Using water auditing to assess irrigation efficiency: a comparative assessment of trickle, sprinkler and rain-guns for potato production in the UK

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Abstract

In the UK, supplemental irrigation is an essential component in the production of high value crops, such as potatoes, where continuous and reliable supplies of premium quality produce are demanded by the major supermarkets. However, the rising demand for water is exerting acute pressure on water supplies with many river basins (catchments) now considered to be over-licensed and/or over-abstracted. Promoting efficient use of water has become a major priority for the government and the regulatory authority responsible for water resource planning and allocation.

New legislation in England and Wales requires irrigators to demonstrate efficient use as part of renewing their water abstraction licence (permit). As a result, defining and measuring irrigation efficiency is the subject of national debate within and between the irrigation industry and water regulatory authority. This paper describes the role of water auditing as a tool for assessing the financial benefits (value) of irrigation water as a surrogate for quantifying irrigation efficiency.

Using selected farm sites, an analysis of water use, crop productivity and irrigation costs and benefits for three contrasting systems (trickle, sprinkler and rain-guns) has been completed. The study focuses on potatoes, the most important irrigated crop in the UK. A brief description of the rationale, methodological approaches and implications of the research are outlined.

Keywords: auditing; efficiency; irrigation; potato; rain-gun; sprinkler; trickle.

1. Introduction

Internationally, the rising demand for water, most notably for irrigated agriculture, is exerting acute pressure on water resources. This supply-demand imbalance is unsustainable, particularly if targets for environmental protection are to be achieved. As a consequence, there is an increasing scarcity in freshwater supplies, not only in arid and drought prone areas of the world, but also in more temperate climates where rainfall is abundant. A typical example is in England and Wales, where recent droughts have highlighted the fragile balance that exists between the needs of the water environment and those of abstractors (e.g. Gowing and Ejieji, 2001). Although irrigation is supplemental to rainfall, it is essential for the production of high value crops, such as potatoes, where continuous and reliable supplies of premium quality are demanded by the major processors and supermarkets. As a consequence, the demand for irrigation water in England and Wales is rising steadily, at an underlying rate of 3% per annum (Weatherhead and Knox, 1999). This has contributed to a situation that is considered environmentally unsustainable in many catchments (EA, 2001).

The European Water Framework Directive (2000/60/EC) requires Member States to establish controls over the abstraction (withdrawal) of fresh surface and groundwater, including a register of water abstractions. Almost all water abstractions in England and Wales therefore require an abstraction licence (permit) from the regulatory authority, the Environment Agency (EA). There are currently about 48000 licences in force of which approximately a quarter are for irrigation. Historically, licenses were issued on a first-come first-served basis and allocated in perpetuity (Weatherhead *et al*., 1997). However, all new licenses are now time-limited and subject to renewal conditions. The seasonal volume of water allocated on a new licence now reflects the water required by the farmer in a ‘design’ dry year, equivalent to the 80% probability of non-exceedance, that is meeting demand in 80 years in 100 (Knox *et al*., 2005). In addition to this seasonal restriction, conditions in a licence can restrict peak rates of water use (e.g. daily, monthly), particularly where an abstraction is from environmentally sensitive water source.

As part of a broader project investigating the role of irrigation water auditing and benchmarking, this paper reports on a study that combines fieldwork (water metering and hydraulic performance assessment) with computer analyses (agronomic and economic) to assess the relative "efficiency" of irrigation under three contrasting systems (trickle, sprinkler and travelling rain-gun). The study is focussed on potatoes, the most important irrigated crop in the UK. A brief overview of potato irrigation in the UK is provided. The research approaches, fieldwork and proposed cost-benefit analyses are then described.

At the time of writing this paper (September 2005) the irrigation season was still underway; the final results from the study are not therefore included here but will be presented at the 2005 US Irrigation Association Conference and made available on the author's website.

