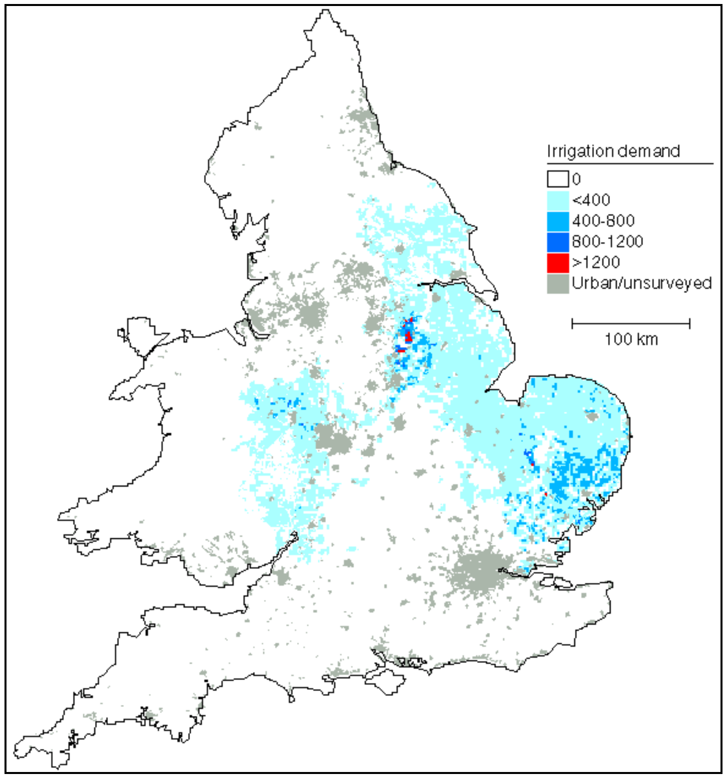

Figure 2-4. Volumetric irrigation demand ($m^3\ km^{-2}$) in a design dry year for sugar beet.

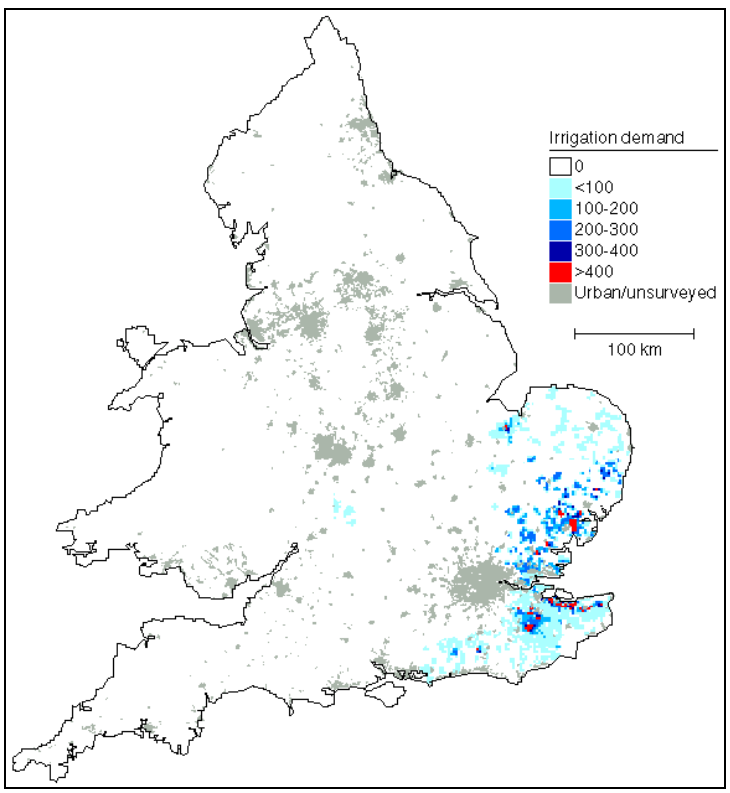

Figure 2-5. Volumetric irrigation demand ($m^3\ km^{-2}$) in a design dry year for orchard fruit.

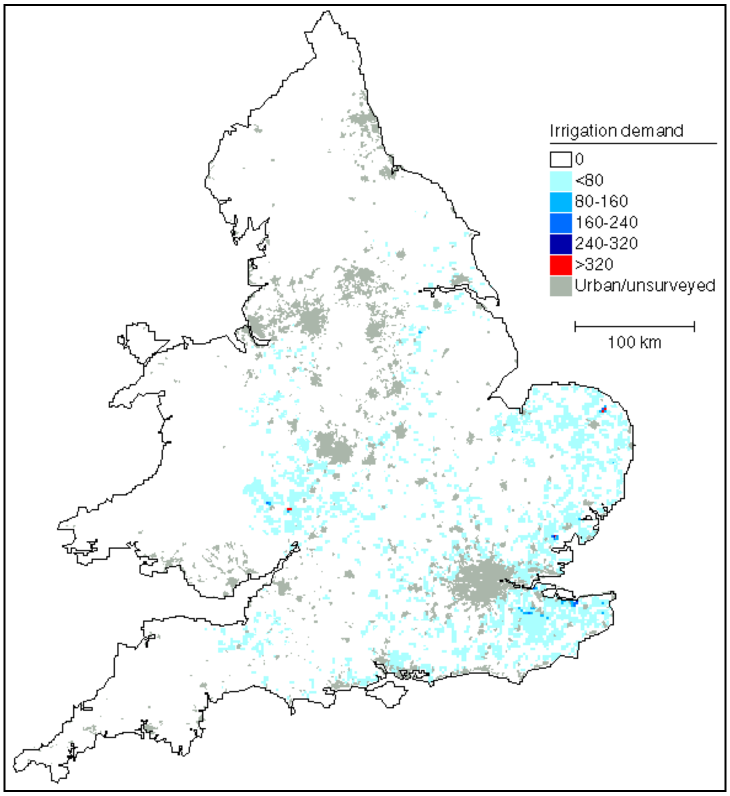

Figure 2-6. Volumetric irrigation demand (m^3 km^{-2}) in a design dry year for small fruit.

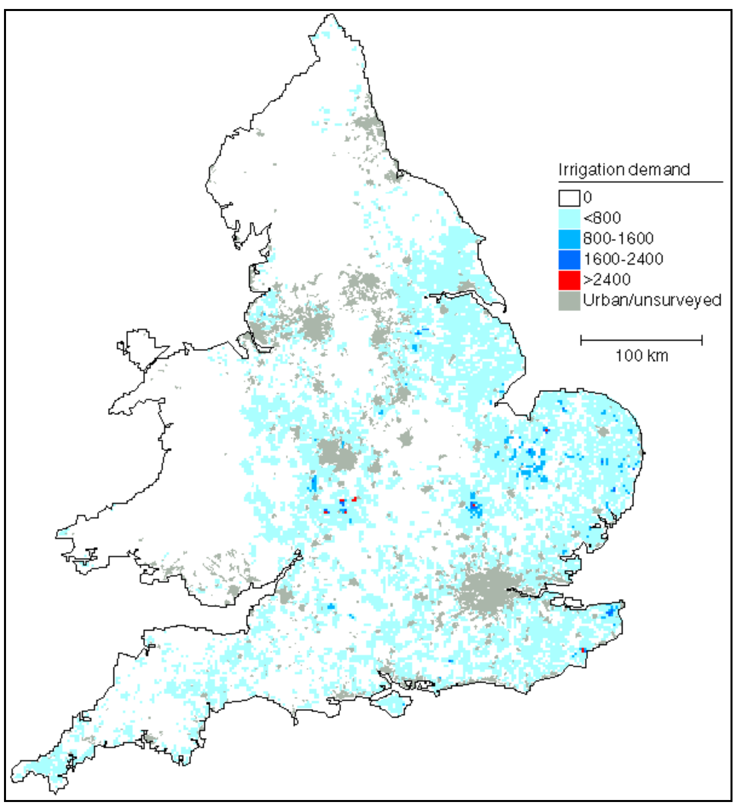

Figure 2-7. Volumetric irrigation demand (m^3 km^{-2}) in a design dry year for vegetables.

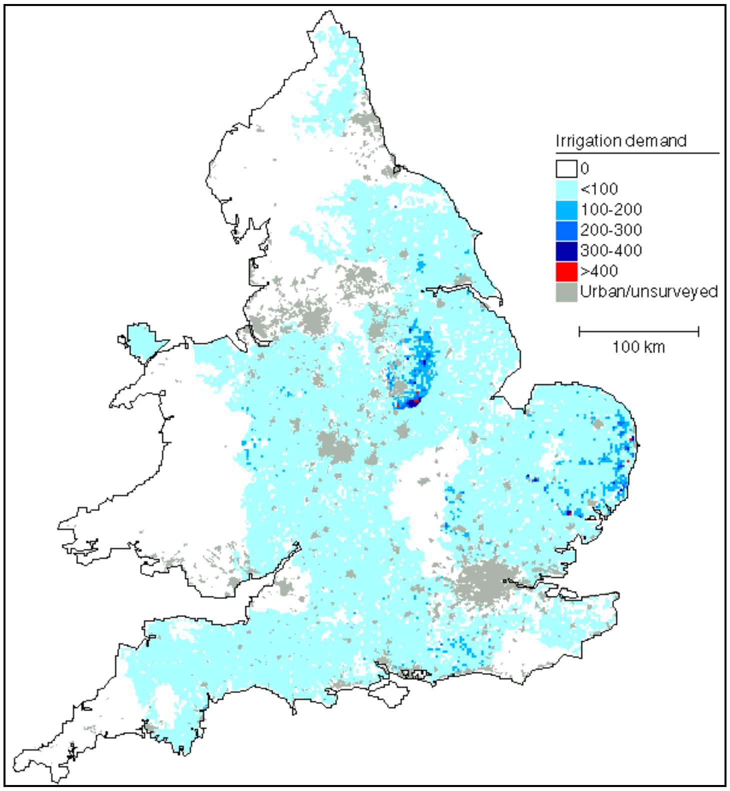

Figure 2-8. Volumetric irrigation demand ($m^3\ km^{-2}$) in a design dry year for grass.

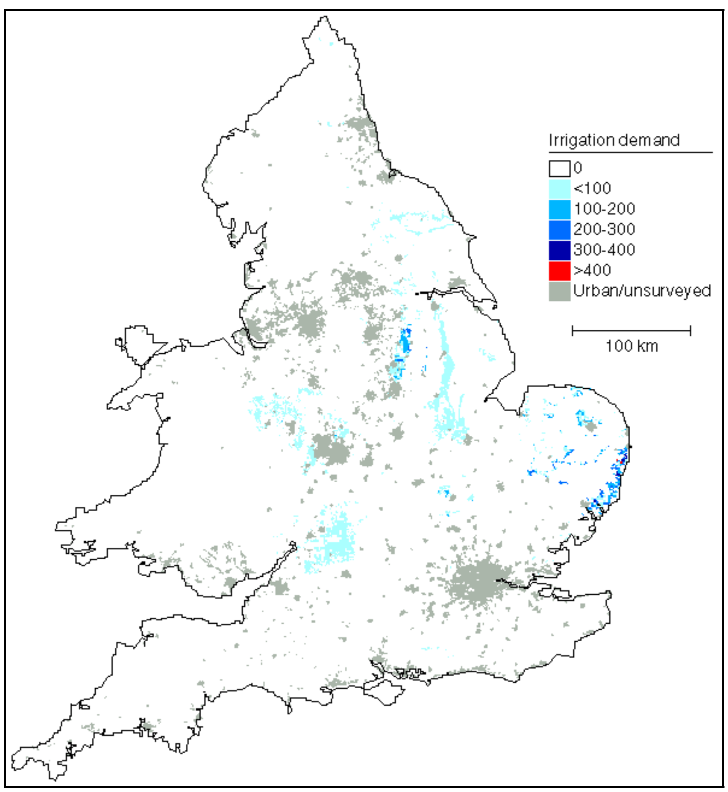

Figure 2-9. Volumetric irrigation demand ($m^3\ km^{-2}$) in a design dry year for cereals.

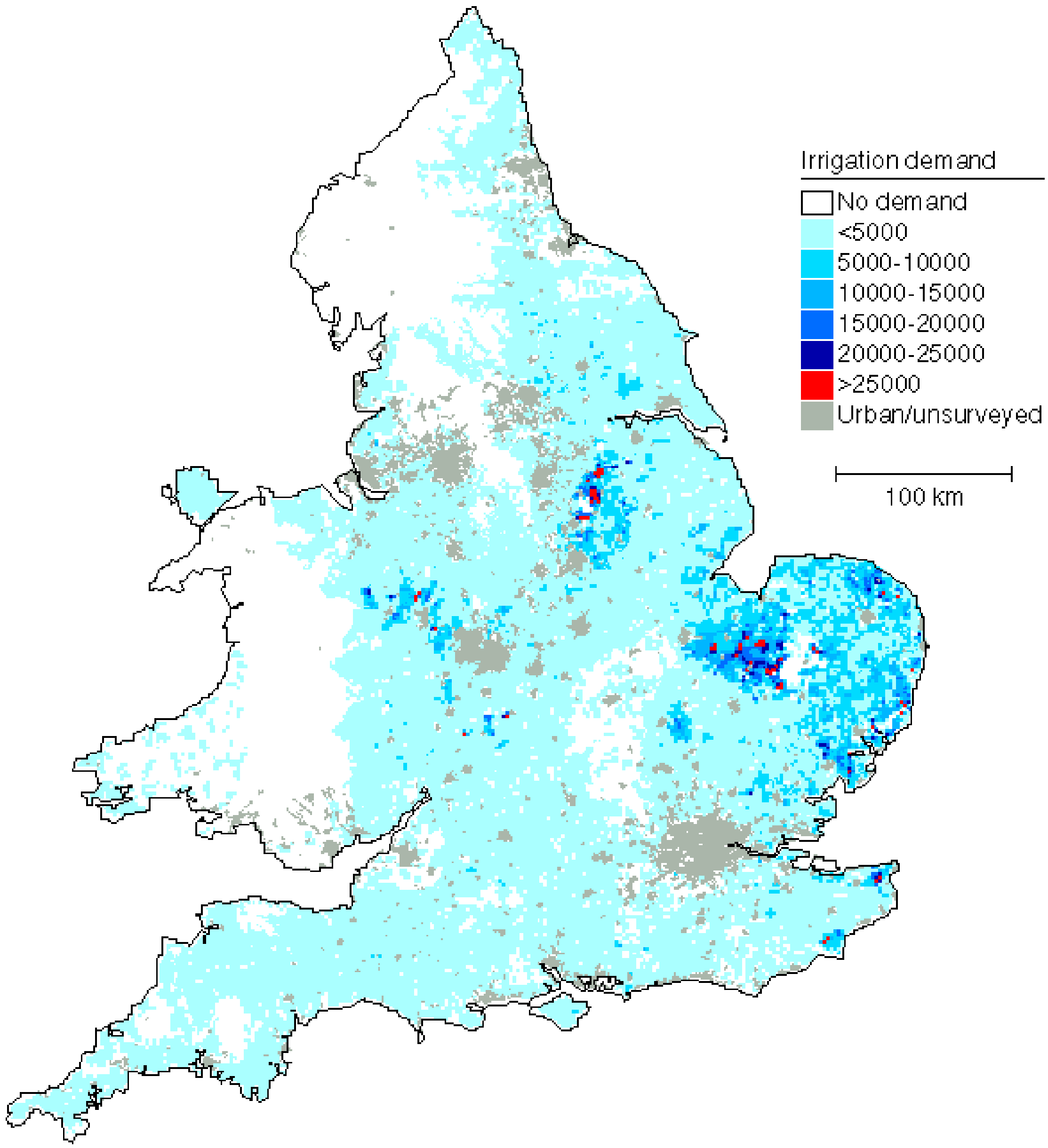

Figure 2-10. Total volumetric irrigation demand ($m^3\ km^{-2}$) in a design dry year for all crops.

As expected, areas of highest total volumetric demand are concentrated in eastern England, notably around the Fens region of East Anglia and on the lighter soils in Nottinghamshire. In contrast, Wales and the west and north-west of England have a very low total volumetric demand for irrigation. However, this pattern does vary markedly for individual crops.

The net volumetric irrigation demand for England and Wales in a design dry year, by crop category, are summarised in Table 2-2. The volumetric irrigation demand for 'other crops grown in the open' would typically add another 4% to the total, giving an overall total dry year demand of 190 x 10^6 m^3.

Table 2-2. Volumetric irrigation demand in a design dry year, by crop category.

Crop category	Cropped area (ha)	Volume ('000m^3)
Early potatoes*	14128	3318
Maincrop potatoes*	114312	91103
Sugar beet	194504	27037
Orchard fruit	27941	4712
Small fruit	10386	5720
Vegetables	114379	34370
Grass	4794585	15429
Cereals	2599007	1312
Other crops**	80316	7000
Total	7949558	190001

* crop area based on PMB (1995) split; ** estimated.

2.4 Discussion

2.4.1 Comparison with MAFF and EA data

The methodology has been validated by calculating dry year demand adjusted for 1995 land use and comparing the results:

(a) nationally, against MAFF Irrigation Survey returns for 1995, for each crop category, and
(b) regionally, against EA irrigation abstraction records for 1995, for each EA Region.

Similar comparisons based on 1990 data are given in Knox et al. (1997).

For most irrigated crops, agronomic demand in 1995 almost equalled 20% exceedance needs, and given equipment constraints, volumetric demand would have been approximately equal to design dry year demands. It should be noted that the irrigation demands calculated in this study represent net values, whereas the MAFF and EA data represent the gross volumes applied including losses.

Table 2-3 compares the 1995 volumetric irrigation demands estimated in this study, with the 1995 MAFF Irrigation Survey data, for each crop category.

Table 2-3. Comparison of irrigation volumes (tcm) reported by MAFF for 1995, with dry year volumetric irrigation demands calculated in this study, adjusted to 1995 land use, by crop category.

Crop category	MAFF Irrigation Survey (1995)	This study based on land use in 1995
Early potatoes	9345	5243
Maincrop potatoes	74461	88597
Sugar beet	21295	26607
Orchard fruit	2444	4962
Small fruit	4320	5822
Vegetables	25499	32243
Grass	9921	13761
Cereals	5622	1015
Other crops	11162	7643
Total	164069	185893

Given the points discussed above, there is good agreement, both in the calculated total values and in the distribution between crop categories. The GIS approach underestimates water use for cereals, possibly due to a failure to allocate the irrigated crop to the correct soil type when only a small proportion (0.5%) is irrigated. Conversely, the maps overestimate water use for small fruit and orchard fruit, possibly due to over-simplification in the choice of representative crop and the defined schedules.

Table 2-4 compares the design dry year irrigation demand derived in this study, with MAFF and EA reported abstraction volumes, by EA Region, for 1995. There are some differences between the types of irrigation included in the EA and MAFF data (including these maps), as discussed earlier.

Table 2-4. Comparison of irrigation volumes (tcm) reported by EA and MAFF for 1995, with dry year volumetric irrigation demands calculated in this study, adjusted to 1995 land use, by EA Region.

EA Region	EA reported abstractions in 1995	MAFF 1995 reported volumes	Design dry year demand based on land use in 1995
North East	15288	18580	14172
North West	2176	3584	2149
Welsh	3883	2630	3236
Midlands	35381	35621	37870
Anglian	54381	82289	105448
Thames	5575	5538	5235
Southern	10004	10897	13329
South West	3817	4240	4454
Total	130505	163380	185893

Statistical analysis of these data confirmed that there is particularly good agreement both in the absolute values and in the distribution between regions. As expected, the calculated value for EA Anglian Region is considerably higher than the actual reported abstractions; due in part to abstraction restrictions and applications for new licences being refused.

2.4.2 Comparison with previous estimates

The results of this study estimated a total dry year volumetric irrigation demand of 190 x 106 m^3. Bailey and Minhinick (1989) estimated 109 x 106 m^3 , with lower demands for all crops. Using 1990 irrigated areas, and schedules similar to those used in this study, Weatherhead et al. (1994) estimated 222 x 106 m^3.

Both previous studies divided the country into a small number of agroclimatic zones, and assumed a single weather station could represent climate conditions across each agroclimatic zone. The GIS procedure used in this study largely removes this source of error.

2.4.3 Applications

This procedure provides the first detailed maps of the spatial distribution of total volumetric irrigation demand for England and Wales. By overlaying appropriate digital boundaries, irrigation volumes can then be summed by crop category for any given catchment, aquifer or administrative area. Table 2-5, for example, shows the composition of demand by crop category for each EA Region.

Sugar beet is the second most important irrigated crop in UK, but Figure 2-4 shows that irrigation demand is located in a relatively small area of eastern England, with 70% concentrated in the EA Anglian Region and none in EA Southern Region. In contrast, Figure 2-5 shows the highest areas of irrigation demand for orchard fruit are located on the east coast and in the south east, notably in Suffolk and Kent, with patches of lower demand spread across Norfolk and in the Fens. For orchard fruit, 61% of demand is concentrated in EA Anglian Region and 37% in the EA Southern Region.

Table 2-5. Split in volumetric irrigation demand (%) for each EA Region, by crop category.

EA Region	Early potatoes	Maincrop potatoes	Sugar beet	Cereals	Grass	Vegetables	Small fruit	Orchard fruit	Other crops
North East	0	77	6	0	9	5	0	0	2
North West	2	49	0	0	17	19	2	0	11
Welsh	6	50	5	0	13	12	8	0	6
Midlands	2	51	18	1	10	15	2	0	2
Anglian	2	47	18	1	5	20	2	3	4
Thames	2	36	3	0	25	17	6	1	9
Southern	2	25	0	0	9	30	14	13	6
South West	2	35	1	0	40	14	3	0	6

This procedure allows the potential spatial impact of particular water conservation measures, such as promoting adoption of trickle (drip) irrigation on potatoes, to be assessed, with measures targeted to areas of greatest shortage. Clearly, national polices affecting the irrigation of sugar beet, for example, would not affect water short catchments in EA Southern Region.

2.5 Summary

A procedure has been developed to model and map the spatial distribution of irrigation needs (depths) and volumetric demands, by crop category and in total. The methodology has been validated nationally and regionally, and results are shown to agree well with reported abstractions in typical dry years.

The present theoretical volumetric irrigation demand for 1995, adjusted for a design dry year, for all crops currently irrigated are estimated to be 186 x 10^6 m^3.

The methodology also enables future irrigation demands to be predicted, by incorporating forecasts of changes in climate, land use, and irrigation practice. This approach therefore provides a powerful decision support system for improving catchment management planning and irrigation management.

