Environment Agency

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A comparative assessment of trickle and spray irrigation

Science Report – SC040008/SR3

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SCHO0408BNXO-E-P

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Steve Killeen

Head of Science

Executive Summary

Recent research (A*ssessing optimum irrigation water use: additional agricultural and non-agricultural sectors* SC040008/SR1) complements existing guidelines (W6-056) for the Environment Agency to assess and set the 'optimum' or 'reasonable' irrigation needs for an abstraction licence, across a wide range of agricultural, horticultural, amenity and sports turf sectors.

For those abstractors with time-limited licences, demonstrating efficient use of water is one of three tests required by the Environment Agency for successful licence renewal. However, the definition of efficiency under UK conditions of supplemental irrigation has been the subject of widespread debate between academics, the regulator, industry and individual abstractors. To improve our understanding of efficiency, and particularly the differences between overhead (spray) and micro (trickle) irrigation, this report offers a comparative study of the efficiency of water use with these contrasting irrigation systems.

During 2005, a series of irrigation field studies (audits) were carried out on selected commercial farms in the UK. These focused on assessing the in-field performance (uniformity) and economic cost-benefit of overhead and micro-irrigation systems used on various crop types under different soil and agroclimate conditions. The general approach was to combine field data with information from crop and irrigation computer modelling. Data relating to equipment costs, crop productivity (inputs, yields and prices) and water use (metered records) were then integrated and used to assess the relative value of irrigated production (expressed as £ per m^3) under each irrigation system.

The study generated useful insight into the practicality of on-farm water audits, and should help guide future discussions on irrigation efficiency. This report's findings also have implications for abstraction licence renewal and time-limiting. However, in order to provide clear guidance to abstractors on how the tests for licence renewal should be applied, it is recommended that the Environment Agency consider carrying out further work on water auditing, particularly within the proposed CAMS risk-based framework.

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1 Introduction

Under the 1991 Water Resources Act, as amended by the Water Act 2003, all abstractions for spray and trickle irrigation above the *de minimis* level (currently 20 m^3 per day) require a licence from the Environment Agency. All licences issued since the Water Act (2003) came into force, and many issued previously, are time-limited. Government policy is to encourage other licence holders to move to time-limited status. Normally, these licences must be renewed at 12-year intervals, although some licences may have shorter or longer durations, and there will be transitional arrangements to bring all licences in each catchment to a common end date (CED). Time-limited licences are subject to a presumption of renewal provided that three tests are satisfied at the time of renewal. The Environment Agency considers these tests to be an 'environmental MOT' for licensed abstraction. The three tests for renewal are:

Test 1: **Continued environmental sustainability:** To assess whether the abstraction can be sustained without significant impact on water resources, other water users or the environment.

Test 2: **Continued justification of need:** To assess whether the abstraction is still required, based on the 'reasonable' requirements of the licence holder, and to check that the maximum levels of abstraction are still reasonable.

Test 3: **Efficient use of water:** To assess whether the right amount of water is being used in the right place at the right time.

Test 1 is largely undertaken by the Environment Agency through their Catchment Abstraction Management Strategies (CAMS) and other water regulation processes, although licence applicants may be required to provide data and/or other information. Test 2 requires the licence holder to submit a structured case for renewal, addressing a range of factors that impact on the requirement for irrigation (justifying 'reasonable' need). The methods already in place for justifying reasonable need for a new abstraction licence provide the basis for judging whether the need is likely to be reasonable, though the use the applicant has made of the licence in previous years can provide additional supporting information. Test 3 requires the licence holder to demonstrate that 'efficient use' will be made of the water in future, but is largely based on evidence of use of water in previous years. However, the definition of 'efficiency' of supplemental irrigation has been the subject of widespread debate between academics, the regulator, industry and abstractors in the UK (Knox, 2004).

In this context, water audits have a role to play in meeting Tests 2 and 3, and the data collected may also be helpful for Test 1. Using water audits to assess efficiency is also the subject of an Environment Agency consultation on the time-limiting of licences (Environment Agency, 2005). Thus, to improve our understanding of efficiency, and particularly the differences between overhead (spray) and micro (trickle) irrigation, a study (audit) of water use under contrasting irrigation systems was carried out here.

The project began in July 2004 and was completed in November 2006. This report provides a summary of the research aims, approaches and key outcomes of the study. The implications of the research and recommendations for further work are provided.