2. Potato irrigation in the UK

Irrigation accounts for less than 2% of total water abstraction in England and Wales, but can nevertheless be environmentally damaging, because it is a consumptive use, concentrated in the driest catchments and in the driest months. During peak periods it can account for up to 70% of total abstraction in intensively irrigated areas. It is mostly used for the production of high value vegetables and potatoes (Knox *et al.*, 1996). Nationally, in 2001, potatoes accounted for 52% of the total irrigated area and 58% of the total volume of water applied (Weatherhead and Danert, 2002). For many farm businesses, irrigation of potatoes is the economic driving force behind investment in irrigation. The main financial benefits of irrigation relate to the value of extra yield and improved quality, less any additional production costs. In the UK, it is often the quality assurance benefits of irrigation that are most significant. These are gained on the whole crop, not just the extra yield from irrigation. In general, the extra net margin per m^3 of water applied is highest for soft fruit (e.g. strawberries), vegetables, potatoes and orchard fruit, and lowest for grass, cereals and sugar beet. For potatoes, irrigation is crucial to minimise skin quality problems caused by common scab (*Streptomyces scabies*). Optimising size, shape and skin finish are also important criteria in irrigation management. Indeed, quality criteria are specified as a condition of producer contracts and supermarket grower protocols. Failure to meet these quality standards often leads to large price reductions and possibly rejection.

Most UK potato irrigation relies on hose-reel systems (travelling guns). These are acknowledged to be inaccurate and inefficient in water and energy use. However, they are robust, versatile, and fit well into typical UK mechanised arable farms (Weatherhead *et al*., 1997), particularly where irrigation has to follow the crop rotation around the farm, often with non-standard field sizes (typically irrigated potatoes are grown in a rotation including non-irrigated cereal crops). However, changes in technology choice are being driven by industry and regulatory pressures for more accurate and efficient irrigation particularly since water is becoming scarce and highly valued. As a consequence, there has been significant growth in the use of trickle irrigation, helped by product improvements and a reduction in the cost of disposable drip tape. In 2003 there were estimated to be 2500 ha of potatoes under trickle irrigation in England and Wales (Knox and Weatherhead, 2005), although this area is small compared to the national total irrigated area (approximately 150,000 ha). Farmer experiences with trickle on potatoes have been mixed, with many finding that their soil conditions make it difficult to achieve sufficient lateral soil wetting, particularly on beds in sandy soils. Many have subsequently reverted back to overhead systems, choosing hose reels fitted with booms in preference to rain-guns. Some are trialling the use of solid set micro-sprinkler systems, which are an economic alternative where frequent applications are required, and well suited to small areas or irregular shape fields that are difficult for mechanized systems.

3. Methodology

In this project, a comparative assessment of water use under trickle, sprinkler and hose-reel (rain-gun) irrigation has been conducted at contrasting agroclimatic sites across the UK. The sites were located on commercial farms involved in the production of high value maincrop potatoes. In summary, the pattern of water use at each site was monitored during the 2005 irrigation season (April to September). The water audit data were then combined with information relating to crop production (yield, prices, labour and management costs) and irrigation (capital (equipment) and operating (energy, labour, water) costs) to assess irrigation water use efficiency (t ha^{-1} mm^{-1}) and the marginal value of water (£/m^3) for each irrigation system. The study involved three main components:

1. An audit of water use under each irrigation system (trickle, permanent set sprinklers, hose-reel fitted with rain gun) during the season;

2. A comparative assessment of the in-field performance of each irrigation system, and;

3. An evaluation of the financial costs and benefits associated with crop production under each irrigation system. This involved a comparison of crop water use and productivity for each irrigated crop against an equivalent non-irrigated (rain-fed) potato crop.

A brief description of each stage is given below:

3.1 Irrigation water audit

The purpose of the water audit was to record the date of each irrigation event, the scheduled depth (mm) of water applied and the volume (m^3) of water diverted (pumped) to each field site during the course of the irrigation season. Water meters were installed at the field hydrant in each field site. A reading was taken at the start and end of each irrigation event. Each farmer was provided with a water audit proforma to record the necessary information. A weather station was used to record local weather data, mainly rainfall and the parameters required to derive reference evapotranspiration (ETo) at each site. A Sentek EnviroSCAN™ was used to monitor changes in soil moisture within the field sites during the season, to assess the relative impact of the timing and frequency of each irrigation event on soil moisture deficits.