The limitations in the analysis must be recognised. The methodology appears to work well for quantifying volumetric demands at a national level. However, for more detailed regional or catchment based assessments, greater attention should be given to choosing specific crop, soil and irrigation schedules. The spatial accuracy and integrity of certain datasets used in the GIS are also a potential source of error.

2.6 Recommendations

A considerable amount of useful information is collected through the MAFF Irrigation Surveys, but only released as national statistics, or by MAFF statistical region (SSR). For this study county level data was requested and released after special processing; more local data could not be released.

- MAFF should consider making MAFF Irrigation Survey data available at a more local level than county, for research and water resource planning purposes. Respondents confidentiality could still be maintained by respecting the ‘minimum of 4’ rule.

- Otherwise, MAFF should consider recompiling the irrigation survey data on a catchment basis. This would considerably improve the usefulness of the census data for water resource planning.

- MAFF should similarly encourage EA to make available licensed *and* actual abstraction data on a catchment basis.

- MAFF should support research to improve irrigation demand forecasts by incorporating remote sensed data on land use and, in the future, irrigated areas.

3. FUTURE PREDICTIONS

This chapter considers future projections of *actual* demand, i.e. projections from the current *usage* described in Chapter 1, and then future projections of *theoretical* demand, i.e. projections from the present theoretical demand discussed in Chapter 2.

All forecasts are for a design dry year. Effects of any climate change have not been incorporated, but the implications of some recently predicted climate change scenarios on the future demand for irrigation are discussed.

It is emphasised that these are predictions of *demand*, under current pricing. Actual water use will be reduced by restrictions on water availability and increased costs of water.

3.1 Future dry year actual demand

This section aims to predict the ‘most likely’ actual irrigation demand for the period 1996-2021. The predictions are based on the methodology developed by Weatherhead et al. (1994), but using more recent data where appropriate.

3.1.1 Previous methodology

Weatherhead et al. (1994) developed a methodology combining technical and economic analysis to predict future regional and national demand for irrigation water. They used the Manchester University Agricultural Policy Model (Burton, 1992) to predict crop areas, prices and yields to the year 2021 for three world agricultural policy scenarios:

- Continuation of the 1992 conditions, prior to the CAP (Common Agricultural Policy) reforms.
- Complete liberalisation and free trade.
- Reform of the CAP under a new GATT (General Agreement on Tariff and Trade).

Future changes in the fraction of each crop that would be irrigated, and the depth of water that would be applied, were estimated by considering:

- Data for the 1990 dry year.
- Underlying trends for 1982 to 1990.
- The likely effects of changes in irrigation economics due to changes on crop prices and yields, market forces and technical developments.
- Expert opinion.

The resulting rate of change factors were applied to the national 1990 MAFF Irrigation Survey data and the forecast crop areas to predict irrigated areas and volumetric demand for each of the nine crop categories used in the MAFF Irrigation Survey, and in total, up to 2021. High, medium and low predictions were produced for each policy scenario.

(For declining factors, a compound rate of decline asymptotic to zero was assumed. For increasing factors, a compound rate of decline in the unirrigated portion, or the un-applied water, was assumed, giving irrigated portions asymptotic to 100% and depths applied asymptotic to (arbitrarily) twice the 1990 value. This approach avoids predicting portions below 0% or above 100%, though in practice values did not approach the asymptotes.)

For the expected scenario (reform of the CAP under a new GATT), they predicted a ‘most likely’ national growth in actual volumetric demand of 1.7% per annum from 1996 to 2001 and 1% per annum from 2001-2021 for a ‘design’ dry year. Growth under the ‘high’ prediction was two to three times higher. It remained positive but very slow under the ‘low’ predictions.

Predictions were also produced for each EA Region, using a similar approach, based on re-aggregated county level 1990 MAFF data and also based on EA 1990 abstraction data.

3.1.2 Revised methodology

For this study, the methodology has been repeated, for England only, based on:

- Average irrigation depths derived from the MAFF 1995 Irrigation Survey, adjusted to a design dry year.

- The Manchester model crop area change predictions for the expected scenario (reform of the CAP under a new GATT), linearly adjusted to account for more recent MAFF land use data (1994). This scenario still appears to be reasonable for the medium term (though it would be worth repeating the modelling in due course as CAP develops).

- two alternative sets of 'rate of change' factors (Table 3-1), for comparison:

  (a) the 'most likely' rate of change factors predicted by Weatherhead et al. (1994). Again these still appear reasonable, with the possible exception of values for sugar beet and cereals.

  (b) rate of change factors based directly on the underlying trends from 1982 to 1995.

Modelling was carried out at national and county level using a spreadsheet approach. County level results were slightly adjusted for consistency with national totals, and re-aggregated to regional level.

Table 3-1. Rate of change factors (initial % change per annum) in the fraction of each crop irrigated and depth of irrigation water applied, based on (a) Weatherhead et al. (1994), and (b) underlying trends from 1982 to 1995.

Crop category	Initial % change per annum			
	Fraction of crop irrigated		Depth of irrigation water applied	
	(a)	(b)	(a)	(b)
Early potatoes	+2	+3	+1	+4
Maincrop potatoes	+4	+4	+1	+2
Sugar beet	+2	-2	0	0
Orchard fruit	+3	0	+2	0
Small fruit	+3	+1	+2	+4
Vegetables	+3	+4	+2	+2
Grass	-4	-4	0	+2
Cereals	-5	-3	0	+1
Other crops	+1	+1	+1	-1

3.1.3 National predictions

The predicted actual irrigated areas and irrigation water volumes from 1996 to 2021, under the two sets of rate of change assumptions, are shown in Table 3-2 and Table 3-3, respectively.

Table 3-2. Predicted actual irrigated areas from 1996 to 2021.

	Predicted irrigated areas (ha)					
Crop category	1996	2001	2006	2011	2016	2021
(a) Based on Weatherhead et al. (1994) rates of change						
Early potatoes	9326	9912	10444	10895	11313	11647
Maincrop potatoes	55429	60566	63008	63866	63697	62930
Sugar beet	27699	30389	33035	35640	38203	40725
Orchard fruit	2459	2496	2521	2532	2543	2558
Small fruit	3901	5143	5958	6662	7187	7592
Vegetables	30606	35636	38901	41857	44741	47587
Grass	11377	8987	7099	5596	4415	3509
Cereals	17765	14762	12290	10142	8287	6628
Other crops	8379	8792	9203	9612	10018	10422
Total	166941	176683	182460	186801	190404	193597
(b) Based on underlying rates of change from 1982 to 1995						
Early potatoes	9417	10397	11232	11912	12502	12957
Maincrop potatoes	55429	60566	63008	63866	63697	62930
Sugar beet	26613	24056	21745	19656	17767	16060
Orchard fruit	2387	2118	1903	1724	1580	1463
Small fruit	3825	4645	5056	5390	5616	5782
Vegetables	30903	37346	41782	45712	49423	52980
Grass	11377	8987	7099	5596	4415	3509
Cereals	18139	16727	15456	14154	12836	11393
Other crops	8379	8792	9203	9612	10018	10422
Total	166470	173634	176483	177621	177854	177496

The results based on the previous rates of change give broadly similar irrigated areas to previous predictions. Potatoes, sugar beet and vegetables account for the majority of growth over this period, with cereals and grass predicted to decline steadily.

The results based on 1982-1995 underlying trends suggest a much slower rate of overall growth in irrigated area, and contrast sharply for sugar beet and orchard fruit, for which significant declines in irrigated area are predicted, and cereals, where less decline is predicted.

Table 3-3. Predicted actual irrigation volumes from 1996 to 2021.

	Predicted actual irrigation volumes (tcm)					
	1996	2001	2006	2011	2016	2021
(a) Based on Weatherhead et al (1994) rates of change						
Early potatoes	9078	10111	11110	12038	12937	13743
Maincrop potatoes	73157	83434	90272	94921	97955	99887
Sugar beet	21645	23742	25800	27820	29801	31746
Orchard fruit	1875	2078	2255	2404	2540	2665
Small fruit	4992	7190	8967	10673	12142	13438
Vegetables	27765	35323	41525	47569	53638	59734
Grass	10508	8300	6556	5168	4078	3241
Cereals	7727	6420	5346	4411	3604	2883
Other crops	11110	12218	13347	14493	15654	16827
Total	167855	188816	205178	219496	232349	244163
(b) Based on underlying rates of change from 1982 to 1995						
Early potatoes	9439	12192	14713	16919	18868	20481
Maincrop potatoes	73881	87819	98003	105471	110750	114395
Sugar beet	20796	18798	16992	15359	13883	12550
Orchard fruit	1785	1584	1423	1289	1182	1094
Small fruit	4991	7093	8638	10006	11102	12002
Vegetables	28034	37025	44615	51972	59276	66525
Grass	10718	9248	7863	6595	5488	4565
Cereals	7968	7701	7426	7071	6645	6094
Other crops	10890	10832	10685	10441	10095	9642
Total	168502	192291	210357	225123	237290	247348

The two sets of assumptions give very similar predictions of total irrigation volumes, although the distribution between crops is different, notably for sugar beet and cereals again. Both scenarios predict a faster growth in volume than Weatherhead et al. (1994), particularly in the period up to 2011.

The national predicted growth rate in actual volumetric demand for a ‘design’ dry year is between 2.5% and 2.8% from 1995 to 2001, and then declines gradually, with an average of about 1.5% from 2001 to 2021.

This compares with the previous estimate by Weatherhead et al. (1994) of 1.7% per annum from 1996 to 2001 and 1% per annum from 2001-2021.

3.1.4 Regional predictions

The analysis has been repeated for each of the eight EA Regions, for the same two sets of rate of change assumptions. The predicted actual irrigated areas and volumetric irrigation demands, are given in Table 3-4 and Table 3-5, based on the re-aggregated MAFF county level data. The same relative growth rates could be applied to the 1995 EA reported abstractions if desired.

Table 3-4. Predicted actual irrigated areas by EA Region from 1996 to 2021.

	Predicted irrigated areas (ha)					
EA Region	1996	2001	2006	2011	2016	2021
(a) Based on Weatherhead et al. (1994) rates of change						
North East	13686	14575	15223	15703	16064	16342
North West	3765	4118	4387	4628	4852	5067
Welsh	4610	4897	5103	5279	5439	5581
Midlands	35690	36975	37520	37823	37982	38130
Anglian	86804	92173	95464	97981	100148	102122
Thames	6106	6418	6527	6593	6644	6652
Southern	11463	12619	13271	13767	14177	14529
South West	4816	4907	4966	5028	5098	5175
Total	166941	176683	182460	186801	190404	193597
(b) Based on underlying rates of change from 1982 to 1995						
North East	13649	14344	14786	15051	15187	15230
North West	3774	4172	4484	4766	5029	5279
Welsh	4619	4936	5148	5312	5445	5549
Midlands	35531	35974	35608	34953	34146	33274
Anglian	86501	90276	91795	92382	92497	92294
Thames	6110	6405	6473	6489	6488	6468
Southern	11462	12579	13153	13551	13859	14109
South West	4823	4950	5035	5117	5203	5293
Total	166470	173634	176483	177621	177854	177496

Table 3-5. Predicted actual irrigation volumes by EA Region from 1996 to 2021.

EA Region	Predicted irrigation volumes (tcm) 1996	2001	2006	2011	2016	2021
(a) Based on Weatherhead et al. (1994) rates of change						
North East	15561	17831	19759	21402	22800	24000
North West	3724	4226	4676	5101	5507	5900
Welsh	3680	4217	4684	5123	5536	5923
Midlands	37613	41165	43655	45729	47460	49068
Anglian	84894	95727	104135	111415	117979	124033
Thames	6430	7254	7880	8459	9010	9480
Southern	11058	13210	14917	16493	17970	19354
South West	4896	5186	5473	5774	6087	6404
Total	167855	188816	205178	219496	232349	244163
(b) Based on underlying rates of change from 1982 to 1995						
North East	15666	18471	20898	22959	24677	26094
North West	3755	4404	4986	5524	6022	6487
Welsh	3711	4386	4953	5452	5891	6268
Midlands	37722	41703	44348	46301	47701	48733
Anglian	85108	96915	105822	113007	118899	123734
Thames	6466	7406	8068	8620	9095	9490
Southern	11112	13466	15245	16776	18112	19281
South West	4962	5539	6037	6485	6892	7261
Total	168502	192291	210357	225123	237290	247348

3.2 Future dry year theoretical demand

The irrigated areas predicted above based on Weatherhead et al. (1994) rates of change have been combined with the theoretical irrigation needs (mm) described in Chapter 2. This procedure produces future projections of dry year theoretical demand, i.e. the volumes that would be required in a *design dry year* for applying the *optimum* applications on those crops that are *predicted to be irrigated.* This concept is useful for mapping future maximum unconstrained demand.

The predicted theoretical total volumetric irrigation demand for a dry year in 2021, is shown in Figure 3-1. The predictions by crop category, over the period 1996-2021, are summarised in Table 3-6. A map showing the spatial distribution of the changes in the theoretical demand between 1996 and 2021 is shown in Figure 3-2.

The maps confirm that theoretical irrigation demand, and growth, will continue to be strongly concentrated in Eastern England, notably around the Fens region, and in parts of North Norfolk and the Suffolk coast. However, parts of Kent, Nottinghamshire and Shropshire also show large increases.

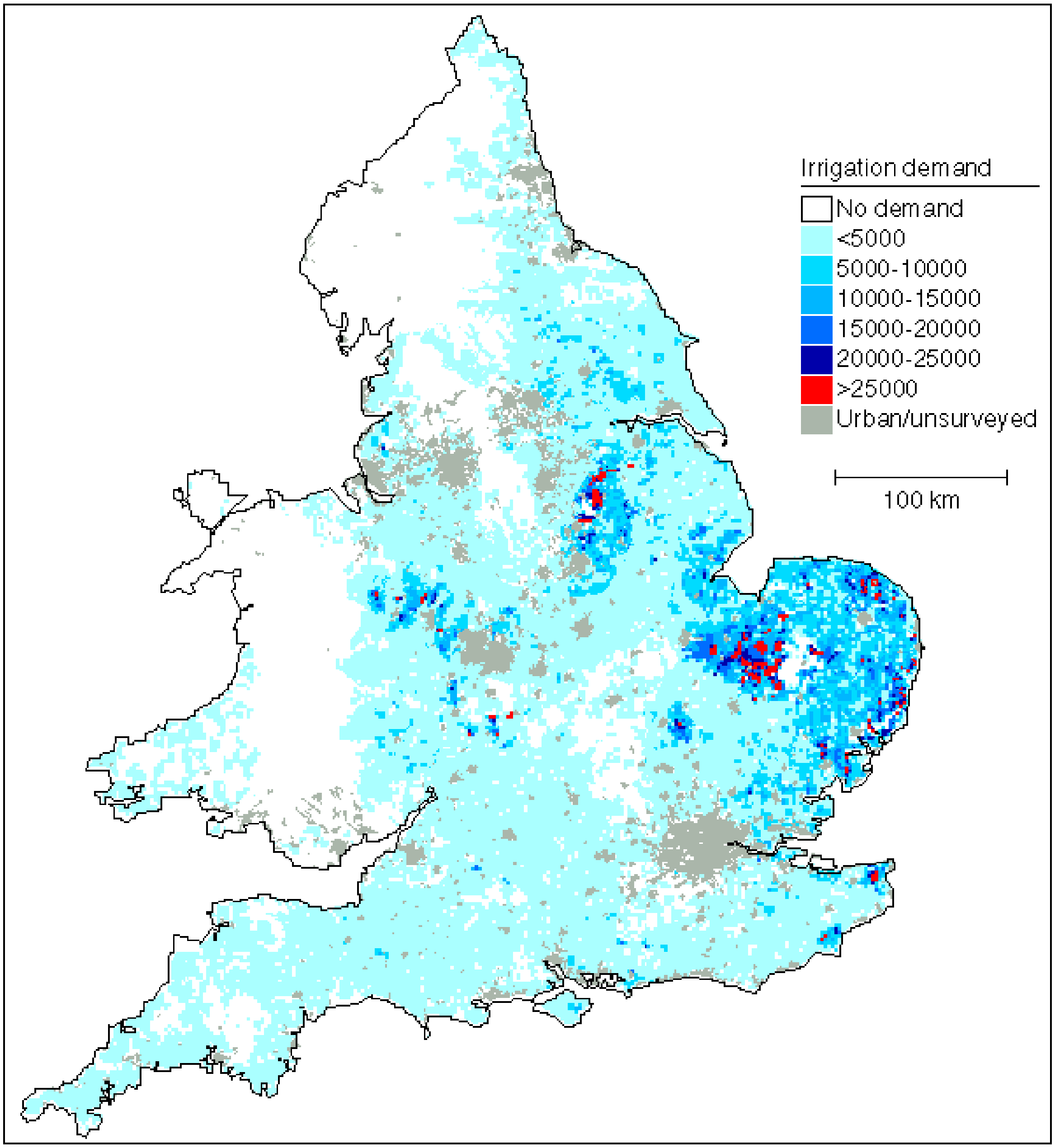

Figure 3-1. Predicted theoretical total volumetric irrigation demand in a design dry year in 2021.

Table 3-6. Predicted theoretical irrigation volumes 1996 to 2021, by crop category.

Crop category	Predicted theoretical irrigation volumes (tcm) 1996	2001	2006	2011	2016	2021
Early potatoes	3259	3478	3673	3867	4010	4159
Maincrop potatoes	99298	108401	113010	113877	113367	111511
Sugar beet	26322	28824	31484	33618	36038	38544
Orchard fruit	4317	4373	4369	4378	4553	4519
Small fruit	6776	9256	10808	12056	12848	13436
Vegetables	37005	43300	47153	50730	54353	57523
Grass	15518	12574	10173	8022	5426	4527
Cereals	1328	1088	922	767	609	474
Other crops*	7753	8452	8864	9093	9248	9388
Total	201576	219746	230456	236408	240452	244801

* estimated.

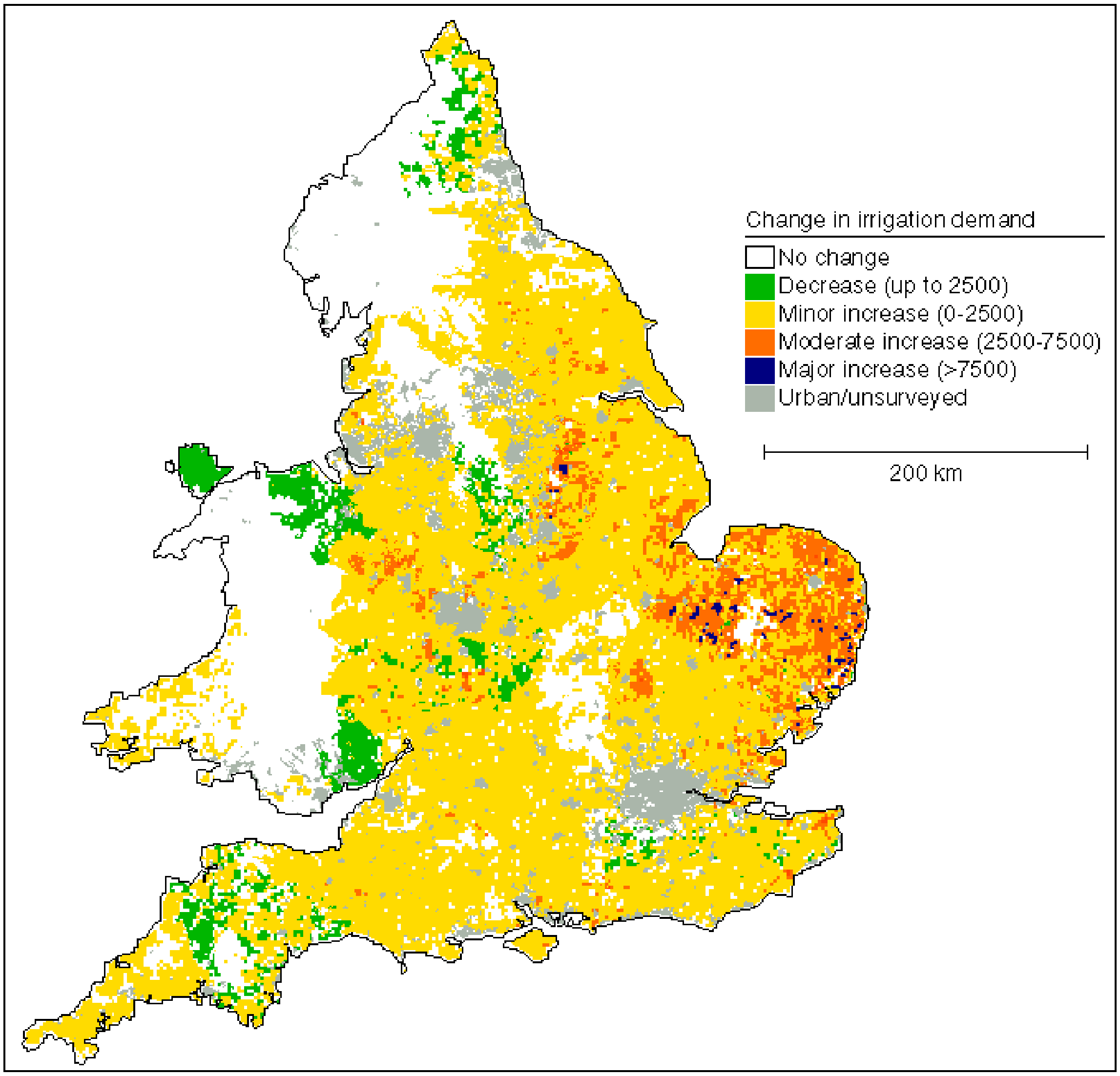

Figure 3-2. Predicted change in the spatial distribution of irrigation demand, between 1996 and 2021.

3.3 The impact of climate change

Climate change is gradually becoming accepted as a reality. The Intergovernmental Panel on Climate Change (IPCC) recently reported that ‘the balance of evidence suggests there is a discernible human influence on the global climate’ (DoE, 1996). Indeed the spate of recent droughts experienced in UK are consistent with a changing climate. However, the likely impacts on UK irrigation are still far from clear.

Some recent estimates suggest higher temperatures with only marginally more summer rainfall in the main UK irrigation areas, (DoE, 1996). Others show a marginal decrease in summer rainfall, further increasing potential soil moisture deficits. Extrapolating from one recent Institute of Hydrology predictions and past quantitative relationships between climate variation and summer rainfall, Herrington (1996) estimated an additional 27.5% demand, above current trends in EA Anglian Region by the year 2021. However, as he cautions, using relationships based on past *variation* to estimate the effects of *change* is likely to give an underestimate. Once the likely effects of climate change are more widely accepted, farmers can be expected to increase system capacity and plan to irrigate more of their crops.