2 Methodology

2.1 Research aim and approaches

The overall aim was to evaluate the role of water auditing as a tool for assessing the efficiency of water use under both overhead (spray) and micro (trickle) irrigation. The study combined data from desk-based research, computer modelling and extensive in-field water use monitoring and evaluation.

An audit of water use under each system was conducted 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 system management (capital and running costs) to assess the relative efficiency of irrigation water use expressed in terms of the marginal value of water (£ per m^3). Equipment performance and operational issues were also investigated, to assess the management implications of switching irrigation technology. The study focused on a selection of commercial farms predominantly involved in the production of high value maincrop potatoes, the most important irrigated crop in the UK.

The study involved three main components:

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

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

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) crop.

A brief description of each stage in the methodology is given below.

2.2 Comparing irrigation water use

A water audit is effectively a short-term operational tool that can be used to monitor and compare the pattern of water use between different irrigation systems. The data derived from a water audit can be combined with other useful information relating to crop production, to assess the relative efficiency (value) of water use.

During 2005, three detailed on-farm irrigation water audits were carried out. The purpose of these were to record the date of each irrigation event, the scheduled depth (mm) of water applied and the volume (m^3) of water diverted (pumped) into each field during the course of the irrigation season. Water meters were installed at the hydrant in each field and a reading taken at the start and end of each irrigation event. The irrigation manager was provided with a water audit proforma to record the necessary information. A Sentek EnviroSCAN™ was used to continually monitor the changes in profile soil moisture content within the field sites during the season. This data was used to assess the relative impact of the timing and frequency of each irrigation event on maintaining the soil moisture within defined limits. For potatoes, it is important to maintain a very low soil water deficit (typically below 15 mm) during tuber initiation, to avoid scab (*Steptomyces scabies*) which can severely reduce crop quality (skin finish). Beyond the scab control period, the critical allowable soil water deficit can be increased (typically 25 to 35 mm).

The water audit data were then combined with information relating to crop production (yield, prices, labour and management costs) and irrigation (capital and running costs) to assess the relative efficiency of irrigation water use expressed in terms of the marginal value of water (£ per m^3) for each irrigation system. Equipment performance and operational issues were also investigated, to assess the management implications of switching irrigation technology. A local weather station was used to record daily rainfall and the parameters required to derive reference evapotranspiration (ETo), based on the internationally recommended FAO Penman-Monteith approach (Smith, 2000).

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 (£ per m^3). The irrigation cost-benefit analysis was therefore based on a method developed by Morris *et al.* (1997), but updated for current prices. A comparison of irrigation benefits less costs (expressed as £ per m^3 of irrigation water applied) provides the farmer and the 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 (such as potatoes, strawberries) and sectors (such as horticulture versus sports turf irrigation). In order to estimate these marginal values of water for each crop grown under each irrigation system, information on a range of parameters were collected (Table 2.1).

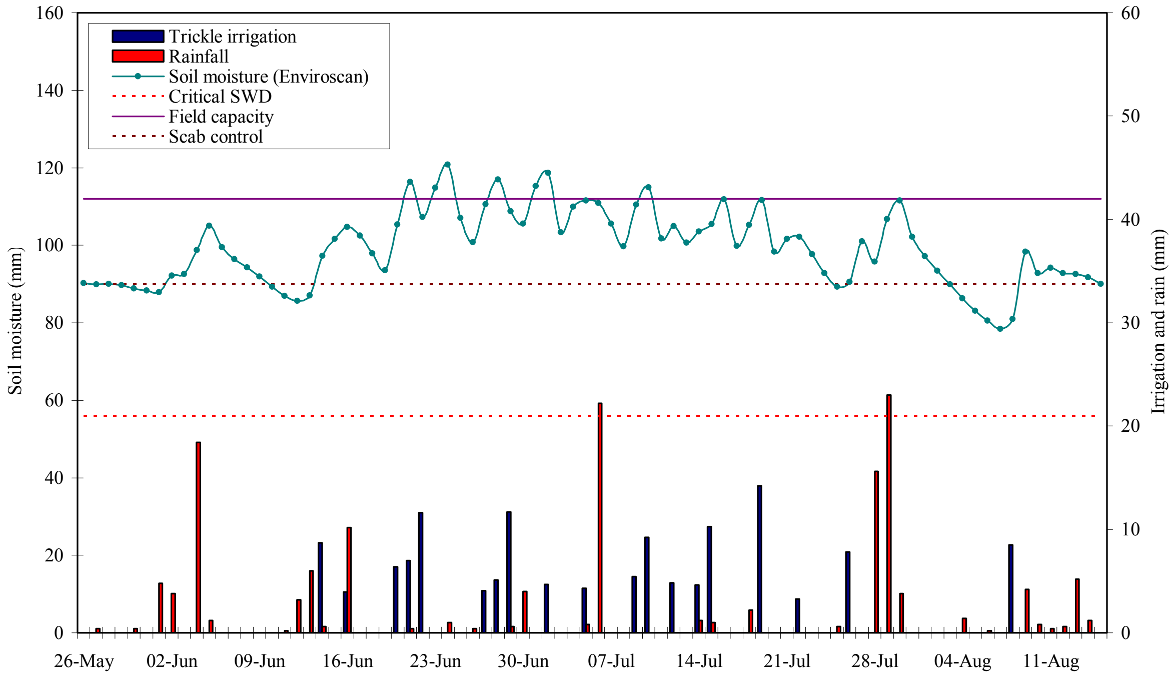
Table 2.1: Summary of the components of crop production used to assess the performance of each irrigation system