Using information relating to local soil, climate and cropping practices (husbandry), the actual irrigation applications (depths of water applied) during the season were compared against simulated applications using an irrigation scheduling water balance model, and assuming the farmer was following best management practice for irrigation scheduling.. The model (Hess, 1996), estimates the daily soil water balance for the potato crop and local soil type, working from daily rainfall and reference evapotranspiration (ETo) data. The model outputs information on the crop water use, the amounts of irrigation water applied and the proportional yield loss due to any water stress. This provides a useful comparison between the theoretical irrigation water requirements (mm) against the actual irrigation applications.

3.2 Irrigation system performance (uniformity)

In addition to measuring water use, it is also important to consider how uniformly the water is distributed across a crop. Non-uniform application inevitably leads to over or under-irrigation in some parts of the field, leading to inadequate or inefficient irrigation, resulting in uneven yield and quality. For the trickle irrigated field site, a hydraulic evaluation was undertaken based on a methodology defined by the American Society of Agricultural Engineers (ASAE, 1999) to evaluate micro-irrigation systems. This included an assessment of irrigation uniformity within selected irrigation blocks, using mini catch-cans to collect the discharge from a series of randomly selected emitters, evaluation of the uniformity along a complete lateral and measurement of pressure variations within the block (header, midpoint and tail-end). For the sprinkler and hose-reel irrigation systems, a procedure defined by ISO (1990) was followed, using catchcans between static sprinklers and across gun travel lanes. Two uniformity indicators were calculated, namely the Christiansen (1941) coefficient of uniformity (CU) and the distribution uniformity (DU) defined as the ratio between the average depth in the lowest quartile and the overall average.

3.3 Irrigation cost-benefit and irrigation water use efficiency

Farmers are generally most interested in maximising their economic returns. Where water is the scarce (limiting) resource, these should be maximised per unit of water applied (£/m^3). The irrigation cost-benefit analysis was based on a methodology developed by Morris *et al*. (1997), but updated for current prices. A comparison of irrigation benefits less costs (expressed as £/m^3 of irrigation water applied) provides the farmer and water regulator with indicative values of water for that enterprise, and hence best economic use. This is probably the most rational indicator to compare different uses of water from an economic viewpoint. The efficiencies of irrigation management and equipment are implicitly included in the appraisal of the value of water. This approach also enables a comparison of the value of water between different crops (e.g. potatoes, strawberries) and sectors to be undertaken (e.g. horticulture versus sports-turf irrigation).

For each crop, the irrigation water use efficiency (IWUE, tonnes per hectare per mm of water, t ha^{-1} mm^{-1}) was also estimated. This is defined as the ratio between the additional crop produced and the irrigation water applied. IWUE is considered one of a useful range of measures to evaluate irrigation system performance (Ayars *et al*., 1999). However, IWUE ignores the role that irrigation plays in attaining premium crop quality, which is particularly important under supplemental irrigation conditions such as in the UK. Price differentials of circa 30% between premium grade potatoes for the pre-pack markets and processing potatoes illustrates the financial benefit of irrigating for quality. Nevertheless, IWUE can be a useful indicator to compare irrigation productivity between individual irrigation systems, assuming they are all scheduled correctly.

In order to estimate the marginal value of water and IWUE for each crop at each site, information on a range of parameters were collected (Table 1).

Table 1. Components of crop production used to assess the performance of each irrigation system.