None of the results presented in this chapter allow for climate change, because the uncertainty would make the results virtually meaningless. By the same token, once the occurrence of climate change is accepted, there is little point improving the accuracy of the forecasts without including it. Clearly, identifying limits for the impact of climate change on irrigation must be a priority in future research.

Potential soil moisture deficit, crop adjusted, is used as the climatic indicator within the GIS model used in this study. Once reliable climate change predictions are available for UK, it will be feasible to estimate future PSMDs, and hence predict the increased demand for the current irrigated cropping, both nationally and locally, under scenarios of climate change. However, it will be much more difficult to model the effects of climate change on cropping pattern and on the economics of irrigation. Furthermore, potential reductions in water availability due to climate change may themselves affect the location of irrigated agriculture.

3.4 Summary

A comparison of the ‘most likely’ predictions of actual total volumetric demand arising from this study based on the updated approach using Weatherhead et al. (1994) rates of change (a), underlying 1982 to 1995 rates of change (b) and from Weatherhead et al. (1994) (c), is shown in Figure 3-3. The predicted theoretical demand is also shown (d).

The predicted total actual volumetric demands are remarkably similar, although there are differences between crops and between areas as discussed earlier.

The national predicted growth rate in actual volumetric demand for a ‘design’ dry year is between 2.5% and 2.8% from 1995 to 2001, and then declines gradually, with an average of about 1.5% from 2001 to 2021.

This compares with the previous estimate by Weatherhead et al. (1994) of 1.7% per annum from 1996 to 2001 and 1% per annum from 2001-2021.

The actual demand prediction approaches the theoretical demand prediction towards 2021, reflecting the increased depths applied on the dominant crops.

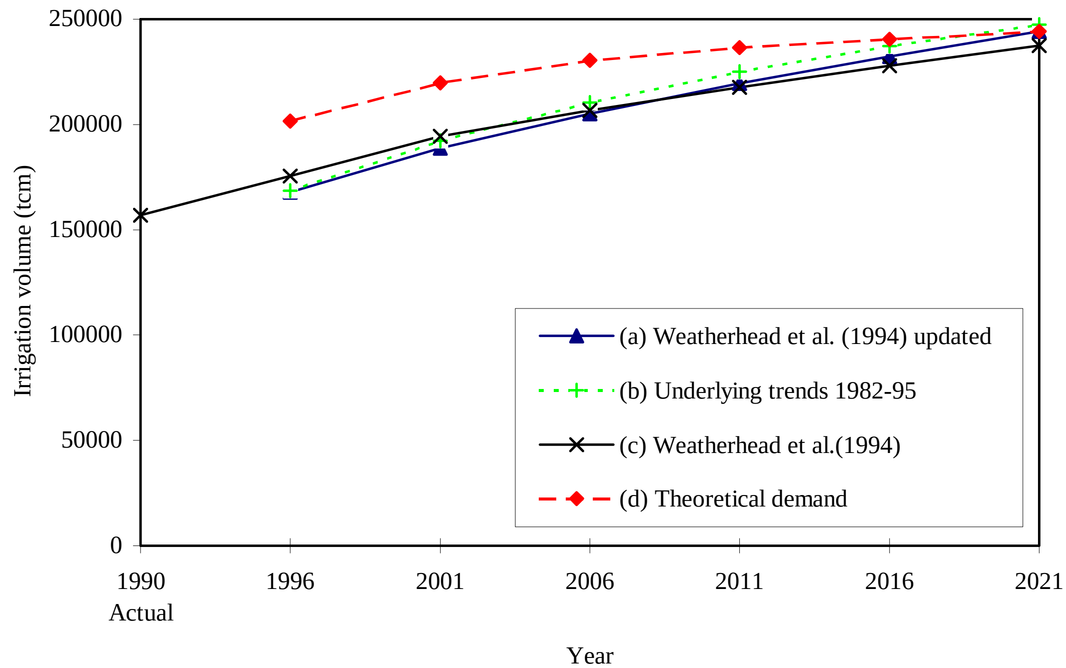

Figure 3-3. Comparison of predictions of future volumetric irrigation demand, from 1990 and 2021.

3.5 Recommendations

The results discussed here show that it is possible to produce reasonably consistent projections of future irrigation demand, at least for the short to medium term. These can be produced by crop category, region or even catchment or aquifer. The results will help identify problem areas, and should be useful for water resource planning by individual farmers as well as MAFF, EA and others.

In the medium to long term there is a risk of missing a new trend, for example, a change in the profitability of irrigating grass, cereals or sugar beet, a change to drought resistant varieties of potatoes, or the spread of new crops such as irrigated maize.

MAFF should fund the periodic review and updating of these forecasts. It would be most worthwhile repeating the modelling after irrigation surveys in dry years, and as agricultural policy (particularly CAP) develops.

MAFF should fund research to evaluate the impact of climate change on irrigation needs. Once reliable climate change predictions are available, it will be feasible to use the GIS approach described here to predict and map the increased demand for the current irrigated cropping. Research would also be needed to predict the effects on cropping pattern and on the economics of irrigation, and to estimate how reductions in water availability could affect the location of irrigated agriculture.

4. THE VALUE OF WATER CONSERVED

On-farm water conservation only makes financial and economic sense if the value of the water conserved is greater than the costs of conserving water.

A study by Morris et al. (1996), on the feasibility of tradeable abstraction permits, found that although the farmers had a rough idea of the capital costs involved in irrigation, they found it very difficult to value the water itself.

The value of the conserved water depends on how else it would be 'used', for example:

- left in the river or aquifer, to avoid damage to the environment or other non-abstracting users, such as navigation and fisheries.
- abstracted for other uses, such as mains water supply or industry.
- used for irrigation of crops that would otherwise remain un-irrigated or inadequately irrigated.

No attempt is made here to discuss the value of water to the environment or to non-agricultural users. Environmental benefits are notoriously difficult to express in money terms. The Environment Agency, which has a legal duty to consider the likely costs and benefits of its policies, is trying to address this. Estimating values for drinking water or industrial use is easier, although the results may be site specific.

With the existing licensing system, it is the on-farm value that will most influence individual farmers' actions. This chapter discusses first the financial value of the conserved water to the farm enterprise, and then considers its economic value, assuming it is used on-farm.

4.1 Water resource scenarios

For each farm enterprise, three broad scenarios exist:

1. Irrigation water resources and application equipment are sufficient to meet all the irrigation requirements. The value of conserving water is then given by the reduction in the cost of abstracting, storing and applying that water.

2. Irrigation water resources are not sufficient to meet all the irrigation requirements, and as a result some crops are under-irrigated or not irrigated at all. The value of conserving water or developing new resources is then the potential benefit on those crops.

3. The enterprise has no access to water resources at all. Conserving water is not an immediate option, but the value of developing new resources for use on existing rain-fed crops, is similar to scenario 2.

Most irrigating farms are likely to move between scenarios 1 and 2 depending on weather conditions in a particular year, but some are 'over-licensed' and have excess water even in dry years.

With the present abstraction licensing system, it is quite possible for all three scenarios to occur in close proximity. A farmer may be investing in expensive water conservation techniques while one neighbour has unused water and another has to rely on rain-fed crops. The introduction of more flexible (or even locally tradable) licences would tend to equalise the value of water locally, such that (in a perfect market) the value would depend on the overall scenario in each catchment rather than on the scenarios in each enterprise.

The above analysis is complicated by the longer-term possibility that water conservation could result in a change in the cropping pattern. The value of the water would then depend on the difference in net margin between the new and old crops.

4.2 Water conservation to reduce irrigation costs

The costs of irrigation vary considerably according to local circumstances, therefore generalisation of costs is difficult (Morris, 1994). Costs vary according to:

- the crop requirements for irrigation;
- source of irrigation water (surface or groundwater);
- the need for water storage;
- type of application system; and,
- the size, configuration and topography of the irrigated area, its distance from and height above the water source.

Most agricultural irrigation in England is applied through hosereel-gun systems. A summary of the typical costs of irrigating with hosereel-gun systems using water from various sources is presented in Table 4-7. The initial investment (capital) costs, the annual fixed costs (amortisation of capital costs plus insurance), the annual variable costs (repairs, fuel, labour and water charges), and the average costs per unit of water applied (net of losses) are shown.

Table 4-7. Summary of typical average costs of irrigation.

Water Source: Direct Abstraction or Storage: Application Method:	Surface Direct Hosereel-gun		Borehole Direct Hosereel-gun		Surface Reservoir (unlined) Hosereel-gun	
	£	*%*	£	*%*	£	*%*
Capital Costs (£/ha)						
Initial cost	2799		3214		5304	
Annual Costs (£/ha/yr)						
Fixed costs *	314	*63*	358	*64*	579	*74*
Variable Costs:						
repairs	75	*15*	82	*15*	112	*14*
fuel	40	*8*	49	*9*	42	*5*
labour	17	*3*	17	*3*	22	*3*
water	53	*11*	53	*9*	7	*1*
reservoir engineer fees	0	*0*	0	*0*	24	*3*
Total variable costs	185	*37*	201	*36*	207	*26*
Total Annual Costs	500	*100*	559	*100*	786	*100*
Unit Costs (£/m^3 applied net)						
fixed	0.25		0.29		0.46	
variable	0.15		0.16		0.17	
Total Unit Costs	0.40		0.45		0.63	

Notes: 1996/7 prices.
Costs are per m^3 usefully applied, i.e. net of losses, at an assumed 80% efficiency.
Assumes 24 ha irrigated with average annual application of 125mm net of losses.
* Including amortisation of initial capital cost over 20 years at 6%.

For a typical hosereel system without winter storage, capital costs are £2800-£3200 per hectare irrigated, the total annual cost is approximately £500-£600 per hectare irrigated, and the average cost per unit of water applied is around £0.40-£0.45 per m^3 applied net of losses (£4.00-£4.50 per ha.mm).

Adding winter storage typically increases the annual costs per hectare, and the costs per unit of water, by 50% and 130% for unlined and artificially lined reservoirs respectively. Average unit costs with unlined reservoirs are approximately £0.63 per m^3 net of losses. Artificial lining would increase this to about £0.92 per m^3, although there may be economies of scale for larger reservoirs.

The structure of these costs is important. Fixed costs account for over 60% of total costs even for direct abstraction to hosereel-gun systems, and over 70% with storage. The more efficient systems, including boom systems, center pivots, and trickle systems, have an even higher proportion of fixed costs to variable costs. If fixed costs are already 'sunk', water conservation measures can only hope to recoup some of the running or variable costs. Total running costs for hosereel systems are typically about £0.15 per m^3 net of losses, or £0.12 per m^3 including losses, and not all of these are directly related to the volume of water applied.

Irrigators using hosereel-gun systems with an ample water supply and sunk capital costs might therefore typically hope to save around £0.10 per m^3 of water conserved by reducing losses. Savings would be less with more automated systems.

In 1996, water charges in EA Anglian Region were only £0.0224 per m^3 for direct summer abstraction and £0.00224 per m^3 for winter abstraction, and half these are fixed costs under the present two part tariff system. Measures to increase supply, such as water harvesting or re-use, will save only the variable part of the abstraction charges, i.e. around £0.01 and £0.001 per m^3 of extra water produced in summer and winter respectively.

Where a new system is being installed, conservation measures would allow a reduction in system capacity. If costs were linearly proportional to volume applied, the benefit would be given by the total unit cost of applying water, i.e. £0.40, £0.63 and £0.92 per m^3 of net water saved (or £0.32, £0.50 and £0.74 per m^3 of gross water saved) for hosereel-gun systems using surface abstraction for direct use, unlined and lined winter storage reservoirs respectively. In practice, many costs are independent of volume or subject to economies of scale, and therefore actual savings would be substantially less.

4.3 Water conservation to reduce losses in yield and quality

Irrigation serves mainly to increase crop yield and crop quality over and above that obtained through rain-fed crop production. The size of the benefit depends on crop type and variety, the stages in the crop cycle when water is applied, the standard of crop husbandry, and environmental factors; especially soil and climate.

In addition, irrigation may also:

- enable a wider range of crops to be grown;
- enable multiple cropping;
- improve seed bed preparation;
- provide protection against frost damage;
- enable effective use of herbicides and fertilisers;
- soften tillage pans and clods.

These additional benefits are not considered here.

Irrigation improves yield (t/ha) and quality (£/t), with consequences for revenue (£/ha). The two effects are multiplicative, rather than additive. For example, Table 4-8 shows the impact on potato yield, price and revenue for 'with' and 'without' irrigation on a medium AWC soil 'on average' and in a 'design dry year' in the Fens (adapted from Morris et al., 1997). In very dry years, irrigation benefits are increased due to the higher commodity prices associated with reduced market supply.

Table 4-8. Example of yield and quality benefits associated with irrigation on a potato crop, on a medium AWC soil in the Fens.

	With irrigation	Without irrigation	Difference due to irrigation
Averaged over 20 years:			
Yield (t/ha)	50	40	10
Price (£/t)	95	66.50	28.50
Gross Revenue (£/ha)	4750	2660	2090
Design dry year:			
Yield (t/ha)	50	36	14
Price (£/t)	175	96	79
Gross Revenue (£/ha)	8750	3456	5294

Note: Additional costs of extra yield (harvesting etc.) must be deducted to determine benefit due to irrigation.

4.3.1.1 Yield benefits

The yield benefit provided by irrigation depends on many factors such as crop type and variety, the growth stage at which irrigation is applied, crop husbandry and environmental factors such as soils and climate. Irrigation has encouraged the movement of field-scale vegetables and root crops to light soils, where potential yield loss is highest, in order to facilitate timeliness of planting and mechanical harvesting.

Table 4-9 estimates average yield benefits per unit of water applied to the main irrigated crops, using average prices for quality (irrigated) produce. The extra costs include additional harvesting, handling, drying, and where relevant, direct packaging and marketing costs. The yield responses are averages based on available experimental data and field experience for well managed crops in areas of established irrigation need (ADAS 1977; MAFF 1984; Bailey, 1990). They represent the average returns to water application *over the relevant range* of water applied, with the latter varying according to soil and climatic conditions. Yield response to water and hence irrigation is reasonably documented for potatoes, sugar beet, grass and some fruit and vegetables under specific circumstances, but for many other crops reliable data is limited.

The yield related benefits, per unit of water applied, are highest for soft fruits, followed by horticultural crops, field vegetables and maincrop potatoes. The yield benefits on cereals and grass are relatively low. For example, for the assumptions made, irrigation of maincrop potatoes generates an average yield benefit of about £0.65 /m^3 applied net of losses (£6.50 /ha.mm).

Table 4-9. Average yield benefits (£/m^3) in Eastern England.

Crop	Potential yields (t/ha)	Crop price (£/t)	Extra crop costs (£/t)	Extra net margin (£/t)	Crop response (t/ha.mm)	Extra net margin (£/m^3)
Maincrop potatoes	50	95	14.25	80.75	0.08	0.65
Early potatoes	25	150	22.50	127.50	0.08	1.02
Sugar beet	42	40	4.00	36.00	0.13	0.47
Cereals	7	100	3.00	97.00	0.02	0.19
Peas - dried	4	115	3.45	111.55	0.04	0.39
Peas - vining	5	315	78.75	236.25	0.04	0.95
Carrots	45	90	13.50	76.50	0.13	1.00
Parsnips	40	200	30.00	170.00	0.13	2.21
Beetroot	40	60	9.00	51.00	0.13	0.63
Turnips (culinary)	35	100	15.00	85.00	0.13	1.10
Swede (culinary)	32	100	15.00	85.00	0.14	1.19
Celery	25	400	60.00	340.00	0.08	2.72
Leeks	25	500	75.00	425.00	0.08	3.40
Cabbage (spring)	35	130	19.50	110.50	0.14	1.55
Calabrese	8	675	101.25	573.75	0.05	2.87
French beans	7	280	42.00	238.00	0.06	1.43
Runner beans	21	450	112.50	337.50	0.05	1.69
Brussel sprouts	13	300	45.00	255.00	0.04	1.02
Cauliflower	15	240	36.00	204.00	0.07	1.43
Lettuce (outdoor)	30	450	112.50	337.50	0.05	1.69
Bulb onions	40	100	15.00	85.00	0.08	0.68
Salad onions	18	800	200.00	600.00	0.08	4.80
Radish	5	450	112.50	337.50	0.03	1.01
Asparagus	3	450	112.50	337.50	0.02	0.67
Grass-graze	6	95	0.00	95.00	0.03	0.28
Grass-silage	6	95	20.90	74.10	0.03	0.22
Strawberries	8	1700	425.00	1275.00	0.03	3.83
Raspberries	6	2000	500.00	1500.00	0.03	4.50
Blackcurrants	6	650	162.50	487.50	0.03	1.46
Rhubarb	35	550	137.50	412.50	0.05	2.06
Dessert apples	15	400	100.00	300.00	0.02	0.60
Pears	10	450	112.50	337.50	0.03	1.01
Plums	8	1350	337.50	1012.50	0.02	2.02
Cherries	8	1000	250.00	750.00	0.02	1.50

Additional costs:	*% of gross output*
Combinable crops	3
Sugar beet	10
Potatoes and field scale vegetables	15
Fruit and Horticulture	25
Grass (grazed)	0
Grass (silage)	22

Notes:
Average response based on ADAS (1977), MAFF (1984) and Bailey (1990).
Extra cost including additional harvesting, handling, drying, & where relevant, direct packaging & marketing costs.
Estimates based on Nix (1995), ABC (1996), Outsider's Guide (1995), Renwick (1997).

4.3.2 Quality benefits

For most irrigated crops, the quality assurance benefits of irrigation are substantial. They relate to the whole crop, not just to the extra yield due to irrigation. Quality criteria are increasingly specified as a condition of contract and sale. Failure to meet quality standards can lead to large price discounting, and possibly to rejection and loss of contract.

The link between irrigation and crop quality is complex. Much of the evidence is anecdotal. A review of research literature, information derived from interviews with farmers and marketing agents, and analysis of published price data were used to derive estimates of possible price reductions due to poor quality. Key quality indicators, such as size or skin quality, were identified and related to market prices. The link between quality indicator, water stress and hence irrigation was explored in an attempt to attribute quality assurance benefits to irrigation.

4.3.3 Combined Yield and Quality Benefits

The average combined benefit can be calculated by adding the yield and quality benefits and dividing by the depth of water applied. For simplicity (and for lack of better data in most cases), a linear relationship between benefits and irrigation depth over the normal range of irrigation has been assumed. The results are site specific, because of variation in soils and climate.

Table 4-10 summarises the average combined yield and quality benefits (£/m^3 of water applied), for selected crops grown near Mepal, Cambridgeshire. (This table assumes mathematically that the quality benefit is applied to the unirrigated yield, then the yield benefit is valued at the full quality price; the reverse approach would show higher quality benefits and lower yield benefits but the same total benefit).

In a dry year, the benefits of irrigation *per hectare* are of course much higher than the average. For most crops, the benefits *per m^3 of water applied* do not change so much, because more water has to be applied. Exceptions occur where dry years lead to increased prices. This used to be very noticeable for potatoes, but the increased area irrigated and the number of growers with reservoirs are reducing the influence of dry weather (in terms of irrigation need) on price.

Table 4-10. Average combined yield and quality benefits attributable to irrigation on a medium AWC soil at Mepal, Cambridgeshire.

Crop	Net depth	Unirrigated yield	Quality premia	Qualitybenefits		Yield Benefits			Total Benefits
	mm	t/ha	% price	£/ha	£/m^3	t/ha	£/ha	£/m^3	£/m^3
Maincrop potatoes	125	40.0	30%	1140	0.91	10.0	808	0.65	1.56
Early potatoes	44	21.5	23%	741	1.68	3.5	450	1.02	2.70
Sugar beet	77	32.0	3%	38	0.05	10.0	361	0.47	0.52
Cereals	37	6.3	0%	0	0.00	0.7	71	0.19	0.19
Peas - dried	66	1.7	18%	35	0.05	2.3	258	0.39	0.44
Peas - vining	44	3.2	16%	163	0.37	1.8	417	0.95	1.31
Carrots	77	35.0	15%	472	0.61	10.0	768	0.99	1.61
Parsnips	66	31.4	6%	377	0.57	8.6	1463	2.21	2.78
Beetroot	103	26.6	13%	208	0.20	13.4	683	0.66	0.86
Turnips (culinary)	74	25.4	8%	204	0.28	9.6	813	1.11	1.38
Swede (culinary)	74	21.7	8%	174	0.24	10.3	875	1.19	1.43
Celery	74	19.1	40%	3089	4.20	5.9	2000	2.72	6.92
Leeks	92	17.6	13%	1147	1.25	7.4	3125	3.40	4.65
Cabbage (spring)	74	24.7	7%	225	0.31	10.3	1138	1.55	1.85
Calabrese	81	4.0	12%	320	0.40	4.0	2320	2.87	3.26
French beans	74	2.6	17%	123	0.17	4.4	1050	1.43	1.60
Runner beans	88	16.6	16%	1194	1.35	4.4	1489	1.69	3.04
Brussel sprouts	74	10.1	14%	422	0.57	2.9	750	1.02	1.59
Cauliflower	74	9.9	14%	331	0.45	5.1	1050	1.43	1.88
Lettuce (outdoor)	147	22.6	40%	4076	2.77	7.4	2482	1.69	4.46
Bulb onions	99	32.1	24%	769	0.78	7.9	675	0.68	1.46
Salad onions	92	10.6	20%	1704	1.85	7.4	4412	4.80	6.65
Radish	74	2.8	8%	101	0.14	2.2	744	1.01	1.15
Asparagus	59	1.3	16%	95	0.16	1.2	397	0.68	0.84
Grass-graze	51	4.5	3%	13	0.02	1.5	147	0.29	0.31
Grass-silage	51	4.5	3%	13	0.02	1.5	114	0.22	0.25
Strawberries	40	6.8	11%	1269	3.14	1.2	1547	3.83	6.96
Raspberries	37	4.9	11%	1077	2.93	1.1	1654	4.50	7.43
Blackcurrants	37	4.9	11%	350	0.95	1.1	538	1.46	2.41
Rhubarb (in the open)	74	31.3	8%	1378	1.87	3.7	1517	2.06	3.94
Dessert apples	74	13.5	20%	1082	1.47	1.5	441	0.60	2.07
Pears	74	7.8	14%	491	0.67	2.2	744	1.01	1.68
Plums	74	6.5	14%	1234	1.68	1.5	1489	2.03	3.70
Cherries	74	6.5	14%	914	1.24	1.5	1103	1.50	2.74

Example calculation: Quality benefits on potatoes: 40t/ha x £95/t x 30%/ 125 ha mm x 10m^3/ha mm = £0.91/m^3
Yield benefits on potatoes: (10t/ha x £80.8/t net)/ (125 ha mm x 10m^3/ ha mm) = £0.65/m^3

4.4 Changing cropping patterns

The benefits shown in the tables assume the farmer would grow the same crop with or without adequate irrigation. Rather than under-irrigate, farmers without adequate water resources may restrict the area of crops that need irrigation. Conserving water would allow them to grow more irrigated crops. The value of the water would then depend on the difference in net margin between the irrigated and the rain-fed crops. For example, farmers in the South Level said that without irrigation they would revert to a mainly cereals and oilseed rotation, moving out of root crops (Morris et al., 1997). In this case, the water would only have been worth around £0.80/m^3 net of losses, rather than the £1.56/m^3 shown in Table 4-10.