Indicator	Description and units of measurement
Crop husbandry and production	Cropped areas (ha). Crop configuration (planting depth, ridge spacing, plant spacing). Crop calendar (planting, establishment and harvest dates). Other costs of production (such as 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 (labour, fuel, water and repairs). Water sources, costs and volumes abstracted (m^3).

The water audit (metered) data were combined with information from the Sentek EnviroSCAN™ and with rainfall data from the automatic weather station to compare water inputs (irrigation and rainfall) and their consequent impacts on soil moisture under the trickle (Figure 2.1) and sprinkler (Figure 2.2) irrigation systems. Indicative values for field capacity and the trigger soil water deficits to avoid crop stress (critical) and prevent scab infection (*Steptomyces scabies*) on the potato crop were identified.

The data presented in Figure 2.1 clearly shows how the trickle irrigation system was used to apply small, frequent applications to maintain the soil moisture content between field capacity and the trigger deficit for scab control. However, by maintaining a very small deficit within the profile, occasional rainfall events resulted in some drainage (for example, in June) due to the soil moisture content exceeding field capacity.

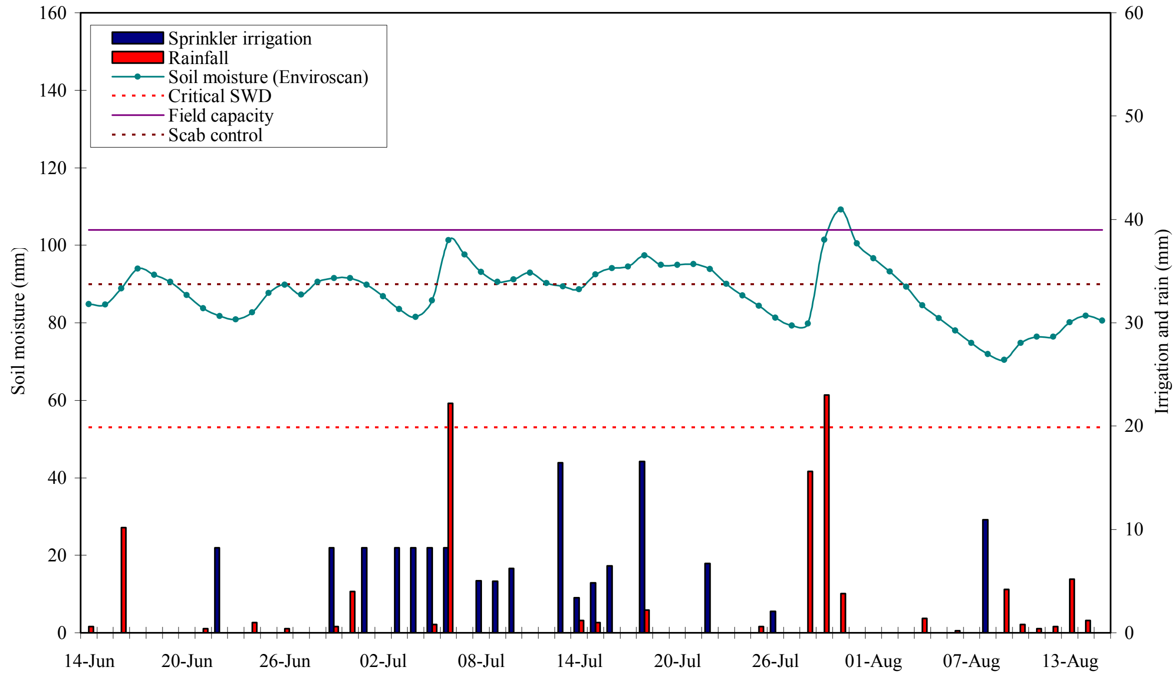
Figure 2.1: Summary of recorded trickle irrigation applications and monitored changes in soil moisture on potatoes in 2005. The critical soil moisture deficit (SWD), field capacity and critical deficit for scab control are also shown.