Indicator	Description and units of measurement
Crop husbandry and production	Cropped areas (ha). Crop configuration (planting depth, ridge spacing, plant spacing) Crop growth (planting, establishment and harvest dates) Other costs of production (e.g. fertilizer application) Farm labour inputs for irrigation management (hours) Yields (t/ha) for irrigated and un-irrigated crops. Crop prices (£/t).
Irrigation system and water use	Irrigation system design and capital cost (£/ha) Annualised in-field costs (£/ha/year) for each system, comprising the capital costs amortised over their estimated useful lives, together with estimated in-field running costs (i.e. labour, fuel, water and repairs). Water sources, costs and volumes abstracted (m^3)

4. Results

Unfortunately, at the time of preparation of this paper (September 2005) the irrigation season was still underway. A complete set of results cannot therefore be produced. The results will be presented at the US Irrigation Association Conference (November 2005) and reported on the authors website and in a scientific irrigation journal in due course.

5. Discussion

A brief discussion of the rationale for evaluating irrigation efficiency and the implications for improving water resource management is given below.

In many countries where water resources are under pressure, improving irrigation efficiency has become the main objective of irrigated agricultural production. In the UK, rising demands for water, increased competition between sectors and the longer-term threat of climate change are also highlighting the limitations on available supplies for irrigation. Improving irrigation efficiency has therefore become the focus of significant industry and regulatory attention. However, despite broad acceptance of the overall concepts of making best use of water, improving crop productivity and obtaining more crop per drop, the term "irrigation efficiency" has been very loosely used, often without clear definition, including in the new Water Act (2003). Clarifying its interpretation has become particularly important since new water regulation came into force whereby abstractors may have to demonstrate "efficiency" at licence (water permit) renewal. Whilst this might sound straightforward in practice, there is currently widespread confusion due to the many definitions of "efficiency".

In order to compare irrigation systems, a range of indicators that provide an assessment of performance has been widely used internationally. These have generally been termed *efficiencies,* for intuitive appeal (Burt *et al*., 1997). Unfortunately, in many cases, the same term *irrigation efficiency* has been used, but each time assuming a slightly different technical definition. This has led to widespread confusion. To exacerbate the problem, another criterion, *irrigation uniformity*, has also been widely used; in many cases the terms have been used interchangeably without recognising their fundamental differences (Burt *et al*., 1997). A seminal paper by the on–farm irrigation committee of the American Society of Civil Engineers (ASCE, 1978) defined *irrigation efficiency* as the ratio of the average depth (or volume) of irrigation water which is beneficially used, to the average depth (or volume) of irrigation water applied. But estimating irrigation efficiency is not straightforward. It requires a detailed consideration of the various hydrological inputs and outputs through an irrigation water balance, clear definition of the study area boundaries (e.g. field, farm or catchment) and quantification of the fate of the various fractions of the irrigation water that is applied. Failure to define these scale and boundary issues has led to problems in comparing efficiency values for different systems (Clemmens and Burt, 1997). Furthermore, efficient systems by some definitions can be very poor performers by other definitions (Rogers *et al*., 1997). Use of the term efficiency to assess individual systems and to set benchmarks for comparison between different methods is therefore likely to be misleading. Indeed, its misuse has been noted to occur most often when adopted as synonymous of irrigation performance (Pereira *et al*., 2002).

Whilst there is a significant volume of published research that deals with the efficiency of individual irrigation systems for a wide range of crops, there is very little published information on studies that specifically compare trickle with rain-gun irrigation on crops under UK weather conditions (low evapotranspiration and significant rainfall). Most studies identified relate to the USA and for crops not grown in the UK (e.g. cotton, sorghum). Many of the papers focussed on comparing trickle with either sprinklers or more usually surface (furrow) irrigation. This reflects the dominance of surface irrigation internationally. The findings confirm that the levels of efficiency attained in practice depend more on the suitability of that crop to a particular irrigation method rather than the method of application *per se*.