4.5 Economic Benefits

The preceding analysis adopted a financial perspective whereby yield and quality losses, net of savings in expenditure, were valued at the market prices received by farmers. That analysis shows the value of the conserved water, or additional water supply, *to farmers*, and hence how much they should be prepared to pay to conserve water.

From the national viewpoint, an economic perspective is required. Amongst other things, this requires adjusting financial prices to economic values to reflect the real value of resources used and outputs produced. This adjustment is particularly difficult in agriculture because of the complexity of direct (such as commodity price support) and indirect (trade protection) measures. Two relatively straightforward (but not necessarily reliable) measures of adjustment involve removing relevant taxes and subsidies, and/or expressing commodities values at international rather than protected internal market prices.

In the flood defence sector, MAFF advise the use of adjustment factors to net out the costs of support and subvention for commodities which are heavily supported and or regulated.

With respect to irrigation, however, the preceding financial analysis can be used as a reasonable indicator of the short term economic impact, without the need for further adjustment, because:

- the commodities affected are mainly non-regulated produce (including potatoes now). They operate in a relatively free market where prices reflect willingness to pay and the benefit derived.

- the significant rise in prices during dry years is indicative of the value of consumption of these commodities.

- shortfalls in irrigated produce are partly substituted by imports (and lost exports) which involve foreign exchange costs and balance of payment impacts.

- the loss of output from irrigation reduces activity levels in local agri-business and food industry sectors. These are major employers and income generators in predominantly agriculturally dependent communities.

4.6 Summary

The above analysis shows that the marginal benefit *to the farmer* of conserving water varies enormously between enterprises. For farmers with adequate licences, reducing application losses is typically worth less than £0.10/m^3 of water saved, whilst re-using waste water or developing new on-farm resources would be worth as little as £0.01/m^3 at present abstraction charges. For farmers with inadequate supplies, saving water to avoid water stress on maincrop potatoes could be worth on average £1.50/m^3 net of losses, and by much more on some other specialist crops. Saving water to move land from rain-fed cereals to maincrop potatoes could be worth £0.80/m^3.

These figures are all site specific, and will vary greatly between enterprises, but they do show clearly the widely different values of water even within agriculture. Clearly this will cause a very ‘patchy’ uptake of on-farm water conservation measures. This can already be observed in practice, with some enterprises undertaking considerable investment in reservoirs, while others are relatively unconcerned about efficient water use. This will not lead to a sensible allocation of national resources on water conservation.

4.7 Recommendations

Some farmers clearly have little financial incentive to save water, because abstraction charges are very low and because they cannot easily pass unused water or conserved water to other farms under the current licensing system.

Two recommendations follow from these observations:

- MAFF should consider proposals for a levy (e.g. through an increase in abstraction charges) on summer abstraction from sources where water is scarce, both increasing the incentive to save water *and* generating funds to support water conservation measures in those catchments.

- MAFF should support proposals to make the licensing system more flexible, so that water is conserved first where it is cheapest to do so, and then applied where it is most beneficial.

5. REDUCING WATER USE ON-FARM

This chapter considers the potential for reducing water use on the farm. It considers first improvements to the application system, then the use of scientific scheduling methods, and finally ways in which the crop demand itself might be reduced.

5.1 Overhead irrigation

Over 97% of irrigation in UK is applied by overhead methods, i.e. with the irrigation falling from above like rain. All methods of overhead irrigation are prone to losses through evaporation in the air, from wetted foliage and from the soil surface. The poor application uniformity from many systems, particularly when windy, can result in some plants suffering water stress and/or others being over-irrigated, wasting water. Wind drift can also carry small droplets out of the irrigated area. Reducing each of these losses is one key to improving application efficiency.

5.1.1 Overhead irrigation systems

Overhead irrigation methods used in the UK include *fixed* systems using conventional rotary impact sprinklers or micro-sprinklers, *set move* systems such as conventional hand-move sprinklers and side-roll systems, and *continuously moving* systems such as hosereels, center-pivots and linear-moves. The driving forces for change have been (a) reduction in labour costs, leading either to electronically controlled fixed systems or large automated moving systems, and (b) the search for uniform growth on high value crops such as salads. Water conservation and energy conservation have been relatively unimportant considerations, and have mainly occurred as side-effects. In the UK, the relatively short irrigation season, the small seasonal application depths and the annual rotation of the irrigated area around the farm have also favoured flexible systems with low capital costs per hectare covered.

5.1.2 Current Use

Most UK irrigation is applied through hosereel systems, and most of these hosereels are fitted with guns. These systems are widely acknowledged to be inaccurate and inefficient in water and energy use. However, they are robust, versatile, and fit well onto typical UK mechanised arable farms. They cope particularly well with the flexibility required by rotational cropping patterns (e.g. following potatoes around a farm with non-standard field sizes). The MAFF statistics show that the number of ‘self-propelled irrigators’, predominantly hosereels, is growing by 3% to 4% per year (Table 5-1). It is also believed that the average capacity of these machines is growing, though data on this is not readily available.

Table 5-1. Hosereel systems in England and Wales, 1987-1995.

Hosereel system	1987	1990	1992	1995
Total ‘self-propelled’ irrigators	4880	5550	6120	6610
fitted with guns	4530	5270	5790	6140
fitted with booms	350	280	340	470
% fitted with guns	93	95	95	93

Recent improvements in the design of booms, which replace the gun by a row of spray nozzles, have overcome many of the problems which made them unpopular with users. The largest booms can now irrigate a strip of equal width to a gun, and the latest designs are simpler to fold up for moving between strips. Fields with uneven topography, low infiltration rate soils, and irregular shapes can create problems, but on large flat fields, booms are now almost as easy to use. Sales are reported to be growing, particularly to field-scale vegetable and salad growers, for whom uniformity is particularly important.

Center pivots and linear move systems can provide accurate efficient irrigation, with very low labour costs. Unfortunately, they are difficult to site on most UK farms, and despite their attractions are likely to account for only a small portion of the irrigated area.

Solid set micro-sprinkler systems are claimed to be an economic alternative where frequent applications are required, and are well suited to small areas or irregular shape fields that are difficult for mechanized systems. Similar claims are made for the South African manufactured ‘Floppy’ sprinkler system (Knox, 1993), not used commercially in the UK. The cost of close spacing and extensive pipe networks are supposedly compensated for by the relatively low pressures allowing cheaper plastic pipe to be used. This sort of system, with advanced computer design and control to optimize pipe costs, may well have a bigger role in future in the UK, particularly on specialist crops grown in smaller blocks than needed by hosereel systems. More information and example applications are needed to allow farmers to assess their merits.

5.1.3 Water efficiency of overhead irrigation systems

Despite the criticisms, there is surprisingly little hard data on the efficiency of water application from overhead systems under UK conditions. Agronomists scheduling commercial crops by neutron probe have reported that, in hot dry weather, sometimes only 60% to 70% of the water reportedly applied from hosereel-gun systems appears to be accountable for in their soil moisture measurements. However, these measurements have not been controlled by simultaneous catch-can or gun discharge measurements. Incorrect settings or low pressure could have meant less water was applied than intended, or the poor uniformity and limited number of probe sites could have distorted results.

In recent water distribution measurements in France (CEMAGREF, 1997), at temperatures up to 31^{o} C and a range of wind speeds, 85% to 90% of the water discharged from guns was collected in catch-cans at canopy level. Evaporation from foliage could account for another say 2 mm loss, i.e. 8% of a typical 25 mm application. This suggests at least 80% should reach the soil in daytime summer conditions, and more at night (probably over 90%). Given that other overhead systems have similar foliage losses, plus daytime aerial losses of say 5%, switching between overhead methods may not drastically improve application efficiency. Indeed, the very fine drops from some spray nozzles are more likely to evaporate and drift than the large drops from guns.

These estimates need experimental corroboration under UK climatic conditions for the range of overhead systems likely to be used in the future.

An equally important problem, particularly with guns, is the poor uniformity of water application. This can result in drainage losses on a fully irrigated crop, particularly where a farmer tries to compensate by applying even more water. Scheduling by point measurement methods, such as neutron probes, is also potentially inaccurate if the water is not uniformly applied, again leading to wasted water. The use of booms should help significantly here by applying water accurately, saving water and helping provide a more uniform and higher quality crop.

Evaporation from foliage and the soil surface could be reduced by minimizing the area wetted, e.g. by irrigating only between alternate rows on a bed. This would be possible with precision hosereel- booms and linear move systems, using drop tubes or sub-canopy sprays, which also avoid aerial evaporation and drift losses. The higher application rates could be a problem on some soils, necessitating the use of special tillage or small basins. Some research and product development has already been undertaken in the USA along these lines, with application efficiencies of over 95% claimed (Hoffman and Martin, 1995), and would be worth investigating further for use under UK conditions.

5.1.4 Costs

To replace a gun by a modern boom irrigating a 72 m strip with spray nozzles would cost about another £8000. Spread over 30 ha, this would increase in-field capital costs by £36 per ha/per year (amortising over 10 years at 6% real interest rate, and assuming other costs remain unchanged). If a 10% saving of water resulted, this would cost about £0.25/m^3 of water saved.

5.1.5 Summary

The overhead application methods predominantly used in the UK are inaccurate, and potentially wasteful. This was less important in the past, when few crops were fully irrigated, scheduling itself was inaccurate, quality was not a main objective, and water was more readily available. The changed circumstances require a move to more accurate and efficient application systems, but farmers have largely stuck with hosereel-guns because of their flexibility and ease of use. The increasing interest in other systems, including booms (and trickle as discussed in the next chapter), suggests this could be changing, particularly where water is highly valued. More information is needed for farmers contemplating new systems, and for MAFF, EA and others to judge whether pressure and/or support should be given for such a change.

5.1.6 Recommendations

It is recommended that MAFF should fund a scientifically designed field study to determine actual losses from overhead irrigation systems under UK farm conditions, as a basis for justifying or otherwise the pressure on farmers to move away from hosereel-gun systems to more expensive but supposedly more efficient systems. The study should include micro-sprinkler and hosereel-boom systems as well as hosereel-gun systems.

MAFF should also investigate, in that or another study, the potential for water saving by precision irrigation from booms (and linear moves) onto bed systems.

5.2 Trickle irrigation

Trickle (or drip) irrigation has been described as the irrigation of the future:- accurate, energy efficient, easily automated, and producing high yields of high quality produce. Its potential to save water is particularly attractive where water resources are scarce or expensive. This section summarises results from published data and market surveys, a workshop involving researchers, growers and equipment suppliers, and discussions with users and suppliers.

5.2.1 Trickle irrigation systems

Trickle irrigation systems apply small amounts of water slowly and frequently, directly into the root zone, usually through emitters spaced along polyethylene tape or tubing. The laterals are either laid directly on the surface (e.g. in orchards), shallow buried (e.g. for potatoes) or sub-surface buried, depending on the crop and local soil conditions. Trickle is ideally suited to flat or gently sloping land, although more sophisticated pressure compensating emitters now allow it to be used on relatively steep or undulating terrain.

Trickle irrigation can potentially use less water than spray irrigation. The crop water use (transpiration) from a fully irrigated crop is similar whatever the method of water application. Using trickle, however, spray evaporation, wind drift, and leaf interception are avoided, and soil evaporation is reduced. As a static (solid-set) system, it allows smaller and more timely applications, and is easier to automate than portable or moving overhead irrigation systems. This permits more accurate scheduling. Potentially, trickle can also give a high uniformity of application, reducing the need to over-irrigate to compensate for dry spots.

Two main types of lateral trickle pipe are available. Tube is hard walled, typically 25-30 mil thick (1 mil = 0.001 inch). Tape is softer-walled, generally 4-15 mil thick, and lies flat when not pressurised. The choice of product and wall thickness will depend on factors including the crop type, soil texture, and topography, and whether the trickle pipe is to be replaced annually, or re-used. The cheapest thinner walled tape is normally regarded as disposable, while the more expensive thicker walled tapes can be lifted and re-laid several times.

Tape products are more suited for the irrigation of short season crops (e.g. strawberries and a range of vegetables). For permanent installations, such as orchards, soft fruit, vines and landscape, tube products are recommended. For many such applications, the trickle pipes are only installed once. In contrast, using trickle on arable row crops, such as potatoes, introduces problems of retrieving and relaying the system on an annual basis. Careful handling of the pipe, particularly when using tape, is the key to successful installation, retrieval and, where appropriate, re-use.

The emitters are normally situated ‘in-line’, either as an integral part of the tape wall or as a discrete internal emitter, partly to allow the pipe to be coiled for laying and retrieval. There are now a very wide range of emitter designs to choose from, giving a solution to most problems, albeit at a price. Pressure compensating emitters can retain acceptable uniformity on longer runs and on sloping or undulating terrain. Self-flushing emitters can reduce the filtration requirement and reduce the risk of blockage.

5.2.2 Current use

The flood of research publications and intense marketing can give the impression that most growers are moving to trickle irrigation. Indeed, by 1994, ‘low-flow’ irrigation methods accounted for 15% (600,000 ha) and 24% (215,000 ha) of the total areas irrigated in California and Florida respectively. Across the USA as a whole, however, it still accounted for under 5% (1,050,000 ha) (Irrigation Association, 1995).

The MAFF Irrigation Survey for 1995 suggested trickle accounted for 2.5% of the total area irrigated in England (MAFF, 1997). According to the MAFF surveys, the total area equipped with trickle irrigation grew steadily until 1982, declined slowly until 1987, and is now growing strongly again (Figure 5-4).

The area under trickle more than doubled between 1992 and 1995. Recent industry estimates confirm that the market share of trickle is still growing strongly.

Unfortunately, the MAFF statistics do not indicate which crops are being trickle irrigated, nor on which crops the growth is occurring. However, regional growth trends can be observed. Figure 5-5 shows the areas equipped for trickle irrigation in 1990 and 1995 for the top ten counties. The data confirms that trickle usage remains heavily concentrated in areas growing top fruit, small fruit and vegetables. In 1995, a quarter of the entire trickle irrigated area was in Kent alone, where it accounted for 14% of the total irrigated area. Kent was also the predominant user of mains water for irrigation, suggesting another possible link.

The MAFF figures are lower than private estimates from within the industry. Trickle has become well established in some specialized markets where it has particular advantages. Table 5-2 lists cropped areas from the 1994 MAFF Agricultural and Horticultural Cropping Census together with industry estimates of the percentages of each that were trickle irrigated in 1994. This approach suggests a trickle irrigated area of over 8,000 ha in 1994.

Table 5-2. Industry estimates of individual crop areas irrigated by trickle in 1994.

Crop	MAFF reported crop area (ha)	Estimated proportion irrigated by trickle (%)	Implied area irrigated by trickle (ha)
Cauliflower	9500	0.1	10
Carrots	12100	0.5	60
Onions	8800	0.5	44
Runner Beans	900	40	360
Celery	700	0.5	3
Lettuce	4500	1	45
Sweet corn	1600	10	160
Dessert apples	11900	25	2975
Cider apples	4300	2	86
Pears	3600	2	72
Cherries	800	15	120
Strawberries	5200	60	3120
Raspberries	2800	20	560
Black currants	2900	20	580
Hops	3400	1	34
Potatoes	128000	<1	10
Sugar Beet	194500	0	0
Total			8240

Estimating trickle irrigated areas based on equipment sales data is difficult, due to commercial confidentiality, double counting, and hidden imports. Best guestimates suggest 1994 annual UK sales were around 15,000 km of tape and 2,000 km of tube (Batho, 1994). This would imply at least 2,000 ha were either installed or renewed that year, and a much larger area if it was widely spaced as in orchards.

Whatever the true figure, it is clear that trickle irrigation is growing strongly in the UK. However, all these estimates are still small when compared with the 194,000 ha farmers said ‘they would irrigate in a dry year’ (MAFF, 1997). Most of the crops on which trickle irrigation has become established cover relatively small total areas. The MAFF Irrigation Surveys suggest that the average trickle area per holding was still only 5 ha in 1995.

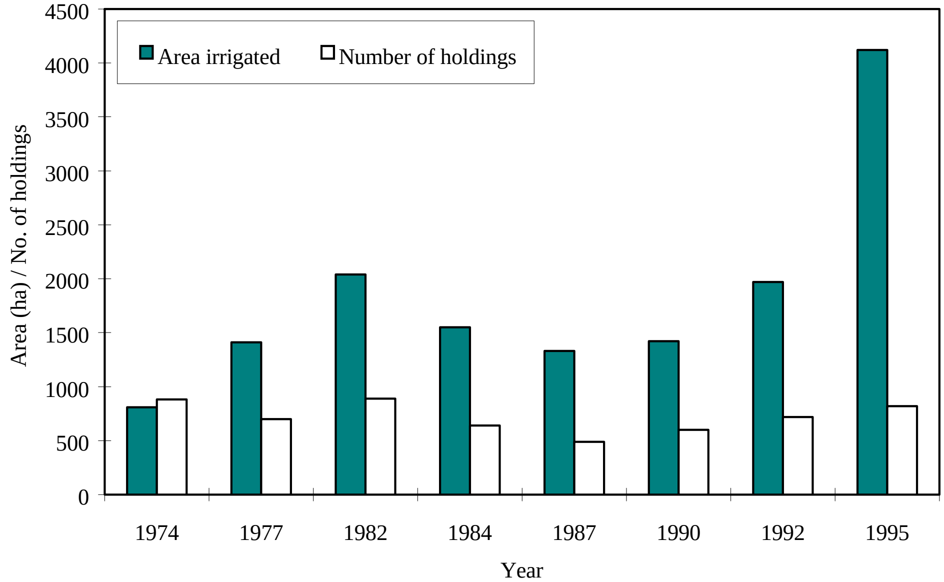

Figure 5-4. Total number of holdings and total area equipped for trickle irrigation, 1974-95.

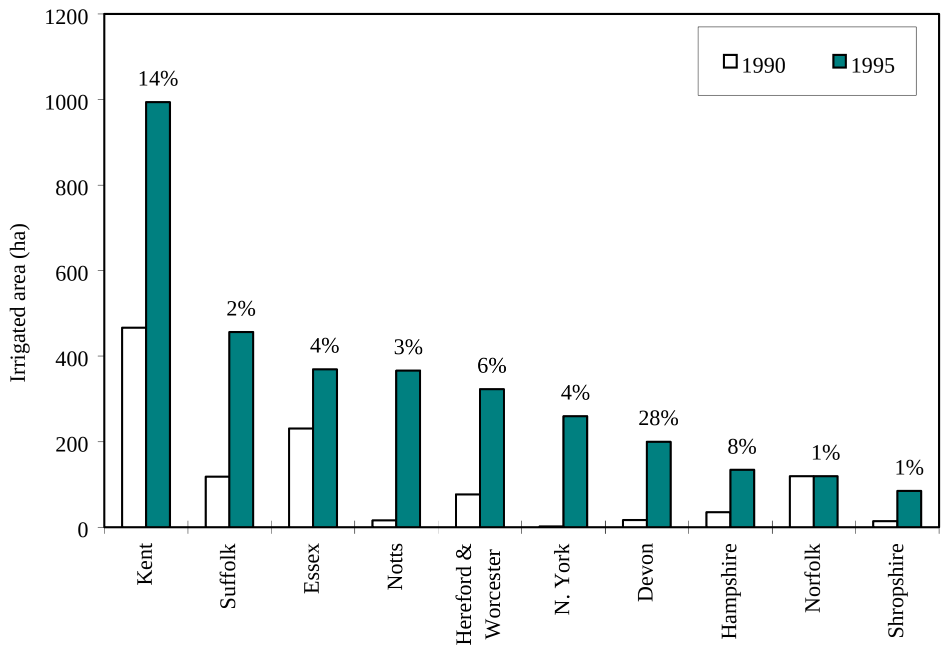

Figure 5-5. Area equipped for trickle irrigation, in 1990 and 1995, for the top 10 counties. Values (%) represent trickle irrigated area as a percentage of total irrigated area.

5.2.3 Trickle for potatoes

If trickle is to make a significant contribution to water saving, it must adapted for use in field-scale arable row crops where most water is used. Under present conditions, potatoes are the obvious target application (Weatherhead and Knox, 1997).

5.2.3.1 UK trials

A large scale observation study of trickle irrigation on potatoes was carried out by ADAS in 1984, in conjunction with Osberton Grange Farms (Worksop) and Cameron Irrigation Ltd. This was seen by many visitors to ‘Sandlands 84’. The study overall showed that trickle was practicable and gave good results, but was simply far too expensive for field scale arable crops, at 3 times the cost of a hosereel system (Basford, 1986). The study was not continued after the first year.

However, UK potato growers’ interest in trickle has been reawakened in the last few years, largely due to product improvements and the introduction of low cost drip tape. A number of commercial potato growers are again experimenting with trickle, though so far the areas remain relatively small. Whilst some trials have been well publicised (see Box 3), data from most remains confidential. Few of the trials are scientifically replicated or fully instrumented, but they have usefully identified field-scale problems.

Box 3. Some publicised on-farm trials

In 1994**,** Field Fumigation in conjunction with Rendlesham Estates (Suffolk), carried out a small trial using tape on 1 acre of second crop potatoes on a light sand soil. A single line of tape was buried 35 mm deep within each ridge. The results were reportedly very impressive, with a 13% increase in yield and excellent scab control (Grower, 1994). However, when the trial was repeated in 1995, the results were apparently far less favorable, with poor scab control. The trial was not continued into 1996.

In 1995, Wyant & Son (Kent) started a trial on potatoes. They compared tape on 5 acres of potatoes (Desiree) against 1 acre irrigated with micro-sprinklers. Irrigation was applied three times a week when needed, scheduled by neutron probe. Roughly similar yields were attained under the trickle and micro-sprinkler plots, but both were higher than under the rain-gun where irrigation was limited due to system constraints. The results were considered very satisfactory. The area under trickle was extended to cover 13 acres in 1996, and 26 acres in 1997 (Farmers Weekly, 1996).