In contrast, the fluctuations in soil moisture observed under the sprinkler irrigation system (Figure 2.2) are very different, despite a similar number of irrigation events (Table 2.2). Whilst the number of sprinkler irrigation applications were not dissimilar to that of the trickle, the soil moisture status under the sprinkler system was maintained at a lower level, allowing for more effective use of rainfall, thus avoiding over-irrigation (apart from one event in late July). However, maintaining the soil moisture slightly below the critical allowable deficit for scab control during key periods in the irrigation season did not, fortunately, appear to have impacted on the final crop quality at harvest for this variety of potatoes (Table 2.3).

A summary of the total number of irrigation events, and a comparison of total scheduled applications with actual applications (based on metered water use), for each irrigation system, is shown in Table 2.2.

Figure 2.2: Summary of recorded sprinkler irrigation applications and monitored changes in soil moisture on potatoes in 2005. The critical soil moisture deficit (SWD), field capacity and critical deficit for scab control are also shown.



The data in Table 2.2 show that a similar number of irrigation applications were made on both the trickle and sprinkler systems (approximately 20). The average application depth in both systems was six mm. In contrast, with the hose-reel rain gun system only three applications were made, with the average depth of water applied equivalent to 17 mm.

Table 2.2: Recorded total number of irrigation events, and comparison of scheduled irrigations with metered water use, for each irrigation system used on potatoes in 2005

Parameter	Irrigation system		
	Trickle	Sprinkler	Rain gun
Number of irrigations	20	19	3
Total amount scheduled (mm)	123	121	50
Total metered water use (mm)	144	153	75
Total volume (m^3/ha)	1,436	1,531	500

The water audits also show significant differences between the total amount of water scheduled and total amount applied (metered). For example, the trickle irrigation system applied a total of 144 mm water compared to a total scheduled depth of 123 mm. This represents a 17 per cent difference between the amount of water scheduled by the farmer and the amount diverted (pumped) into the field. Similarly, for the sprinkler irrigation system, 26 per cent more water was pumped into the field than planned (scheduled). These differences may represent efficiency losses (for example, through conveyance) within each system and scheduling errors, but may also be due in part to meter inaccuracies.

These differences in scheduling also had an impact on the seasonal volume of water applied under each system. For example, the audit data shows that the total volume of irrigation water applied with the trickle and sprinkler irrigation systems was quite similar, equivalent to 1,436 m^3

ha^{-1} and 1,531 m^3 ha^{-1} respectively. In contrast, on the hose-reel rain gun system, only 500 m^3 ha^{-1} were applied, representing 65 per cent less applied water (by volume) than under the trickle and sprinkler systems. This clearly demonstrates that the water savings (reduction in water use) often assumed to be made with modern semi-permanent systems, such as trickle and sprinklers, are not always achieved in practice. Unfortunately in this study, differences in crop cultivars and hence farmer goals and water use made it difficult to make an objective comparison between each system in terms of irrigation water use efficiency.

Finally, differences between the total amounts of water applied under each system have implications for on-farm water resource management and irrigation costs and benefits. An assessment of the estimated marginal value (benefits) of irrigation water (comparing irrigated to an equivalent rain-fed crop) under each system is given in Table 2.3.