In the UK, trickle irrigation has been widely described as being more efficient. On this basis there have been suggestions that the government should encourage or even require irrigators to use trickle irrigation, and/or should exempt trickle from abstraction licensing. For this reason, trickle irrigation is being heavily promoted, often by regulators and governments as well as the trickle industry. Compared to traditional surface or overhead methods, trickle irrigation offers the potential for greater water use efficiency and has often been reported to produce crops of higher yield and quality (Knox and Weatherhead, 2003). Despite its higher costs, these characteristics make trickle an attractive option in regions where irrigation water resources are scarce and/or expensive. Our initial findings confirm that trickle irrigation is potentially more efficient than overhead irrigation. However, in practice its *actual* efficiency depends as much on the level of on-farm water management being practised and on the crop being grown. Another problem interpreting on-farm trial data is in distinguishing between water savings directly due to the use of trickle irrigation, from that due to better scheduling and more intense management. Whether water savings will persist once a trial is less closely monitored is unknown.

A number of field-scale farm trials using trickle on potato crops have been undertaken in the UK. None were scientifically replicated or fully instrumented, but they usefully identified field-scale issues and problems. None reported on direct water savings or increased irrigation efficiencies attributable to trickle. A major problem in interpreting findings from all trials is in distinguishing between any water savings (efficiencies) arising directly due to the use of trickle irrigation, and those due to better scheduling and more intense management during the trial. Although figures of 90% efficiency are often quoted from research and demonstration plots, the *actual* efficiency of trickle under field conditions as evidenced in this study suggest the values significantly below this figure, depending on the level of on-farm water conservation being practised.

A number of farm trials have also been reported in Australia where trickle has been compared against other irrigation methods for use on various crops including potatoes, tomatoes and cotton. For potatoes, farmer experiences are broadly similar to those experienced by many UK growers. Greater responses to irrigation have been shown giving improved water use efficiency as well as crop quality benefits. However, few of the studies have reported direct water savings attributable to trickle. On one comparative study of trickle on tomatoes, it was reported that it was the skills of the grower that had the most impact on yield and water use efficiency. Whilst some crops have shown 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 hose-reel-gun irrigation, probably related to poor uniformity and inadequate irrigation under the hose-reel (Weatherhead *et al*., 1997).

Finally, there are policy implications for promoting water efficiency. Water can generate very high financial returns where supplementary irrigation assures first class quality high value crops. The profitability of irrigation depends considerably on the price differentials offered for quality produce in the market. In situations where water is limiting and returns per m^3 of water are high, as they are in the case of potatoes, previous research (Morris *et al*., 2003) suggests rationing water through increased water prices could have a major impact on farm incomes before it substantially changes water use behaviour. In such situations restrictions on abstraction licences may be a more effective and equitable mechanism to achieve beneficial change. Some increase in abstraction charges, however, could help fund water resource management initiatives by the regulatory agency. For example, further research into the impacts of irrigation non-uniformity on crop yield and quality and the development of precision irrigation application systems to increase water use efficiency, constitute two areas that might help to deliver additional improvements in efficiency and water savings.

6. Conclusions

Water auditing studies have been undertaken to compare and assess the water use efficiency and value of water under contrasting irrigation systems (overhead and trickle). The research is helping to improve levels of understanding of irrigation system performance for the industry and water regulator. Clearly, if meaningful comparisons between different irrigation systems (e.g. trickle versus sprinkler) are be made, it is essential that those who undertake such work and the stakeholders for whom the results will be relevant (e.g. government, regulatory authorities, irrigation industry and farmers) understand and agree from the outset the various definitions and their appropriateness. This will enable more rational assessments of actual farm irrigation practices to be made and referenced against recognised industry and government benchmarks.

The study so far has confirmed there are practical difficulties in assessing application efficiency, and risks in using it as an indicator of best use. If efficiency assessments are required legally for abstraction licensing control, then it is suggested they should be more closely related to the marginal IWUE and/or the economic benefits (value) of the water being used. However, these definitions can themselves become subjective in defining costs and benefits, and still omit non-economic issues, such as rural development and fairness.

7. Acknowledgements

This study forms part of a research project funded by the UK Environment Agency. The authors are grateful for the support of the individual farmers involved, Anthony Hopkins (Wroot Water Systems) for helping to identify the field sites and Juan Pablo Marmol and Juan Rodriguez-Diaz for their assistance with fieldwork. The views expressed are those of the authors and not necessarily the EA.