In 1995, Andrew Kerr, Mr. Wyant’s farming neighbour, also decided to experiment with trickle on potatoes, since the farm has been severely constrained by water availability. In 1995 6 acres of Desiree and Ailsa were irrigated by trickle. Despite problems of installation and retrieval, the farm were delighted with the trickle performance, and extended the system to 14 acres in 1996, and plan for 30 acres next season (Farmer Weekly, 1996).

5.2.3.2 Installation, retrieval and re-use

Installation is now relatively straightforward. For potatoes in the UK, trickle tape is typically installed 3-7 cm below the ridge crest, to reduce soil evaporation, prevent the tape from being displaced by wind, and minimise rodent attack. The heavier tube can either be similarly shallow buried in the ridge, or laid on the surface for bed systems. Tape installation is easily combined with planting, but tube installation requires a separate operation after planting, and then re-ridging, due to its larger bulk and weight.

Retrieval of tape can be done manually, which is time-consuming and laborious, or mechanically, either before, during or after harvest. Retrieval before harvest can cause problems by exposing tubers. Although combining tape retrieval and potato harvest in a single operation would be ideal, the technology is still in the development stage. Some users have commented that it complicates and slows down the harvest, particularly if the tape must be lifted in good condition for re-use. The ‘harvest window' is often short, labour and equipment resources are already stretched, and speed is crucial. It is often simpler to drop the tape again behind the harvester, and retrieve it later.

Retrieval of the (stronger) tube is easier, and can often be done by pulling mechanically from the end of the row. Some suppliers now offer specialised equipment for laying and retrieving tube, either for hire or purchase.

Re-use introduces other problems. Re-used tape cannot be expected to lay as easily as new tape. Stretching and tearing may have occurred during retrieval, and repairs may be needed. Unless the new field is the same length, the lateral pipes will also need rejoining. The repairs and joints can cause problems both when re-laying and later when retrieving again. Before re-use, the tape may also need cleaning externally to remove soil and old plant debris, cleaning/flushing internally, and possibly sterilising. Any blockages or emitter clogging problems are carried forward from one crop to the next. Damage and joints may cause leakage when in use. Obviously, the problems get worse the more times the pipe is re-used. Although manufacturers can quote expected livespan, there is little information available yet on actual livespan on potatoes under UK conditions.

Researchers in USA are currently evaluating potato irrigation using trickle tube permanently buried 30-50 cm below the soil surface, in a system termed subsurface drip irrigation (SDI) (ASAE, 1995). SDI has the potential to allow annual cropping and cultivation without lifting the tube. However, due to the supplemental nature of irrigation and the system of crop rotation, SDI is unlikely to be used for potato irrigation in the UK.

5.2.3.3 Water saving

Water savings obtained on UK potato trials are varied. ADAS reported water use was not significantly different between trickle and sprinklers on the 1984 trial. Some recent farm trials suggested savings up to 40% between trickle and hosereel-gun systems. Accurate comparisons are difficult without replicated trials using a range of treatments and measuring yield and quality.

Overall, both theory and the limited data available agree that significant water savings can be made by changing from hosereel-gun to trickle under carefully managed conditions. However, accurate scheduling and effective management and maintenance of the system are crucial to achieve any water savings at all. It is more difficult for the users to assess how much water is needed, and easy to switch trickle systems on too often or for too long. The use of a scientific approach, such as the neutron probe, is strongly recommended by all proponents of trickle. Unfortunately, scheduling trickle irrigated crops accurately can be difficult. The wetted area is localised and conventional soil moisture measurements may be unrepresentative of the actual soil profile wetness.

Another problem interpreting trial data is in distinguishing between water saving directly due to the use of trickle irrigation, from that due to better scheduling and more intense management. Whether the savings will persist once a trial is less closely monitored is unknown.

5.2.3.4 Yield and quality

Some crops show spectacular increases in yield when irrigated using trickle. This does not seem to be the case for potatoes; yields appear to be similar to those from fully irrigated sprinkler plots. However, there is evidence of increase in yield and quality when compared to hosereel-gun irrigation, probably related to poor uniformity and inadequate irrigation under the hosereel-gun.

5.2.3.5 In-field costs

The costs of installing a complete trickle irrigation system are site specific, particularly for the water supply and main distribution network. The in-field costs, i.e. costs downstream of a pressurised hydrant at the field edge, are easier to compare, although they still vary depending on row/bed configuration, line spacing, lateral length, topography (slope), and water quality.

UK prices, for field-scale quantities, are approximately £0.05/m for a thin disposable tape (4 mil), £0.075/m for a medium reusable tape (10 mil) and £0.10/m for a thicker reusable tape (15 mil). Tube is more expensive, ranging from £0.25/m to £0.40/m depending on type and specification. For a 'typical' layout (assuming 0.9 m ridge spacing with one trickle pipe per ridge and 0.3 m emitter spacing), this gives lateral costs of £522, £833, and £1111 per hectare for tape, and £2778 to £4445 per hectare for tube. In-field filtration, fertiliser injectors, automatic controllers, header pipes and valves can add substantially to these costs, say £200-£1000 per hectare, depending on the level of sophistication desired. For comparison, the 'infield' capital cost currently quoted for one fully automated reusable tape system is around £1750-£2000 per hectare, with the tape accounting for half this cost and the remainder for the infrastructure. Placing one lateral line down a two row bed system, or in the inter-row between ridges, would of course reduce the tube or tape costs proportionately.

To allow for the different product lives and compare annual costs, Table 5-3 compares the annualised in-field costs for three basic systems, comprising the capital costs amortised over their estimated useful lives, together with estimated in-field running costs (i.e. labour, fuel, water and repairs). Typical in-field costs of a hosereel-gun system are added for comparison. A real interest rate of 6% pa has been assumed, and a 10 year life assumed for everything except the tapes. Water has been charged at the EA Anglian Region unsupported direct abstraction rate (zero for trickle). The cost per m^3 is calculated assuming 125 mm average annual net application, after allowing for differences in efficiency.

It is important to recognise that the costs shown in Table 5-3 do not represent the full costs of either trickle or rain gun irrigation. Costs of pumping, storing and delivering water to the field hydrant are excluded. These can be substantial and vary considerably, depending on source of water, and whether on-farm storage is necessary.

The analysis suggests that the annualised in-field costs of trickle systems are still substantially greater than those of typical hosereel-gun systems. Reusable tape is the cheapest trickle system, providing it can be retrieved and re-used successfully. However, altering tape life and interest rates can reverse the result, confirming the choice is not clear-cut. Disposable tape, although most expensive, simplifies retrieval and avoids problems with re-use, and does not commit the farmer to long term use. Tube has the highest initial cost and requires a long-term commitment, but is the simplest to manage and is nearly competitive with reusable tape.

Assuming a 20% water saving, irrigation demand would typically be reduced by about 25 mm and 50 mm in an average and dry year respectively (250m^3 and 500m^3 per hectare). This would allow 25% more area to be irrigated from the same source, or potentially (if not already constructed) reduce pump, reservoir and pipe costs by about 10-15% for the same area (allowing for economies of scale), as well as reducing fuel costs. At bulk mains supply prices, average water charges would be reduced by around £150 per hectare per annum. From direct abstraction, water charge savings would be much less.

On these figures, requiring potato growers to use trickle irrigation instead of hosereel-gun systems solely to save water, would increase in-field costs by between £170 and £388 per hectare per annum, and by between £0.68 and £1.55 per m^3 of water saved. Thus trickle irrigation could not be justified by water savings alone, even at bulk mains supply prices.

Table 5-3. Typical in-field annualised capital costs (£/ha/year) for basic trickle systems for potatoes.

Lateral type	Disposable Tape	Reusable Tape	Tube	Hosereel-gun
Thickness (mil)	4	10	26	
Lateral lines (£/m)	0.05	0.075	0.25	
Lateral lines (£/ha)	522	833	2778	
Headworks (£/ha)	300	300	300	
Total capital cost (£/ha)	822	1133	3078	900
Life of lateral (yrs)	1	3	10	10
Life of other equip. (yrs)	10	10	10	10
Real interest rate (%)	6	6	6	6
Annual costs (£/ha/yr):				
Amortised lateral cost	554	312	377	102
Amortised 'other' costs	41	41	41	20
Subtotal	594	353	418	122
Running costs	37	63	93	121
Total costs (£/ha/yr):	632	415	511	244
Total costs (£/m^3 net)	0.50	0.33	0.41	0.20

5.2.4 Summary

Despite its attractions, trickle has so far remained concentrated on particular high value crops, including soft fruit, dessert apples and certain high value vegetables. On these, its use appears to be growing rapidly. Significant use on other crops in the future is possible but not definite.

There are potential water savings from using trickle, but these alone would certainly not justify a change to trickle irrigation at current water charges where direct abstraction is possible. If water has to be obtained from the mains, or a lined reservoir has to be constructed, or where water is scarce and hence has a high opportunity value, the higher cost may be justifiable.

The major water saving opportunity is on potatoes. Experiences in the UK and elsewhere confirm that good results can be obtained with trickle on potatoes, but also that some problems remain. The likely rate of future uptake is difficult to predict. Adoption will be concentrated among the more progressive, innovative farmers with high value potatoes in particular circumstances. Unless prices drop substantially, the retrieval technology is improved, or external pressures are applied, adoption will be a slow process and trickle will probably not account for more than 10% of the total irrigated area even in the medium term.

Requiring potato growers to use trickle irrigation instead of hosereel-gun systems solely to save water would increase in-field costs substantially.

5.2.5 Recommendations

For those specialised crops where trickle irrigation is already being adopted, MAFF should concentrate on assisting technology transfer between growers, through the promotion of farm visits, demonstration days and workshops. No crop specific research on water saving aspects alone is proposed (though research may be justifiable for other reasons).

Before promoting trickle irrigation on potatoes, research is needed on wetting patterns and on correct scheduling under UK conditions, and product development is required on equipment for lifting tape without damage and without slowing the harvest. Research must incorporate proper scientific control and replication and be carried out for a sufficient number of years to ensure a range of weather conditions are experienced. Growers need to be confident that scab is controlled and high quality potatoes will be produced under all weather conditions.

It is recommended that MAFF support one or more on-farm trials on potatoes, under scientifically monitored and replicated conditions for at least 3 years, comparing different systems. The trials should be alongside normal commercial irrigated potato production, and at sufficient scale to identify labour issues during laying and retrieval. The trials should also be used as a demonstration site(s) along the lines of ‘Sandlands 84’ providing this does not compromise the research. Product development for the retrieval equipment should be encouraged by involving the manufacturers.

For other crops there is limited water saving potential, either because areas are small or trickle is unsuitable or still uneconomic. No immediate action is recommended, but MAFF should reassess opportunities crop by crop at regular intervals.

It is likely that the anomaly of trickle irrigation being outside the abstraction licensing system will be increasingly questioned. It is recommended that MAFF support bringing trickle under the system, but urge this change is simultaneous to allowing more flexibility in varying licences and removing specification of the application point from licences. This would allow licensed abstractions to be moved from other crops to the high value crops normally irrigated by trickle. Otherwise there is a real danger of stopping the current growth in trickle irrigation, and hence losing the water saving benefits.

5.3 Irrigation scheduling

Since 1990, the use of commercial irrigation scheduling services has grown steadily in UK, primarily in response to the increasing demand for quality produce. This chapter reviews current usage of the various scheduling methods available to farmers, assesses their potential for saving water, and considers likely future developments.

5.3.1 Scheduling methods

Scheduling is defined as determining which fields to irrigate, when and how much. The objective is to maintain an optimum soil water environment, to ensure that the most economic yield, most efficient use of water *or* highest crop quality are achieved.

A wide range of irrigation scheduling methods are currently available and used commercially under UK conditions. These broadly fall under two categories, either water balance methods (e.g. agroclimatic models) or direct measurement techniques (e.g. neutron probes).

5.3.1.1 Water balance methods

Water balance methods keep a running mathematical balance of the water in the soil profile. They can be either manually calculated (e.g. on a balance sheet (MAFF, 1982)) or more recently, computer modelled. There are a number of commercial 'bureau' scheduling services using water balance models (e.g. ADAS 'Irriguide', CUPGRA, and Levington Agriculture). The farmer is responsible for collecting and reporting local rainfall and irrigation, usually on a weekly basis. Irrigation forecasts for the following week are then sent back to the farm. However, with many farms now having microcomputers, there has been rising demand for scheduling computer packages for use on-farm (Hess, 1994).

Water balance models are prone to variation in the accuracy of data input, due to spatial variability in soil type, crop development, rainfall and irrigation uniformity.

5.3.1.2 Direct measurement techniques

Direct measurement techniques measure soil water content (e.g. neutron probe) or water potential (e.g. tensiometers) in-field. The neutron probe is undoubtedly the most common method currently used by farmers in UK, and almost exclusively provided by commercial scheduling services (e.g. Neutron Probe Services, Fullpoint Probe Services, Agritech). Although portable and quick, they remain expensive (£6000-£7000) and therefore not viable for individual farm use. They are also subject to strict legal controls. Usually a consultant visits the farm on a weekly basis, collects and analyses field data on-site, and provides an immediate report to the farmer on the current soil water status and forecast for irrigation for the following week. This direct contact approach has proved popular with farmers and gained confidence within the irrigated farming community and hence continues to grow strongly.

Other methods (e.g. capacitance probe) are also used, but their adoption has so far remained limited. Independently operated capacitance probes are likely to become a more widespread scheduling method in the future, with more robust, low-cost models currently being developed.

Tensiometers, which are cheap and easy to read, are particularly suited to scheduling water sensitive crops grown on sandy soils. Although they are popular within the horticultural sector, they require careful installation, can be unreliable and are difficult to interpret accurately.

Neutron probes may give inaccurate readings if calibrated from a manufacturer's chart rather than from on-site measurements. Capacitance probes have only a small sampling range, making measurements sensitive to compaction or soil disturbance caused by access tube installation.

There are also a number of new scheduling methods (e.g. using remote sensed data) being researched and developed but not yet available in the UK

5.3.2 Current usage

A telephone survey of commercial irrigation scheduling companies was conducted to estimate the total number of farmers subscribing to such services. The results are summarised in Table 5-4, and suggest that approximately only 1000 farmers are currently using commercial services. This represents roughly 10% to 15% of the total number of irrigators in England.

Table 5-4. Estimated number of farmers currently using commercial irrigation scheduling services in England.

Organisation	Type	Approx. number of users
CUPGRA (Cambridge)	Water Balance Bureau Service	110
Levington Agriculture (Suffolk)	Water Balance Bureau Service	100
ADAS Irriguide (Notts)	Water Balance Bureau Service	400
Neutron Probe Services (Kent)	Neutron Probe	100
Fullpoint Probe Services (Suffolk)	Neutron Probe	125
Agritech (Bedfordshire)	Neutron Probe	100
P&D Water Management (Suffolk) }	Neutron Probe	30
	Capacitance Probe	40
Total		**1005**

Bureau water balance services currently dominate the market (61%), with neutron probe/capacitance probe services accounting for the remainder. Some farmers rely on a combination of both methods. There are also a number of farmers receiving independent scheduling advice from specialist agronomy consultants (e.g. potato growers co-operatives), or using their own spreadsheet models (e.g. Hess, 1993).

The total irrigated area currently scheduled is difficult to gauge. Most services provide advice which is field and crop specific, after which farmers may then use the suggested plan as a basis for scheduling several other fields, or indeed the whole farm. However, CUPGRA, who deal exclusively with potato farmers, reported 4,500 ha under scheduled irrigation with their service (M.Stalham, pers. comm).

Crop specific information on which irrigated crops are scheduled are similarly difficult to obtain. Estimates reported by the bureau services suggest potatoes account for between 25-50%. Soft fruit (particularly strawberries) constituted 35-60% of crops scheduled by neutron probe, partly due to the concentration of fruit growers within the services' vicinity, but also due to the particular advantages gained by direct soil moisture monitoring under trickle irrigation, the predominant method used by soft and orchard fruit growers. Other crops scheduled included salad vegetables, root vegetables such as carrots and parsnips, apples and hops. Interestingly, a few farmers also request bureau forecasts for cereals and even grass.

5.3.2.1 Cost

Charges levied by bureau services vary, since scheduling is often provided as part of an overall agronomic consultancy package. For scheduling only advice, cost depends on the total number of sites forecast per farm or the size of field for which information is collected. For bureau water balance services, typical quotes range between £100-£150 per site per season, or £10-£12 per ha per year.

Neutron probe service costs range from £200-£300 per site (based on 2 or 3 access tubes) per season. Some companies also charge an initial access tube installation fee (£50). For capacitance probes (e.g. Enviroscan) a typical installation comprising up to 32 soil moisture sensors, a monitoring system with a central data logger and staff training costs around £10,000.

A computer based water balance scheduling model for use on-farm, such as IMS (Hess, 1994) costs £150. Other data necessary (evapotranspiration data) supplied by the Met. Office typically costs £200 per season. Alternatively, an automatic weather station suitable for irrigation scheduling costs about £2000 (Hess, 1997b).

5.3.3 Scheduling to save water

The main water saving benefit from scheduling is in avoiding unnecessary irrigations or excessive irrigations. It is impossible to quantify this saving accurately, because farmers who are not scheduling rarely have enough records for modelling losses. It is unrealistic to compare scheduled irrigation with continuous application on a fixed cycle, because almost all outdoor irrigators will respond somehow to rainfall and changes in weather. The saving will also depend on the previous level of irrigation. Scheduling under-irrigated crops should result in better irrigation, and could lead to increased water use rather than water saving. The evidence from Chapter 2 suggests that the majority of irrigated crops in the UK still receive less than full irrigation.

Best guestimates of savings due to introducing scheduling alone are around 10% for fully irrigated crops under hosereel-gun systems. Savings are potentially larger with more sophisticated application systems which can optimise depth and timing of irrigation. Most of the savings would be in average or wet years, when rainfall complicates planning. In the driest years, many farmers cannot keep up with demand, because of water resource or equipment constraints, and scheduling advice may be of limited benefit to save water (though it may be invaluable in getting the most benefit from the water that can be applied).

There are limited opportunities for reducing water use through optimising existing schedules, e.g. applying smaller irrigation depths at more frequent intervals whilst retaining a greater soil moisture storage margin for storing rainfall. Figure 5-6 shows, for example, the effect on seasonal irrigation needs (mm) for maincrop potatoes grown on a medium AWC soil by applying smaller irrigation depths, at the same recommended trigger soil moisture deficit of 55 mm.

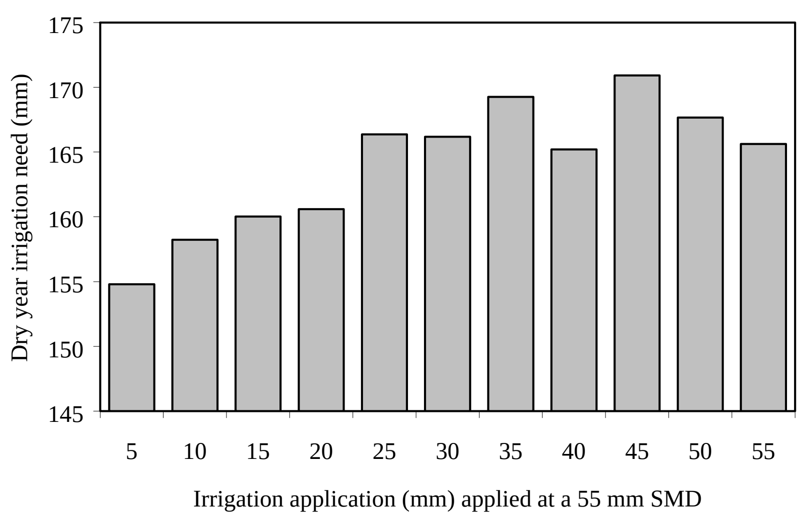

Figure 5-6. Effect of application depth on irrigation needs (mm) for maincrop potatoes grown in Cambridge on a medium AWC soil.

Farmers at present typically apply 25 mm per irrigation. Maximising the storage of rainfall by applying only 5mm at the same deficit (e.g. by using centre pivots, linear moves or boom irrigation) and assuming the same application efficiency, would provide only modest water savings of 11 mm in design dry year (about 6%). However, applying small amounts at the critical deficit entails a risk to crop yield and quality should the irrigation equipment or water supply fail temporarily. Farmers would need to be very confident in their water supplies before adopting this strategy too far. In practice, increased foliage interception could outweigh the savings.

Figure 5-7 shows the effect on crop evapotranspiration by irrigating at different trigger soil moisture deficits, assuming irrigation is applied through a system capable of applying small 5 mm applications (efficiency is assumed constant).

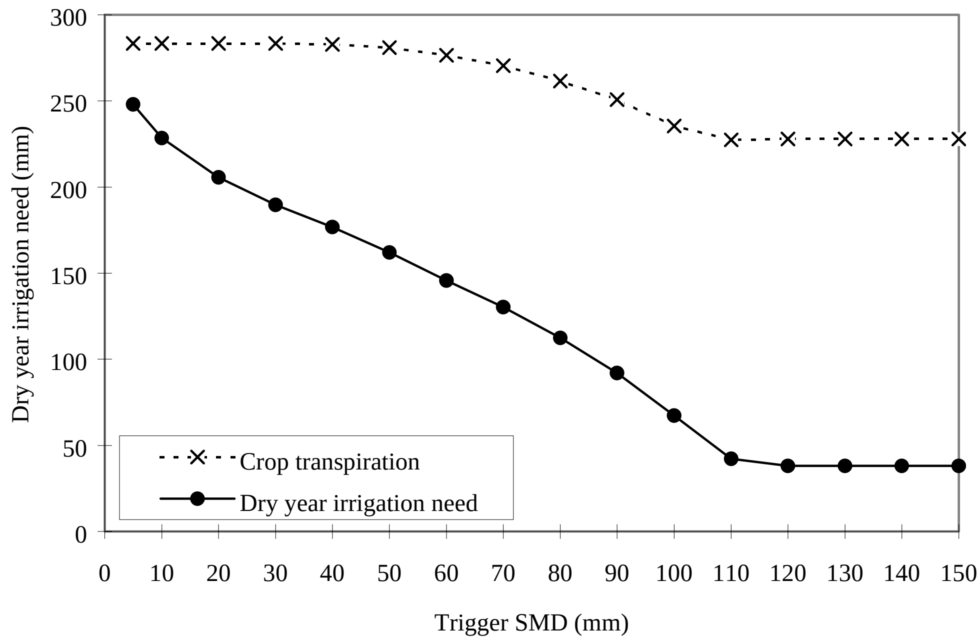

Figure 5-7. Effect of trigger SMD on crop transpiration and seasonal irrigation need in a dry year for maincrop potatoes, grown in Cambridgeshire on a medium AWC soil.

Irrigating at high trigger SMDs will increase the irrigation interval, and potentially allow more effective use to be made of available rainfall. Increasing the trigger SMD from 40 mm to 60 mm, for example, reduces net seasonal irrigation needs by 31 mm, with only a small reduction in crop transpiration. Although adopting such deficit irrigation has the potential to save water, in UK its scope may be limited where irrigation at low SMDs are required to obtain the premia quality potatoes demanded by supermarkets. This approach also requires the farmer to have a detailed knowledge of the soil available water capacity and soil variability. Above a trigger SMD of 60 mm, crop transpiration and consequently yield will be reduced.

5.3.4 Summary

Scheduling has grown rapidly since 1990, and this growth is likely to continue, primarily on potatoes, soft fruit, salad and root vegetables. About 10% to 15% of irrigators now use commercial scheduling services, and there is rising demand for scheduling computer packages for use on-farm.

The main benefits of scheduling are in improving the effectiveness of irrigation, particularly where crop quality benefits are important. Scheduling will increase water use efficiency, but it may lead to increased water use. Water saving is most likely in average or wet years. Schedules can be optimised to save some water by making better use of rainfall, but farmers would need to be very confident of their water supplies and soil properties before adopting extreme schedules, and application efficiencies could be reduced.

5.3.5 Recommendations

Seeking improvements in the effectiveness of irrigation through improved scheduling should be part of water conservation strategy, in terms of making better use of water. It is recommended:

- MAFF continue to promote information exchange on scheduling through conferences and publications.
- MAFF actively promote the extra yield and crop quality benefits achievable through scheduling.
- MAFF fund research into identifying optimum scheduling methods for trickle irrigation in the UK.

5.4 Changing agronomic practices

5.4.1 Introduction

In theory, it should be possible to reduce irrigation needs by manipulating crop development, for example, advancing planting dates, reducing the growing season, increasing rooting depths, or selecting varieties tolerant to higher soil moisture deficits. However, there are physiological and physical limitations to the extent to which these methods may be implemented. This chapter summarises a review of the potential savings for potatoes (Sanders, 1997a). The results are based on a literature review, discussions with agronomists, and modelling using the IWR program (Hess, 1997a).

5.4.2 Changing planting dates and length of growing season

The main strategies available to potato growers are earlier planting alone, the use of already sprouted, physiologically aged seed (chits), and earlier planting using artificial covers such as floating plastic film or fleece to raise soil temperatures.

5.4.2.1 Earlier planting alone

Temperature and soil physical conditions are limiting factors when considering altering planting dates and crop development rates for maincrop potatoes. Most maincrop varieties will not sprout until soil temperatures exceed 9^{o}C. The rate of initial sprout formation is also temperature dependent (Firman et al., 1992), and inhibited below 10 ^{o}C (FAO, 1986). Consequently, planting too early does not advance crop development, and may even extend the total growing period (FAO, 1986).

Planting too early can also risk frost damage, increased vulnerability to stem canker infection before emergence, soil compaction and clod formation. Compaction can delay emergence, tuber initiation and development, reduce nitrogen uptake and significantly inhibit root development and crop water availability (Firman et al., 1992; Parker et al., 1989). Clods can seriously affect final crop quality and yield.

Planting dates each year are thus dictated by weather conditions. Lighter soils become workable earlier in the season, with less risk of clod formation, so may allow earlier planting, if temperatures are sufficiently high. In this case growers may opt for second early varieties to take advantage of higher prices earlier in the season. Maincrop growers already aim to plant as early as conditions allow, as there are yield penalties and harvest problems from planting too late.

There appears therefore to be limited scope for advancing development by bringing forward planting dates alone without increasing the risk of yield and quality losses.

5.4.2.2 Using chitted seed

The use of potato seed that has been physiologically aged and sprouted in controlled temperature storage (chits) results in earlier emergence, tuber initiation and subsequent harvest. Chits can advance crop development by up to 21 days (O'Brien et al., 1983). For maincrop and second early varieties, ADAS recommend seed aged no more than 350 day degrees centigrade above 4^{o}C, which advances development by approximately 14 days (ADAS Advisor, 1990; Farmers Weekly, 1997). Planting dates are unchanged, due to the problems discussed previously.

The main advantage for farmers in using aged seed is earlier harvesting. The financial benefits are greatest with early and second early varieties which command significantly higher prices per tonne earlier in the season. With early varieties, yields from chits are also higher (O'Brien et al., 1983). For maincrop potatoes, using aged seed is only advantageous to avoid late harvest in unfavourable conditions. Otherwise it adds to production costs, yields are lower, and there are other disadvantages (Addison 1986; ADAS Advisor, 1990). If seed is only slightly aged to avoid large yield losses (Buckley, 1990), development would be accelerated by less than 14 days.

Nix (1996) estimates that using chitted seed for maincrop potatoes adds about £110/ha to total costs.

5.4.2.3 Earlier planting using floating plastic film and fleece

Synthetic covers such as floating perforated plastic films or fleece can be used to increase soil and air temperature, accelerating sprout and leaf growth and advancing emergence and tuber initiation. Trials with first early varieties have shown that plastic films can raise daily mean soil temperatures by 2-5^{o}C, advancing final harvest of chitted early potatoes by 10-14 days (Jenkins, 1992). Fleece typically advances harvest by 6-10 days, and affords much better frost protection than plastic covers. It reduces temperature fluctuations, minimising growth checks and overheating, and is particularly suitable for early baking potatoes (Farmers Weekly, 1996).

In theory, covers could be used on maincrop varieties, enabling rapid April emergence and bringing full cover forward into June, allowing the crop to take advantage of higher radiation in June and July and producing good early yields. However, they would still miss the highest market prices (M. Stalham, pers. comm), and the crop would be more stress prone, subject to earlier senescence and have lower yields.

Crop covers should allow recycling of evaporated and transpired water, reducing irrigation water demand whilst the crop is covered. In practice, however, condensation returning to the soil beneath the cover is highly non-uniform, and this can exacerbate problems of drought caused by limited or non-uniform rainwater percolation through plastic or fleece covers (M. Stalham, pers. comm).

Plant covers are currently used primarily for first early crops, where advancing harvest by one to two weeks can significantly increase prices. Covers are not currently used by maincrop growers, mainly due to their high costs, approximately £400/ha for fleece and £300-£500/ha for plastic films (M. Stalham, pers. comm).

5.4.3 Increasing rooting depth

If rooting depths could be increased, more of the winter rainfall stored at depth in the soil profile could be utilised, and the effectiveness of summer rainfall could be increased, reducing irrigation need.

The most influential factor on root depth is soil compaction, which can restrict the ease of root penetration through the soil profile (MacKerron, 1993). Whilst compaction may limit root depth to as little as 0.4 m (Nelson, 1996), even ‘drought susceptible’ varieties, such as Record, can root to depths in excess of 1 m given suitable soil conditions, and other varieties have been observed to root to up to 1.5 m (MacKerron, 1993).

Restricted rooting can be avoided by minimising compaction and plough pan formation during deep ploughing and planting; i.e. waiting until the soil is friable before cultivation in spring and avoiding operations when the soil is wet, re-emphasising the importance of not planting too early.

Research on the effects of sub-soiling on root development, water use and yield appear to be contradictory (Parker et al., 1989). In view of the potential water saving benefits, further research under UK conditions is recommended.

5.4.4 Changing Cultivar

Significant varietal differences exist regarding tolerance to drought, susceptibility to common scab, timing of tuber initiation and overall length of growing season; all of which could influence irrigation need.

However, breeders do not currently select for drought tolerance, apparently because it is not thought important by growers. Over 20% of the maincrop varieties recommended by NIAB (1995) have not even been trialled for drought tolerance. Pentland Crown, described by Lapwood et al. (1970) as almost completely resistant to common scab, even on very low AWC soils, is not widely grown in UK, and is not listed in the top 17 maincrop varieties (PMB, 1996).

Many factors influence choice of variety. The NIAB (1995) list scores varieities for 29 characteristics including agronomic features, yield, disease resistance and quality to guide growers' decisions. Market suitability, particularly cooking quality and tuber shape and size, rather than water conservation appear to be key considerations for growers in selecting a variety. For example, Maris Piper, which is given a high score by NIAB for dry matter content (essential for frying and crisping) and fry colour, but scores extremely poorly for resistance to common scab and drought tolerance, currently accounts for 28% of UK's total area of maincrop potatoes (PMB, 1996). On the scale of 1-9, only varieties scoring 7 or more on relevant cooking quality criteria make the top 5 maincrop varieties (which account for 63% of the total area of maincrop potatoes). Although Cara does score well for drought tolerance, the other varieties mostly score under 7 for drought tolerance and scab resistance.

There is, however, increased interest amongst growers in growing second early varieties in a maincrop role, instead of late maturing varieties such as Cara (Farmers Weekly, 1997). This allows earlier lifting for storage. From 1985 to 1996, second early varieties increased from 20% to 29% of the total cultivated area of potatoes in UK, with much of this growth replacing maincrop varieties (PMB, 1996). In south-east England, second earlies for the early market are planted on light soils only, from early to mid-March. To replace maincrop, second early varieties are likely to be planted in late April for an early to mid-September harvest (M.Stalham, pers. comm). The reduction in irrigation water is modelled below.

5.4.5 Modelling the effect of agronomic practices on irrigation need

The effect on irrigation needs by implementing the various strategies described above were simulated using the IWR model (Hess, 1997a), using climate data for Mepal (Cambridgeshire) and a medium AWC soil.

Planting dates assumed reflect typical climate conditions in south east England. The effects of chitting and plastic covers on crop development were based on expert opinion. Irrigation plans are based on recommended schedules and current practice (Knox et al., 1996; Bailey, 1990). For deeper rooting varieties, irrigation was scheduled to make effective use of rainfall.

The results are summarised in Table 5-5. Strategy A represents a typical 'normal' strategy assuming no alterations to crop development. Strategy B and C represent the use of chitting to advance development by 7 and 14 days respectively. Strategy D represents the use of plastic covers to give 14 days advanced planting. Strategies E to H are similar, but with deeper rooting. Strategies I and J represent the use of second early varieties for early harvest and in place of maincrop respectively.

Table 5-5. Summary of irrigation needs for different crop planting strategies.

	Strategy	Rooting depth (m)	Dry year irrigation need (mm)	Irrigation need expressed as a % of Scenario A
A	Unchitted	0.7	170	100
B	Chitted 7 days advance	0.7	170	100
C	Chitted 14 days advance	0.7	157	93
D	Chitted under plastic	0.7	141	83
E	Unchitted	1.0	149	88
F	Chitted 7 days advance	1.0	140	83
G	Chitted 14 days advance	1.0	133	78
H	Chitted under plastic	1.0	121	71
I	Chitted, second early, early harvest	0.7	84	50
J	Chitted, second early, maincrop harvest	0.7	143	84

The results suggest that chitting reduces dry year irrigation need by up to 9%. Using plastic covers for early planting saves 17% to 19%. Increasing rooting depth from 0.7m to 1.0m (and scheduling appropriately) further reduces dry year irrigation need by about 12% in all cases.

However, plastic covers are not currently financially viable for maincrop production and reduce final yields relative to uncovered crops. Using chitting to advance development by 14 days would also reduce final yields. A 7 day advancement using chitted seed would not significantly reduce yields and similarly would not significantly reduce irrigation needs. Increased rooting depth therefore appears the most important factor in reducing irrigation need.

Second early potatoes grown for early harvest used 50% less water than maincrop potatoes. However, there is a limited market. Soil conditions and regional climate may also constrain a switch to earlier planting using second earlies. Growing a second early variety for a maincrop harvest reduces irrigation need by 16%, and this practice could increasingly be adopted by growers, albeit for quality and marketing considerations, rather than to reduce irrigation need.

5.4.6 Summary

The study suggests that modest reductions in irrigation needs of maincrop potatoes are possible through promoting deeper rooting. Savings may also be achieved by encouraging the switch to second early varieties for maincrop harvest. Advancing planting dates is limited by temperature, soil conditions and vulnerability to disease. Although planting under covers or using physiologically aged (chitted) seed can make small savings in irrigation need, in practice their scope may be wholly or partly limited by cost and undesirable yield reductions.

There may be greater potential for reductions in irrigation need in other crops such as carrots, which have more flexibility in their planting and have a higher market value. However, these constitute only a small proportion of irrigation demand in the UK, so the potential impact is likely to be minor.

There is scope for reducing irrigation needs by developing potato cultivars with increased drought resistance, common scab resistance, and deeper rooting patterns. However, breeders do not currently select for drought tolerance, apparently because it is not thought important by growers. Water shortages may change this view.

5.4.7 Recommendations

MAFF should fund research to clarify the effects of sub-soiling and other deep cultivations on root development, yield and particularly water use for potatoes.

MAFF should urge NIAB to give a more prominant role to water use when scoring varieties, and when developing new varieties, and encourage farmers to select drought resistant and scab resistant varieties where irrigation water resources are unreliable.

5.5 Mulches

5.5.1 Introduction

During the early part of the cropping season a considerable amount of water is lost from the soil by evaporation. If the water could be conserved in the soil for later use, irrigation water requirements for certain crops could be reduced. Indeed studies outside the UK have shown that considerable reductions in soil evaporation can be achieved, increasing water availability later in the season (Todd et al., 1991; Yunusa et al., 1994).

5.5.2 Modelling

The potential saving in irrigation water demand resulting from the restriction of soil evaporation by the use of mulches, for a range of crop and agroclimatic scenarios, was modelled using the IWR model (Hess, 1997a). The modelling was based on the following assumptions:

- The mulch is permeable and allows rainfall and irrigation to penetrate.
- The mulch is present during the cropping season only.
- The mulch can intercept rainfall and irrigation, up to a maximum interception capacity of 2 mm. This depends on the nature and properties of the mulch; figures as high as 2.8 mm have been quoted for sugar cane trash at a leaf area index of 4, Bussiere and Cellier, 1993).
- Mulch prevents soil evaporation according to the ‘density’ of the mulch (i.e. 100% = no evaporation from the soil, 70% = 30% evaporation) (Jalota, 1993; Bussiere and Cellier, 1994).
- The interception of rainfall and irrigation is proportional to the ‘density’ of the mulch (Bussiere and Cellier, 1994).
- Water intercepted by the mulch will evaporate at the potential rate (= ET_o).
- Growth and transpiration of the plant is independent of the presence of mulch. In reality the mulch will change the thermal regime of the soil and therefore change the phenology of the crop. This in itself will lead to changes in irrigation need. There is evidence (Villalobos and Fereres, 1990) that under dry conditions, a reduction of soil evaporation can lead to an increase in plant transpiration.

The potential water savings in a design dry year from using varying degrees of mulch were modelled for two crops, maincrop potatoes and sugar beet. The results are summarised in Table 5-6.

Table 5-6. Water savings in a design dry year from mulching with 50% and 100% mulch for maincrop potatoes and sugar beet, at three sites in UK.

Met Station	Dry year irrigation need (mm/annum)	Water saving (mm/annum)	
	No mulch	50% mulch	100% mulch
Maincrop potatoes			
Wattisham, Suffolk	258	38	66
Mepal, Cambridge	174	32	49
Rosewarne, Cornwall	131	25	40
Sugar beet			
Wattisham, Suffolk	166	32	58
Mepal, Cambridge	104	30	45
Rosewarne, Cornwall	79	25	36

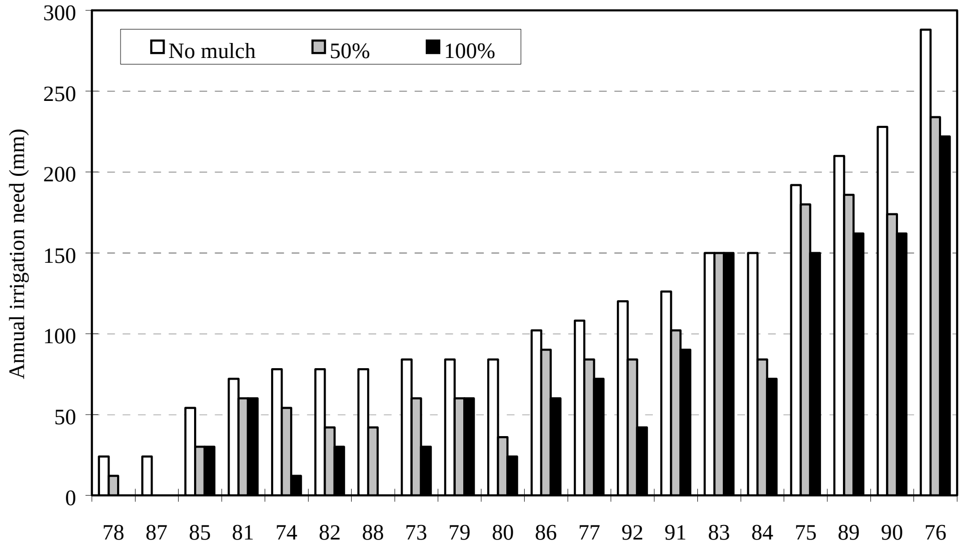

Figure 5-8. Annual irrigation needs (mm) for maincrop potatoes grown at Mepal (Cambridge) with varying degrees of mulch cover.

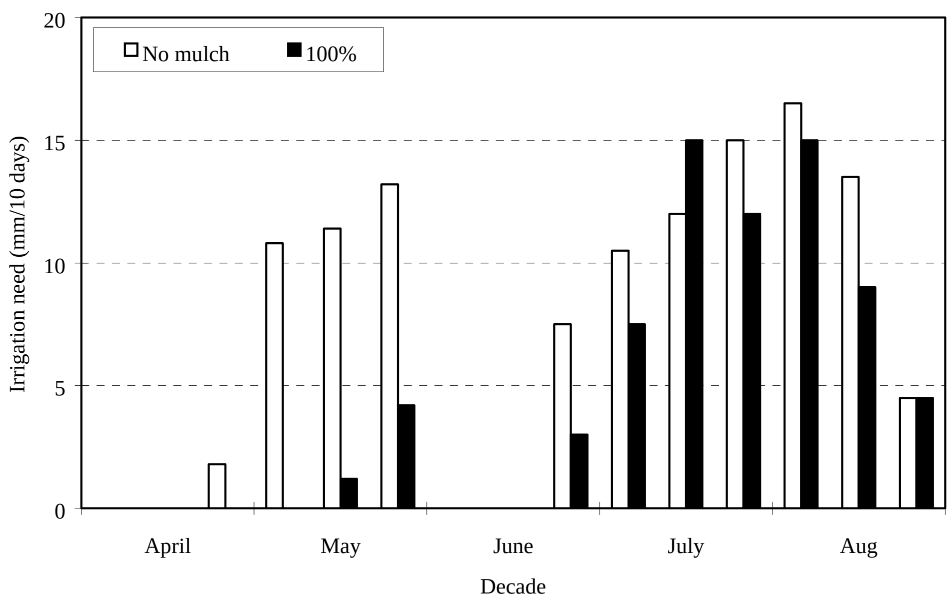

Figure 5-9. Average seasonal distribution of irrigation need for maincrop potatoes grown at Mepal (Cambridge) with varying degrees of mulch cover.

5.5.3 Summary

The modelling shows that the water saving due to mulches may be equivalent to one or two irrigations (25 mm to 40 mm). These savings are similar in different agroclimatic regions of the country, i.e. there is no correlation between saving and annual need. The savings are concentrated in May and June when crop cover is low (Figure 5-9). If May and June are sufficiently wet that irrigation is not needed anyway, then there is no saving (e.g. potatoes in 1983 at Mepal).

The practical feasibility for reducing irrigation water demand through a reduction of soil evaporation by the use of mulches appears limited.

Theses results discussed have depended entirely on modelling, due to the lack of experimental data. They appear to disagree with public perception of the benefit of mulches. The use of mulches on irrigated crops is less effective than on rainfed crops, because of interception and loss of some of the irrigation applied and because rainfed crops are more dependent on retaining winter water in the soil.

5.5.4 Recommendations

It is recommended that MAFF fund a small experimental study to validate (or otherwise) the computer modelling of the effect of mulches on irrigation demand under UK conditions.

5.6 Improving yield through other inputs

It must not be forgotten that, for a given volume of production, increasing yield (t/ha) is an extremely effective way of saving water. Every 10% increase in yield would reduce the cropped area needed by 9%, saving 9% of the total volume of water. For irrigated crops, at least, it is important to continue the trend of steadily increasing yield. In contrast, policies to limit inputs and move to ‘low intensity’ systems in irrigated agriculture could be environmentally counter-productive in terms of water use.

5.6.1 Recommendations

MAFF should continue to research and promote ways of increasing yield (t/ha) of irrigated crops, including plant breeding, cultivations, fertiliser use, etc., as a means of reducing the irrigated area and saving water.

6. INCREASING SUPPLY ON-FARM

6.1 On-Farm Storage Reservoirs

6.1.1 Introduction

On-farm storage reservoirs are being widely promoted to store winter water, which is still relatively plentiful in most catchments, for summer irrigation.

Table 6-7 shows the growth in the number and total volume of on-farm reservoirs as recorded by the MAFF Irrigation Surveys. By 1995, the total gross storage volume was equivalent to 22% of the total abstraction licensed nationally.

Table 6-7. Growth in total number and total storage volume of on-farm reservoirs.

Year	Total number of reservoirs	Total storage volume (tcm)
1965	834	4815
1967	871	5712
1970	878	6782
1972	853	7923
1975	862	6226
1984	2700	32670
1987	2420	36740
1990	2580	36690
1992	2840	41240
1995	3220	63930

Note: Data unavailable between 1975 and 1984.

Figure 6-10 and Figure 6-11 similarly show the number and total volume of winter abstraction spray irrigation *licences* issued in EA Anglian Region (note the associated reservoirs may not have been built yet). By 1996, the total licensed winter abstraction was equivalent to 15% of the total annual licensed abstraction. The mean volume per licence issued has also risen considerably, to around 60 tcm.

Nevertheless, the1995 MAFF Irrigation Survey recorded that only 10% of water used came from winter abstraction.