8. References

ASCE (1978). Describing irrigation efficiency and uniformity. *Journal of the Irrigation and Drainage Division* 104 (IR1):35-41.

ASAE (1999). Field evaluation of mirco-irrigation systems. ASAE EP458 December 1999. American Society of Agricultural Engineers.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., and Eisenhauer, D.E. (1997). Irrigation performance measures: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 125(6):423-442.

Christiansen, J.E. (1941). The uniformity of application of water by sprinkler systems. *Agric Eng*. 22: 89-92.

Clemmens, A.J. and Burt, C.M. (1997). Accuracy of irrigation efficiency estimates. *Journal of Irrigation and Drainage Engineering* 123(6):443-453.

EA (2001). Water Resources for the future: A Strategy for England and Wales. Environment Agency. Bristol.

Gowing, J.W., and Ejieji, C.J. (2001). Real-time scheduling of supplemental irrigation for potatoes using a decision model and short-term weather forecasts. *Agricultural Water Management* 47: 137-153.

Hess, T.M. (1996). A microcomputer scheduling program for supplementary irrigation. Computers and Electronics in Agriculture 15: 233-43.

Knox, J.W., Weatherhead, E.K., and Bradley, R.I. (1996). Mapping the spatial distribution of volumetric irrigation water requirements for maincrop potatoes in England and Wales. *Agricultural Water Management* 31; 1-15.

Knox, J.W. and Weatherhead, E.K. (2003). Trickle Irrigation in England and Wales. Technical Report. Water Resources R&D Project W6-070/TR. Environment Agency.

Knox, J.W., Weatherhead, E.K., and Ioris, A.A.R. (2005). Allocation and control of water for irrigated agriculture in Scotland. *Water International*, *Journal of the International Water Resources Association* (in press).

Knox, J.W., and Weatherhead, E.K. (2005). The growth of trickle irrigation in England and Wales; data, regulation and water resource impacts. *Irrigation and Drainage* 54:135-143.

ISO (1990). Irrigation equipment – rotating sprinklers. Part 2: Uniformity of distribution and test methods. ISO 7749-2: 1990(E).

Morris, J., Weatherhead, E. K., Mills, J., Dunderdale, J.A.L., Hess, T.M., Gowing, D.J.G., Sanders, C.L., and Knox, J.W. (1997). Spray Irrigation Cost Benefit Study. Final Report to Environment Agency. Cranfield University.

Morris, J., Vasileiou, K., Weatherhead, E.K., Knox, J.W., and Leiva-Baron, F. (2003). The Sustainability of Irrigation in England and the Impact of Water Pricing and Regulation Policy Options. Proceedings: of International Conference in Advances in Water Supply Management, Imperial College, London, UK, 15 - 17 September.

Pereira, L.S., Oweis, T., and Zairi, A. (2002). Irrigation management under water scarcity. *Agricultural Water Management* 57: 175-206.

Rogers, D.H., Lamm, F.R., Alam, M., Trooien, T.P., Clark, G.A., Barnes, P.L., Mankin, K.(1997). Efficiencies and losses of irrigation systems. Irrigation Management Series. MF-2243. Kansas State University. Manhattten.

Weatherhead, E.K., Knox, J.W., Morris, J., Hess., Bradley, R.I., Sanders, C.L. (1997). Irrigation Demand and On-farm Water Conservation in England and Wales. Final Report to Ministry of Agriculture, Fisheries and Food. MAFF Project OC9219. Cranfield University, Bedford.

Weatherhead, E.K. and Knox, J.W. (1999). Predicting and mapping the future demand for irrigation water in England and Wales. *Agricultural Water Management* 43: 203-218.

Weatherhead, E.K. and Danert, K. (2002). 2001 Survey of Irrigation of Outdoor Crops in England. Cranfield University, Bedford.