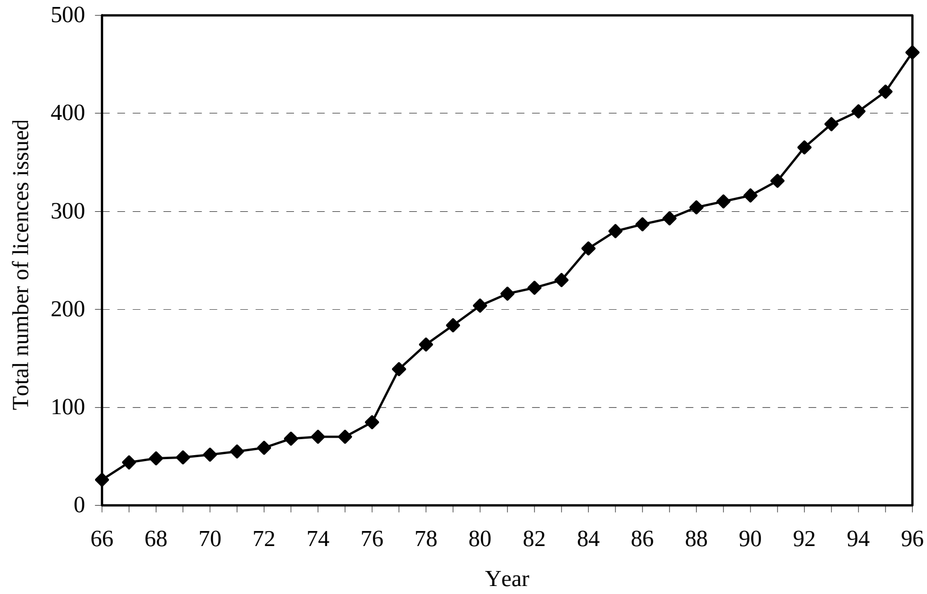

Figure 6-10. Total number of winter abstraction licences for spray irrigation in EA Anglian Region.

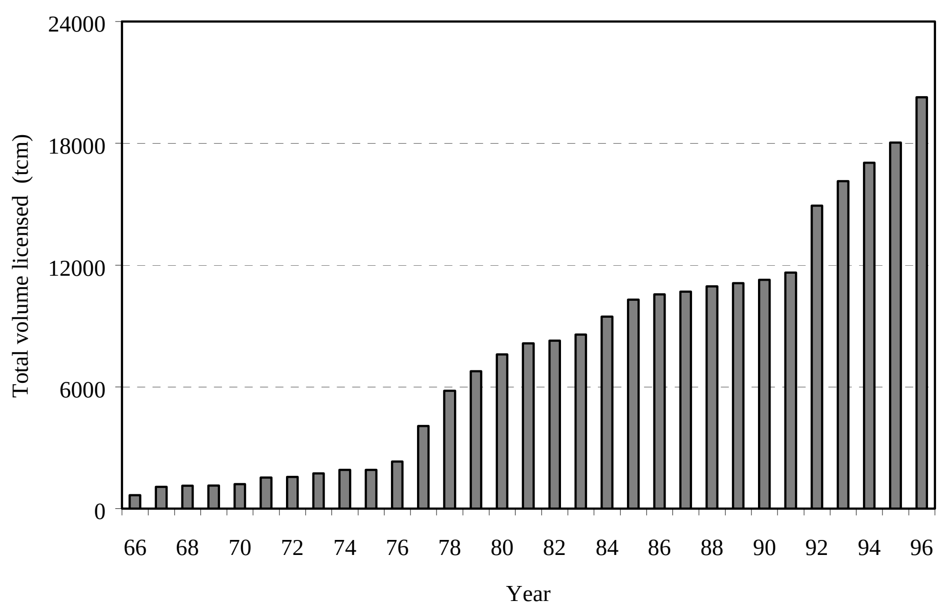

Figure 6-11. Total volume of winter abstraction licences for spray irrigation in EA Anglian Region.

6.1.2 Legislation

Storage reservoirs are mostly filled during the winter season (1 November to 31 March). They can also store unused summer water and act as short-term balancing tanks. Water is usually from surface water sources, but occasionally from groundwater or other sources. An appropriate abstraction licence is required to abstract the water used to fill the reservoir.

Water is pumped from the reservoir for irrigation during the summer. To be used without an abstraction licence from the reservoir itself, the reservoir must be 'discrete'. No unlicensed surface or ground water may enter the reservoir and no significant seepage from the reservoir may occur (if a reservoir contributes to a water course, it becomes a licensable source). This usually requires storage reservoirs to be:

- Non-impounding; i.e. constructed offstream, separate from the water course.
- Built on impermeable clay or lined to prevent seepage into or out of the reservoir.

Appropriate licences are also required if the water is to be distributed to the fields via watercourses. This practice is common in some areas.

Offstream storage reservoirs should not be confused with impounding (on-stream) reservoirs or with seepage reservoirs. These are also used for irrigation but affect summer water resources, and require summer abstraction licences. Impounding reservoirs can sometimes be converted to offstream reservoirs by diverting the source stream around the reservoir.

Any reservoir holding more than 25000 m^3 of water above the lowest adjoining land is classified as a Large Raised Reservoir under the 1975 Reservoirs Act. This Act is intended to ensure the safety of dams, and leads to special requirements:

- Design and construction must be supervised by an independent Panel Engineer.
- There must be regular inspections by qualified Supervising and Panel Engineers.
- Design and inspection details must be submitted to local enforcement authorities.
- The owner must keep and submit records of all water inputs and withdrawals.

Reservoir construction may also be subject to various local planning requirements.

6.1.3 Lining

It is possible to build a raised off-stream reservoir on almost any site. Site conditions will dictate whether lining is needed to prevent excessive seepage. Reservoirs built on some clay soils may not need lining. On other sites, reservoirs can be lined either using clay materials excavated on-site or nearby, or by installing a synthetic liner, such as butyl or more commonly polypropylene sheeting. Farmers often use the term lining to imply synthetic lining.

Synthetic lining has disadvantages:

- It adds greatly to construction costs.
- It deteriorates on exposure to ultraviolet light, e.g. at low water levels.
- It is prone to puncture by underlying flints, and burrowing or sharp hoofed animals.
- Failure can occur if gas or water pressure builds up underneath.
- It will need replacing periodically.
- In some site conditions, a geotextile or a layer of fine sand is required beneath the liner to reduce the risk of puncture.

In practice few reservoirs are 100% watertight. Slow seepage occurs from unlined reservoirs and small leaks are common in lined reservoirs.

6.1.4 Promotion

The benefits of storage reservoirs have recently been widely promoted, e.g. through local conferences, articles in the farming press and a leaflet produced by MAFF (MAFF, 1996).

In addition to securing an irrigation supply where no summer abstraction would be licensed, the promoted benefits of discrete storage reservoirs include:

- Cheaper water charges. Winter water abstraction charges are 10% of summer charges.
- Long-term planning. Winter abstraction licences are usually issued for a longer period.
- Flexibility of supply. There are no flow rate limits on abstraction from the reservoir.
- Security of supply. Abstractions from the reservoir are not subject to Section 57 restrictions.
- Multipurpose use. Reservoirs can provide conservation habitats or generate extra income through amenity or fishery development.
- Increase in farm's capital value.

In addition, a recent EA re-interpretation of the 1991 Water Act now allows the reservoir itself to be given as the application point, meaning that farmers are later free to apply the water wherever they wish, rather than having to specify land boundaries as in other spray irrigation licences.

Although it is MAFF and EA policy to encourage on-farm reservoirs, investment is left to individual farmers and no subsidies or grants are available for their construction (though grants may be available for other objectives, e.g. environmental gain, creating rural employment).

6.1.5 Reservoir costs

A postal survey was carried out to obtain information on recently constructed winter storage reservoirs. Questionnaires were sent to 103 of the 131 farmers in the EA Anglian Region with winter SI abstraction licences issued since 1990. A 41% response was received, providing details of 57 reservoirs. Details of an additional 10 reservoirs were provided by two engineering consultancy firms specialising in reservoir design, giving a total of 67 reservoirs with a total storage capacity of almost 5000 tcm.

Additional information was subsequently collected from engineers, farmers and conservationists through informal meetings and at an On-Farm Reservoirs Workshop organised at Silsoe.

6.1.5.1 Reservoir construction costs

Reservoir construction is the major capital cost involved. Figure 6-12 and Figure 6-13 show reported construction costs per m^3 storage capacity for unlined and lined reservoirs respectively. These costs include preliminary site surveys, engineers' fees for design and supervision of construction, earthworks, lining and any additional landscaping and fencing costs. (Typically, a complete site feasibility study might cost £4000, and design and construction supervision fees might each cost up to 10% of the earthworks costs).

Lined reservoirs are clearly more costly to construct than unlined reservoirs. Both appear to show economies of scale as size increases. However there is considerable scatter around the trendline, particularly among unlined reservoirs.

Inlet works, supply pipes and pumps, power supply and other costs are excluded from these figures, as they tend to be very site specific. On average they added around another £22000, more than doubling the cost of the small reservoirs.

6.1.5.2 Capacity and volumes used

The volume actually usable for irrigation will be significantly less than a reservoir's total storage capacity and the winter abstraction. MAFF (1982) recommended that reservoir design allows for an average of 500 mm evaporation and seepage losses, and for at least 300 mm of 'dead water' to be permanently retained to prevent the clay base drying and cracking. Lined reservoirs require a similar depth of dead storage to hold down the liner. CIRIA suggests allowing 600 mm and 300 mm for annual evaporation and seepage respectively, plus 500 mm dead storage (Kennard et al., 1996). For small reservoirs particularly, losses and dead storage add significantly to costs. Computer modelling and monitoring give more accurate estimates of usable storage.

Actual usage will be less than usable capacity. Where a reservoir is a sole source of supply, it is usually sized to meet demand in the design dry year. In that case, the reservoir would not be emptied in most years. The average volume supplied to the field would typically be about two thirds of usable capacity. Due to economies of scale, and the lumpiness of reservoir investment, reservoir are often sized to allow for future expansion and a margin of safety. This extra capacity is also unused, at least initially. Where a reservoir compliments summer abstraction, it makes sense for the farmer to keep the reservoir as the emergency supply, using other sources first. The reservoir might then not be used at all in many years.

After use the reservoir would be refilled as soon as possible, perhaps even with spare summer abstraction. The volume of refill will be substantially greater than the volume used, to replace evaporation and seepage losses (even if no water is used).

6.1.5.3 Cost profiles

Typical cost profiles were developed for unlined and lined reservoirs at three different sizes, viz. 20, 60 and 100 tcm total storage capacity. Computer modelling was used to estimate the usable storage, after allowing for losses and dead water, the irrigable area of potatoes, and the average volume actually applied. Cost data from the survey and other sources were used to calculate typical capital, operating and total costs. Capital costs were amortised over 20 years at a 6% real interest rate. The results are shown in Table 6-8, as costs per hectare irrigated and per m^3 of water applied net of all losses. These calculations assume the reservoir is correctly sized to just meet demand for a potato crop in East Anglia in the design dry year.

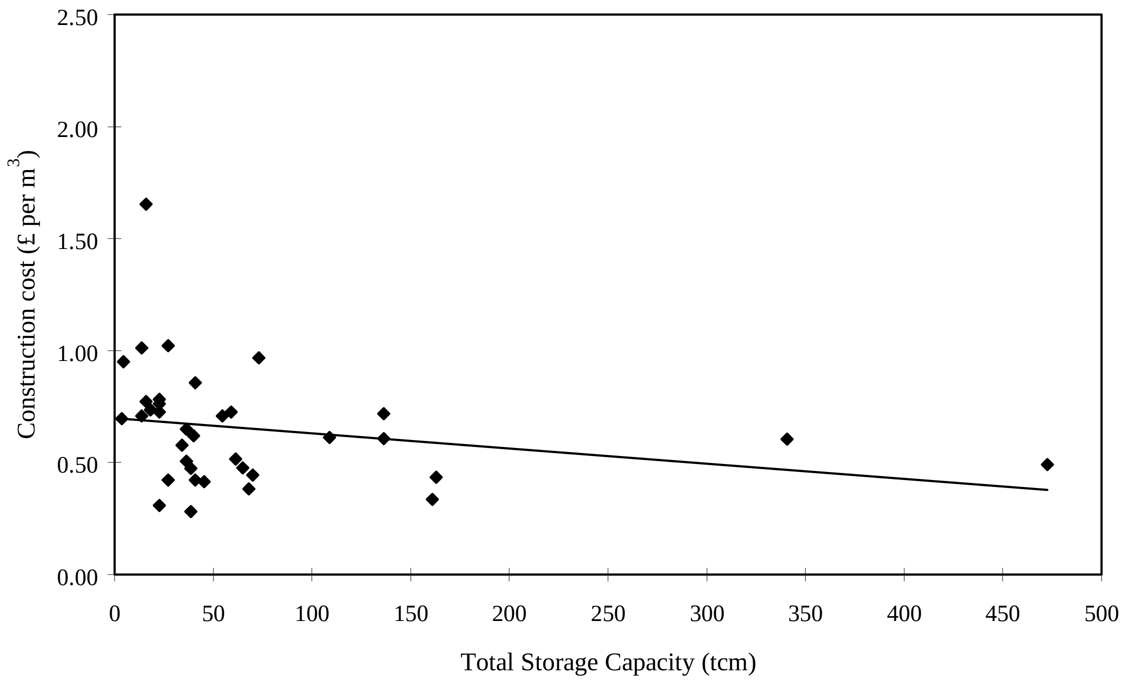

Figure 6-12. Reported construction costs (£ per m^3 gross storage capacity) for unlined reservoirs.

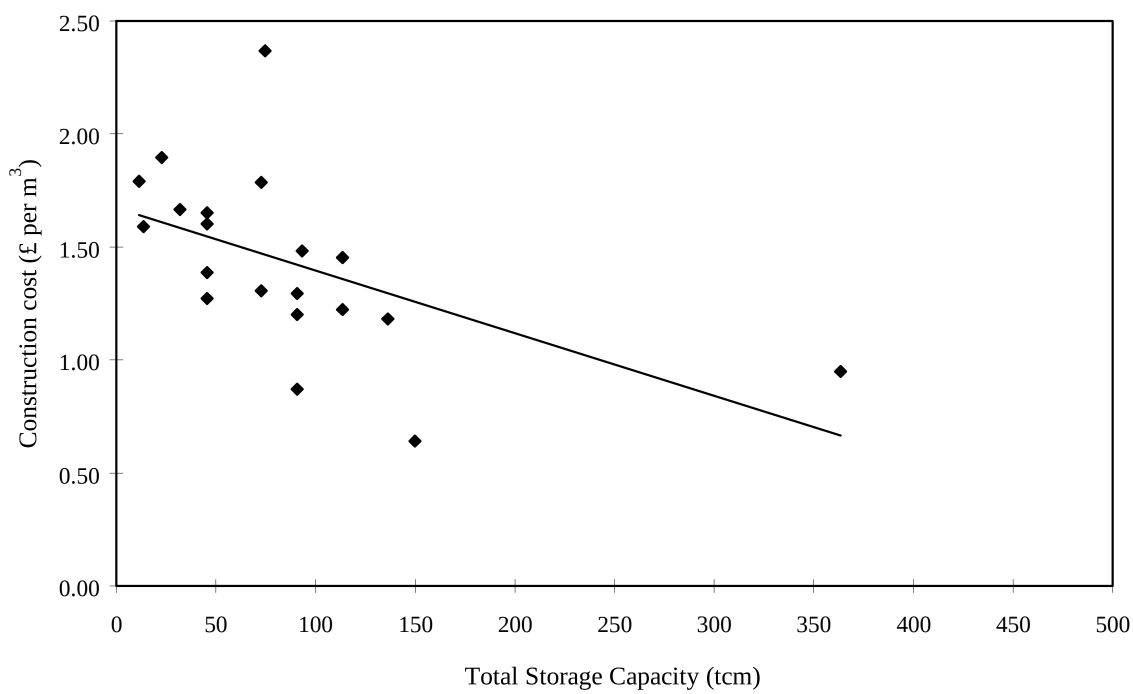

Figure 6-13. Reported construction costs (£ per m^3 gross storage capacity) for lined reservoirs.

Table 6-8. Capital, annual and unit costs for three typical reservoir size categories.

Gross reservoir capacity (m^3)	20 000				60 000				100 000			
Reservoir type	Unlined		Lined		Unlined		Lined		Unlined		Lined	
	£	%	£	%	£	%	£	%	£	%	£	%
Usable storage capacity (m^3)	11840		11840		37376		37376		65280		65280	
Average volume used by crops (m^3)	7877		7877		23602		23602		43430		43430	
Average refill volume (m^3)	12994		12994		38999		38999		65029		65029	
Capital costs												
Total capital cost (£)	38353		56953		55753		103753		82153		150153	
Total capital cost (£/ha irrigated)	7827		11623		3644		6781		3065		5603	
Annual costs: (£/ha/yr)												
Amortisation of capital cost *	682	*79*	1013	*82*	318	*73*	591	*80*	267	*76*	488	*82*
Operating costs												
Engineers' inspection fees	0	*0*	0	*0*	37	*9*	37	*5*	21	*6*	21	*4*
Repairs and maintenance	90	*10*	128	*10*	41	*10*	72	*10*	35	*10*	61	*10*
Energy	4	*0*	4	*0*	4	*1*	4	*1*	5	*2*	5	*1*
Labour	79	*9*	79	*6*	25	*6*	25	*3*	14	*4*	14	*2*
Water abstraction charges	8	*1*	8	*1*	7	*2*	7	*1*	7	*2*	7	*1*
Total operating costs	181	*21*	218	*18*	115	*27*	146	*20*	83	*24*	109	*19*
Total annual costs	863	*100*	1232	*100*	433	*100*	738	*100*	351	*100*	597	*100*
Unit costs												
amortisation of capital costs	0.34		0.50		0.16		0.31		0.13		0.24	
operating	0.09		0.11		0.06		0.08		0.04		0.05	
Total unit costs (£/m^3 supplied)	0.43		0.61		0.22		0.38		0.17		0.29	

Notes: Capital costs include abstraction licence & power supply (which would also supply delivery pumps to field).
*Capital costs amortised over 20 years at 6%.
Total unit costs are for gross volume supplied before application losses.

The results show there are clear economies of scale in both total capital investment costs and operating costs. Total unit costs per m^3 supplied from a 100 tcm reservoir are less than half those from a 20 tcm reservoir. The unit cost, per m^3 of water supplied, varies from £0.43 to £0.17, and £0.61 to £0.29, for unlined and synthetically lined reservoirs, respectively, for the capacities considered.

Table 6-8 also expresses these costs as percentages. Capital costs are the major part of overall costs. Repair and maintenance costs are approximately 10% of overall costs, due to assumptions made in the modelling. For reservoirs within the 1975 Reservoirs Act, engineers' inspection fees can constitute up to 10% of costs. For the smallest unlined reservoirs, labour costs are also significant. In contrast, energy and water charges appear insignificant, each constituting under 2% of costs.

There is an additional cost due to the loss of land occupied by the reservoir. Assuming the land would otherwise be used for winter wheat, this loss equates to around £0.05 per m^3 of irrigation water supplied. This would be much higher if potatoes or vegetables were replaced.

The vast majority of reservoir costs, including operating costs, are fixed, i.e. they have to be paid whether water is used or not.

Caution is recommended in using these figures, because of the scatter in the data, the difference between sites, and the different ways storage reservoirs can be used. Clearly however, water from storage reservoirs is not cheap. The lower winter abstraction charge is almost irrelevant in overall costings.

6.1.6 Constraints to storage reservoir development

Discussions with farmers, EA staff, reservoir designers and others have been used to investigate reasons why more farmers have not invested in reservoirs.

Sanders (1996) collected information on planned construction and constraints to reservoir development from irrigating farmers in upland (non-Fenland) Norfolk (specifically the Bure, upland Wissey and Yare catchments). Only 11 farms out of over 300 irrigating farms in upland Norfolk have licences for winter abstraction into reservoirs, despite the high irrigation demands and fully committed summer water supplies in most of this area. Questionnaires were sent to 100 randomly selected irrigators and a 52% response was achieved. Interviews were held with 12 of the irrigating farmers, five with reservoirs. Interviews were also conducted with three EA Anglian Region Abstraction Licensing Officers, an EA Conservation Officer, an engineering consultant and an English Nature representative.

These studies have identified a number of constraints.

6.1.6.1 Financial Constraints

Many farmers quote high reservoir costs as a constraint (Morris et al., 1996; Sanders, 1996), even when growing high value crops in water short areas. Rees et al. (1993) similarly identified loan unavailability due to indebtedness as a key constraint amongst surveyed Cambridgeshire farmers. Given the high returns identified earlier, and the relatively modest cost compared to other farm investments, this at first seems surprising. However, reservoirs are not financially attractive to all farmers, because for example of:

- Lower cost alternative supplies.
- Higher costs due to site conditions, difficult access, and/or fragmented land-holdings.
- Insecure land tenure.
- Uncertain long term cropping plans.

Other income generating benefits of reservoirs, such as amenity development and fishing, attracted little interest from landowners, who did not favour public access on their land, fearing vandalism or theft.

6.1.6.2 Inadequate information

Sanders (1996) reported that many farmers had misconceptions, particularly about licensing, water availability, reservoir costs and the need for lining, leading them to dismiss reservoir options prematurely. These were sometimes reinforced by inaccurate published information and misleading informal advice.

6.1.6.3 Farmer attitudes

Whilst many progressive farmers recognise reservoirs as a key investment strategy, others cite the uncertain farming future as a reason to avoid long-term commitments. Farmers may also find the long-term legal obligations and potential liability for reservoir safety off-putting.

6.1.6.4 Hydrological constraints

Uncertainty about whether reservoirs can be refilled is a major disincentive. Although the EA have previously stated that winter water is available in most areas, problems are now arising in some catchments. Environmental worries are resulting in high minimum residual flow requirements. In base-flow dominated catchments, recharge and hence river flows are reduced following a dry summer, when reservoirs are most likely to be empty.

This is likely to be an increasing constraint for the future if the present growth in storage reservoirs continues, and a source of conflict between farmers with the present first come-first served allocation system.

6.1.6.5 Conflict with conservation interests

Although nationally, organisations such as the RSPB and English Nature support on-farm reservoir development, there is often considerable local-level opposition (e.g. Sanders, 1996), sometimes over siting and sometimes over the effect of winter abstraction on river flows. There is often insufficient scientific evidence to either prove or disprove claimed environmental effects, but a precautionary approach is taken by the EA.

6.1.6.6 Planning constraints

Problems with planning regulations have been reported where proposed reservoirs fall outside permitted development, partly due to different local interpretations of the legal position. This issue is currently being addressed nationally.

6.1.7 Reservoir suitability maps

The application of a GIS to produce irrigation demand maps was discuused in Chapter 2. Similar methods can be used to produce reservoir suitability maps, taking into account land use, soil type, underlying geology, etc. These can then be overlaid with maps of irrigation demand and water availability to identify opportunities for reservoir planning at catchment scale. Figure 6-14 shows a map produced for a pilot area in Bedfordshire (Knox, 1996). It was intended to extend this methodology nationally, but the necessary high resolution computerised geological datasets are not yet available. It is hoped that this can be completed in a future project.

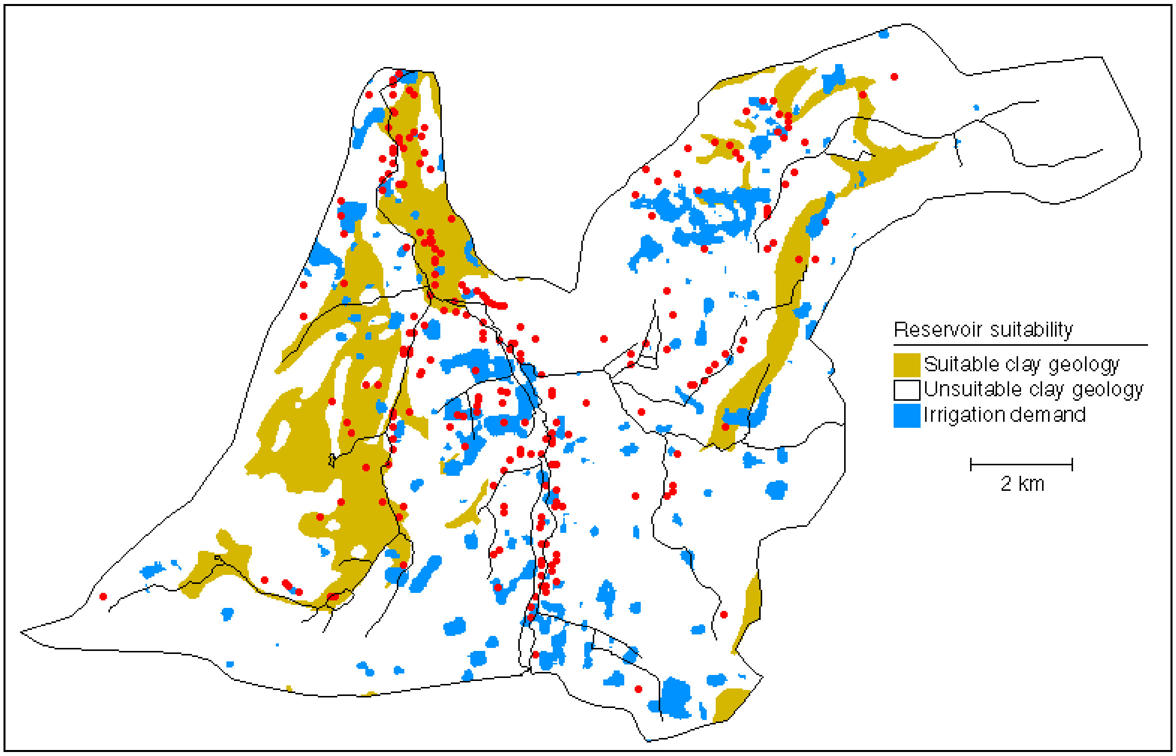

Figure 6-14. Irrigation demand and unlined reservoir suitability in a sub-catchment of the Ivel River Basin, Bedfordshire. Red markers indicate licensed abstraction points.

6.1.8 Summary

On-farm reservoirs have an important role in making more water available and in assuring reliability of supply. Actual water supplied will be much less than either total capacity or usable capacity. They may have limited effect in reducing summer abstraction in conjunctive use schemes in average years, but their presence as an emergency supply will greatly reduce the cost of summer restrictions.

There are significant economies of scale in constructing and operating larger reservoirs. Water from reservoirs is not cheap, but would be justified for many crops if summer sources are unavailable. Capital investment is the main cost, but repair and maintenance, inspection fees for reservoirs covered by the 1975 Reservoirs Act, and labour costs for overseeing pumping, are significant.

Current uptake of reservoirs is rapid in particular areas where conditions are favourable. However there are some areas where uptake appears to be constrained, despite high irrigation demands and insufficient summer supplies. Cost is claimed as a key constraint, particularly where lining is required. This is exacerbated by inadequate information about costs and the need for lining.

In some catchments, winter water is unreliable. Better information is needed from the EA for planning such long-term investments. In some areas, environmental concerns are constraining reservoir development, and research is needed to clarify the impacts of reservoir construction.

6.1.9 Recommendations

It is recommended that MAFF continue to support storage reservoir development where appropriate. The emphasis should be on providing better information to farmers, on identifying and removing unnecessary constraints, and on encouraging planning at group or catchment level.

A re-introduction of construction grants for all reservoirs is not recommended. Reservoirs should only be constructed where already viable. However, this should not preclude part funding winter storage reservoirs where summer abstraction has to be reduced, funding to encourage environmental benefits, or support in preliminary planning stages, particularly to encourage group reservoirs or innovative ideas.

To improve information available to farmers, it is recommended that:

- MAFF should continue to support publications, conferences etc.
- MAFF should fund research to better quantify reservoir costs under different site conditions, and develop methods for optimising reservoir capacity.
- MAFF should fund the development of reservoir suitability maps when the base data is available.
- MAFF should request the EA to clarify the availability and reliability of winter water in each catchment.

To reduce constraints:

- MAFF should support current moves to reduce reservoir operating costs by amending the Reservoirs Act for reservoirs which do not present risks to life or property.
- MAFF should continue to seek to identify and resolve planning regulation conflicts with reservoir development.
- MAFF should encourage farmers to consider joint reservoirs to reduce costs. Funding should be provided for setting up local groups and undertaking preliminary studies, at least for pilot areas.

6.2 Water harvesting

In the UK, considerably more rain falls than is needed for irrigation. Rainwater harvested on-farm provides one of the few sources totally under the farmer's control. Provided the water is intercepted prior to entering a watercourse or groundwater, an abstraction licence is not required.

For effective water harvesting, the catchment area is normally an impervious surface, such as a roof or a paved area. Artificial surfaces include concrete, butyl rubber and plastic sheeting. In Australia, some farms use compacted soil, in catchments of up to 40 ha, arranged in parallel cambered strips with dividing ditches which channel water into storage reservoirs (Pacey and Cullis, 1986).

Drainage from subsurface drains in clay soils can also be harvested.

6.2.1 Rainwater harvesting from roofs and paved areas

A number of farms and organisations in the UK already collect rainwater from roofs for irrigation, though the areas and volumes are generally small. Hadlow College (Kent) collects runoff from their glasshouse roofs for indoor irrigation, to supplement mains water. Some dairy farms, including the Scottish Agricultural College's Crichton Royal Farm, collect roof water for the cows' drinking supply.

The volume of runoff from impervious surfaces depends mainly on the rainfall pattern and the surface characteristics. Although a small initial amount of each rainfall is held as depression storage and then lost as evaporation, runoff coefficients of 90-95% are typical. Even in Bedfordshire, one of the drier parts of England, this would give average annual runoff of over 500 mm, compared to an average irrigation need of 160 mm for potatoes. Thus one hectare of roof area might theoretically provide sufficient water to irrigate 2.5 hectares of potatoes (at 80% efficiency).

Unfortunately, the majority of rainfall falls outside of the irrigation season, and summer rainfall is lowest in dry years when irrigation is most needed. The provision of adequate storage is therefore crucial to the reliability of rainwater harvesting. The storage capacity needed varies greatly depending on the ratio of catchment area to irrigated area, and the reliability of supply required. This storage is usually the largest element of the cost.

6.2.1.1 Modelling

To quantify these relationships, a simple runoff and water balance model was developed. The model estimates supply reliability and the net benefits with different ratios of catchment area and reservoir volume to irrigated area.

The model requires daily rainfall and potential evapotranspiration data (typically 20 years) for the site, together with previously calculated irrigation needs (mm) derived from the IWR Model (Hess, 1997a) described earlier.

Runoff is calculated from rainfall, assuming an initial depression storage loss and thereafter a constant proportional loss, using coefficients based on previous research conducted in the UK, (Pratt and Parkar, 1987). The runoff is assumed to be gravity channelled via guttering into a synthetically lined rectangular earth storage reservoir, from which it is abstracted for irrigation when required. No allowance is made for gutter overflow, although this may occur during heavy storms. The model calculates a monthly water balance for the reservoir, allowing for rainfall into and evaporation from the reservoir, and the gross irrigation requirements abstracted. Excess inflow is lost as overflow. One year's average inflows and outflows are used to establish the initial volume of water in the reservoir. The model then runs continuously over the 20 years data, carrying forward surplus stored water if necessary.

The model calculates the reliability of supply (defined as the % of the irrigation need that is met by the reservoir) and the net benefits, based on a given value for the water supplied, and can optimise the reservoir capacity and/or irrigated area for a given catchment area.

6.2.1.2 Example application

As an example only, the model was run with 20 years of rainfall data (1973-92) from Mepal, Cambridgeshire, for an existing 25^o smooth concrete tiled roof. For this surface, the initial depression storage loss was taken as 0.02 mm and runoff coefficient as 94%. The reservoir depth was 2.5m. Maincrop potatoes grown on a sandy loam soil were irrigated as described in Chapter 3, with an efficiency of 80%.

Benefits were based on an arbitary assumed value of £0.63/m^3 of water net of application costs. Reservoir construction costs of £1.73 per m^3 of total storage capacity were assumed, based on the average surveyed construction cost of lined winter storage reservoirs under 33 tcm (Sanders, 1997b). These were amortised assuming a 6% real interest rate and a 20 year repayment period. Costs excluded any additional guttering, pipework or pumps needed, and any operation or maintenance cost.

Figure 6-15 shows the predicted annual runoff per hectare (September to August years), before evaporation and overflow losses from the reservoir, and the corresponding gross irrigation demands. The average annual runoff was 5022m^3/ha of catchment, compared to an average annual gross irrigation demand of 148 m^3/ha irrigated.

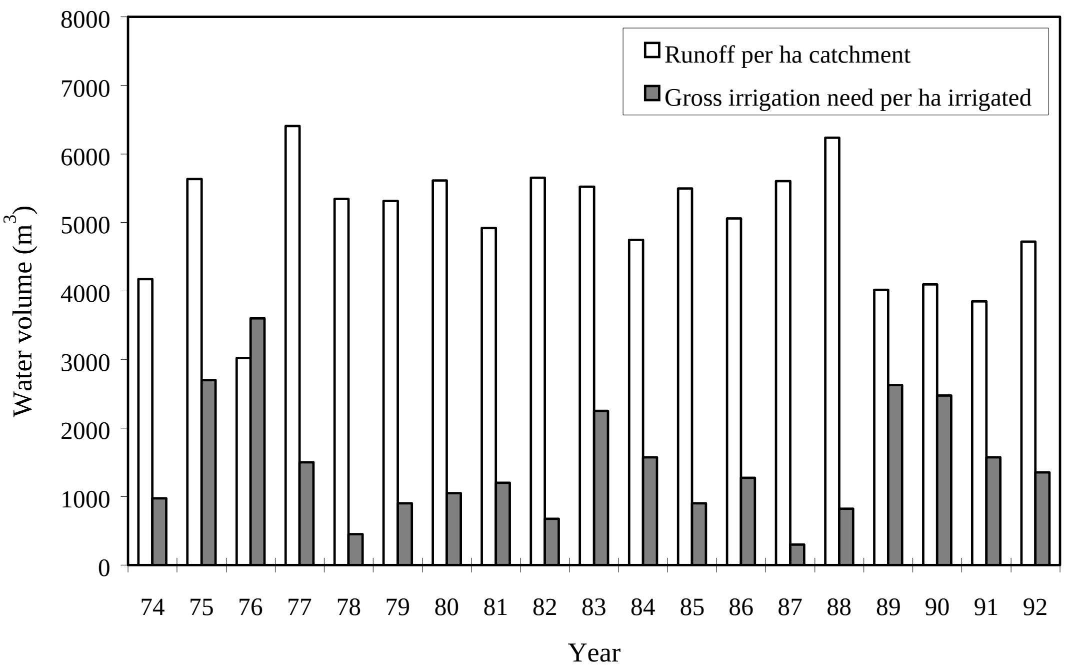

Figure 6-15. Modeled annual runoffs and irrigation demands.

The reliability of the rainwater harvesting system, for different catchment area to irrigated area ratios (CA:IA), and for different reservoir capacity to irrigated area ratios, are shown in Figure 6-16. For 80% or more of irrigation demand to be met, the CA:IA ratio must be above 1:4. For any given ratio, a larger reservoir capacity gives more reliability, but only up to a certain point.

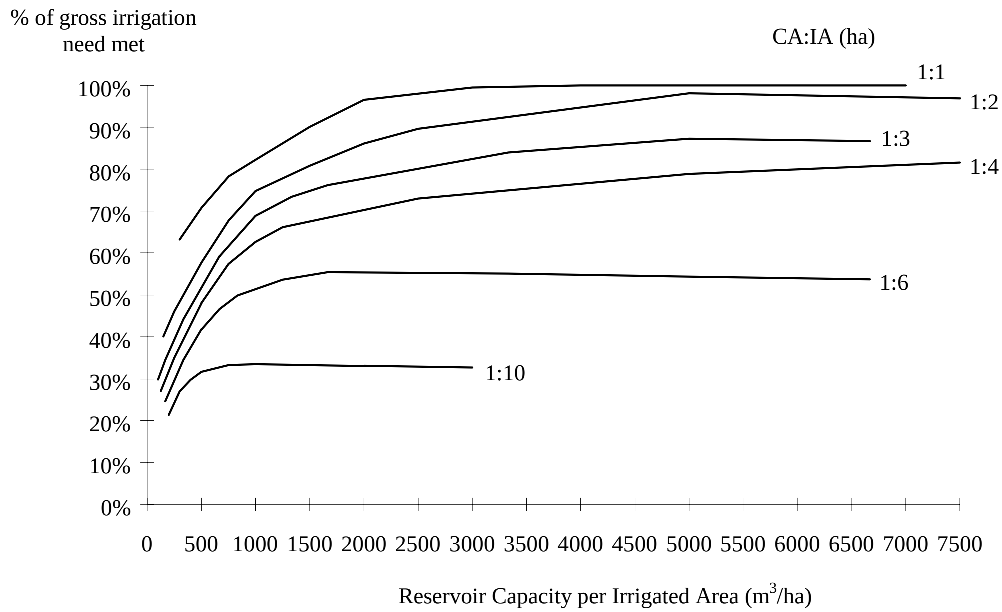

Figure 6-16. Example of reliability of rainwater harvesting (%) in meeting the seasonal irrigation needs for maincrop potatoes under different catchment area: irrigated area (CA:IA) ratios.

Figure 6-17 shows the corresponding net benefits, for the water value and costs assumed. For each catchment area, the figure shows there is an optimum reservoir size. For maximum benefit with 80% reliability, the optimum irrigated area in this example is 2.6 times the catchment area with a reservoir capacity of 4600 m^3 per ha of catchment.

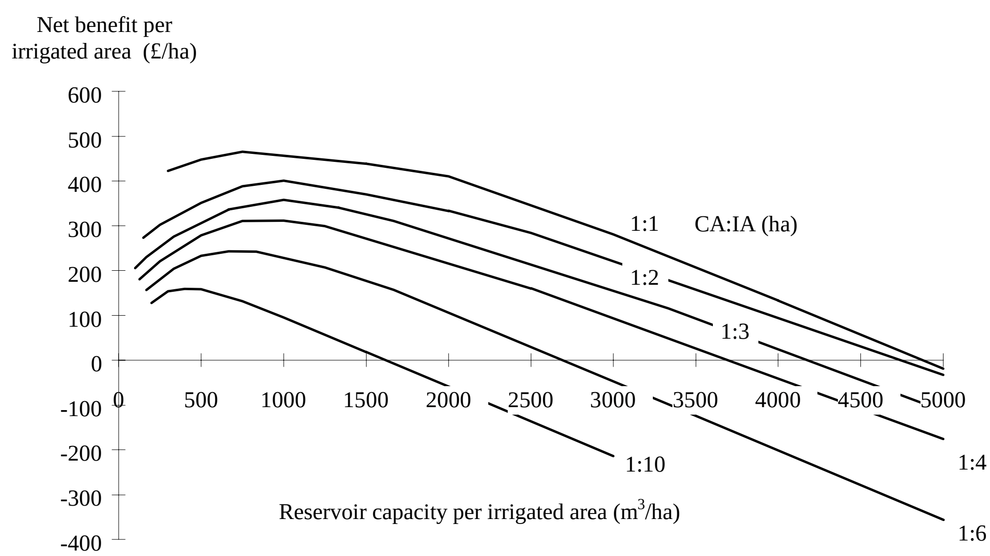

Figure 6-17. Example of net benefits of using rainwater harvesting for maincrop potato irrigation under different catchment area: irrigated area (CA:IA) ratios.

6.2.2 Rainwater harvesting from drains

Collecting the discharge from subsurface drains, particularly in clay soils, provides another method of harvesting rainfall on-farm. The London Golf Club (Kent), for example, obtains most of its irrigation supplies in this way. The drains only flow during the winter, so again storage is essential.

There is little difference in hydrological terms between abstracting directly from the drain and winter abstraction from the stream below the outlet, but a licence is (apparently) not required, and abstraction charges are avoided. The system is therefore attractive to users where a winter abstraction licence would be refused or unreliable. From the environmental viewpoint, the lack of EA control could be regarded as a disbenefit.

Yields can be estimated from data collected in previous drainage research projects. A simple spreadsheet analysis can again be used to model reliability, comparing yield and irrigation requirement over a series of years. In the drier parts of the country, yields can be low after dry winters. For high reliability as a sole source, either a large drained area or a large reservoir (for inter-season storage) would be required, increasing costs. Otherwise, if the drains are already installed, the system costs will be roughly similar to winter abstraction from surface streams.

6.2.3 Summary

Rainwater harvesting has potential for development in the UK, particularly:

- Where mains water is being used (e.g. 1.75 million m^3 used in Kent in 1995), or high value crops are being under-irrigated due to water shortages.
- Where impervious catchments such as roofs already exist, and can be cheaply adapted.
- For glasshouses (where irrigation demand continues in wet periods).

It cannot compete financially with direct summer abstraction at present rates, due to storage costs. It will incur similar or greater storage costs than winter abstraction if a high reliability is required, but could sensibly be used as a supplementary supply to top up winter storage reservoirs.

Calculation of the optimum storage capacity for given catchment areas and irrigated areas is essential, and requires site specific information and computer modelling.

6.2.4 Recommendations

There is surprisingly limited data on the costs and feasibility of rainwater harvesting in the UK. The simple modelling undertaken suggests that it can be financially worthwhile in particular circumstances. A study is recommended that would include:

- An analysis of the financial cost benefit of existing installations.
- Development of an improved computer model for determining optimum catchment areas and storage capacity in different parts of the UK.
- An analysis of the cost and feasibility of providing artificial on-farm catchments in the UK, e.g. using plastic sheeting.
- A study on the net effect on local hydrology.
- Construction of one or more trial installations.

6.3 Waste water re-use

Agricultural irrigation is often cited as a suitable application for the re-use of treated waste water including treated effluent (e.g. NRA, 1995). However, both internationally and within the UK, its potential has not been widely adopted for various reasons, most notably due to concerns over risk to public health. Even in USA, where use of treated water has been successfully developed and regulated, only 3% of municipal waste water is reclaimed, and it provides only 0.5% of all water used for irrigation (Groves, 1997).

6.3.1 Indirect re-use

Indirect re-use, whereby treated waste water is returned to surface watercourses and re-abstracted downstream, is already widely practised in UK. In many rivers, a significant proportion of the baseflow during droughts consists of treated sewage. In the Thames basin effluent is used indirectly for public water supply, where it represents 13% of the river abstraction used for that purpose (NRA, 1995). Indeed, it is often reported that water in the River Thames is used 7 times before it reaches the coast. Similarly, in 1995, abstractors from the River Ouse were told that it was only sewage from Milton Keynes that allowed them to continue abstracting.

Treated wastewater effluent can also be returned to groundwater sources, and used for re-charging aquifers, as for example, the chalk aquifer at Winchester, Hampshire (NRA, 1995).

The advantage of indirect re-use is that it provides some degree of protection to consumers. The EA effectively monitors the discharged water quality, and serious pollution problems would become apparent in river quality deterioration and fish kills. This helps ensure the basic quality of the water re-abstracted, although it would not necessarily protect against all pollution or pathogens etc., particularly if the re-abstraction point was near the discharge point.

Since re-abstraction requires a licence, the EA retain the power to stop abstraction and retain the water in the watercourse during low flows or droughts.

6.3.2 Direct re-use

There are no known examples of direct re-use of treated effluent in the UK at present.

Direct re-use for irrigation initially appears attractive. It is an almost guaranteed reliable source, it avoids licence restrictions, and, if treatment standards are reduced, the farmer might even be paid to take it. However in most cases it is in the wrong location, since most waste is treated close to population centres. The water quality can be variable, deteriorating during dry periods when most needed. If industrial discharges are mixed in the waste water, there could be potential problems with heavy metals etc. Storage would be difficult, so for most of the year the sewage would have to be discharged anyway.

The level of water treatment has to match the type of re-use. For irrigation of salad crops, it would have to meet near drinking water standards. There are also health and safety implications for staff to be considered, including aerosols from spray irrigation. For other uses, sub-irrigation of tree crops for example, it could be argued that a lower standard would suffice. There are examples of this in many countries, including Israel, Australia and USA.

For most applications, the waste water would probably need more treatment than is currently required for discharge to watercourses. Information available on the extra costs of re-using waste water are limited. Direct re-use of waste water would incur extra costs for transport, storage, filtration and chlorination. Groves (1997) quotes research conducted in Florida which suggests extra costs of £0.12-£0.16 per m^3. Although these costs are not prohibitive, they are more expensive than indirect re-use.

Perhaps the most compelling argument against promoting direct re-use of treated sewage is public perception. Irrespective of technical feasibility, the public are unlikely to be confident that the water treatment will always be totally effective. Remembering the damage to the beef industry even before any link between BSE and CJD was scientifically established, any suggestion of consumer illness due to poor quality irrigation water would be disastrous to some sectors of the industry.

6.3.3 Summary

Although research suggests that direct reuse of waste water for agricultural irrigation is technically feasible and would create only negligible risks to users and consumers "providing the effluent has been suitably treated" (Groves, 1997), there are public relations problems and extra costs associated with using it.

6.3.4 Recommendations

It is recommended that MAFF do not actively promote direct re-use of sewage waste water for the irrigation of crops for human consumption at present. Indeed, in the absence of any UK research, we recommend that MAFF should consider banning it for spray irrigation of crops sold directly to the public.

It is suggested MAFF maintain a watching brief on current research (e.g. work being undertaken by UKWIR) on re-use, with a view to possible future research into re-use through subsurface trickle irrigation onto orchard crops and/or irrigation of crops for processing, e.g. sugar beet.

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