Table 2.3: Summary of estimated irrigation costs, benefits and marginal value of water (£/m^3) associated with each system, used on potatoes in 2005

Parameter	**Irrigation system**		
	Trickle	Sprinkler	Rain-gun
Crop type	Potatoes	Potatoes	Potatoes
Variety	King Edward	Maris Piper	Estima
Cropped area (ha)	10.6	25.2	33
Indicative crop quality at harvest	Very good	Very good	Good
Irrigated crop yield (t/ha)	64	57	59
Un-irrigated crop yield (t/ha)	40	37	45
Difference due to irrigation (t/ha)	24	20	14
Irrigated crop price (£/t)	140	140	90
Un-irrigated crop price (£/t)	98	98	63
Irrigated gross revenue (£/ha)	8,918	7,924	5,310
Un-irrigated gross revenue (£/ha)	3,920	3,626	2,835
Difference due to irrigation (£/ha)	4,998	4,298	2,475
Irrigation costs (£/m^3)	0.51	0.49	0.73
Irrigation benefit (£/m^3)	2.31	1.79	2.43
Net irrigation benefit (£ per m^3)	1.80	1.30	1.70

The net irrigation benefits for potatoes grown at this study site in 2005 were estimated to vary between £1.30 and £1.70 per m^3, depending on the crop variety and irrigation system. These values do not represent profit, but rather the potential loss in value if irrigation ceased during the season (for example, through abstraction restriction or bans).

Irrigation costs for the trickle and sprinkler systems are very similar, at approximately £0.50 per m^3 of irrigation water usefully applied. Costs for the gun are marginally higher, primarily as a consequence of only a small volume of irrigation water being applied through the rain-gun in that year (500 m^3 ha^{-1}) compared to the trickle and sprinkler systems, where around 1, 500 m^3 ha^{-1} were applied.

The net (marginal) value varies depending on the irrigation benefits attributed to a particular crop type and/or variety (recognising that different potato varieties have different responses to irrigation in terms of yield and quality) and costs (reflecting the different capital and variable costs of the systems used). The values from this study compare closely with those reported in Morris *et al.* (1997) and Weatherhead *et al.* (1997), who estimated the marginal value of water for maincrop potatoes grown in Eastern England to be £1.56 per m^3. In this study, because different irrigation systems were used to irrigate different potato crop cultivars, a direct comparison between the marginal values of water should not be made. The derived marginal values of water also relate only to one particular year. However, the exercise shows the typical values that might be expected, based on data from a water audit that includes an analysis of the actual costs and benefits of irrigation in that year. The estimated marginal values of water would also vary depending on the weather in each year (volumes of irrigation water applied), as well as annual fluctuations in crop yield and market prices. It would be sensible to conduct similar analyses over a series of wet and dry years, to assess the impact of climatic variability on the costs and benefits of irrigation.

2.3 Comparing irrigation performance

In addition to monitoring water applications, it is also important to consider how uniformly the water is being applied to the crop. Non-uniform application inevitably leads to over or under-irrigation in some parts of the field, leading to inadequate or inefficient irrigation. This can impact on crop productivity (resulting in uneven yield and quality) and on the environment, through the leaching of nitrates and other chemicals via deep drainage.

In this study, a number of in-field irrigation evaluations were conducted during 2005. Given the specific focus on new authorisations for trickle, evaluations aimed to assess the in-field performance (uniformity) of trickle irrigation systems on various crop types under different soil and agroclimatic conditions. The findings of a number of evaluations of overhead (sprinkler and hose-reel rain gun) systems are also provided for comparison. This helps to put in context the observed variability under trickle irrigation with that typically observed under overhead irrigation. A summary of findings is presented below.

2.3.1 Trickle irrigation

For trickle irrigation, hydraulic evaluations were undertaken based on a method defined by the American Society of Agricultural Engineers (ASAE, 1999) to evaluate micro-irrigation systems. These typically 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 (Figure 2.3), an evaluation of the uniformity along a complete lateral and measurement of pressure variations within the block at the header, mid-point and tail-end (Figure 2.4).

For trickle irrigation, the ASAE (1999) method recommends that a maximum of 36 individual emitters (randomly located) are tested. Therefore, in each field evaluation 12 laterals were randomly identified. Along each lateral, measurements of emitter discharge were collected at three points, corresponding approximately to the top, mid-point and end of each lateral (36 emitters in all). For each measurement, a small area in the bed or ridge was excavated, and a catch-can placed under the trickle emitter (Figure 2.3). The irrigation system was then pressurised and the discharge from each of the 36 emitters measured over a period of one hour. The volumes collected from each emitter were recorded and statistically analysed.

Figure 2.3: Measuring trickle irrigation emitter discharge on (a) potatoes and (b) onions

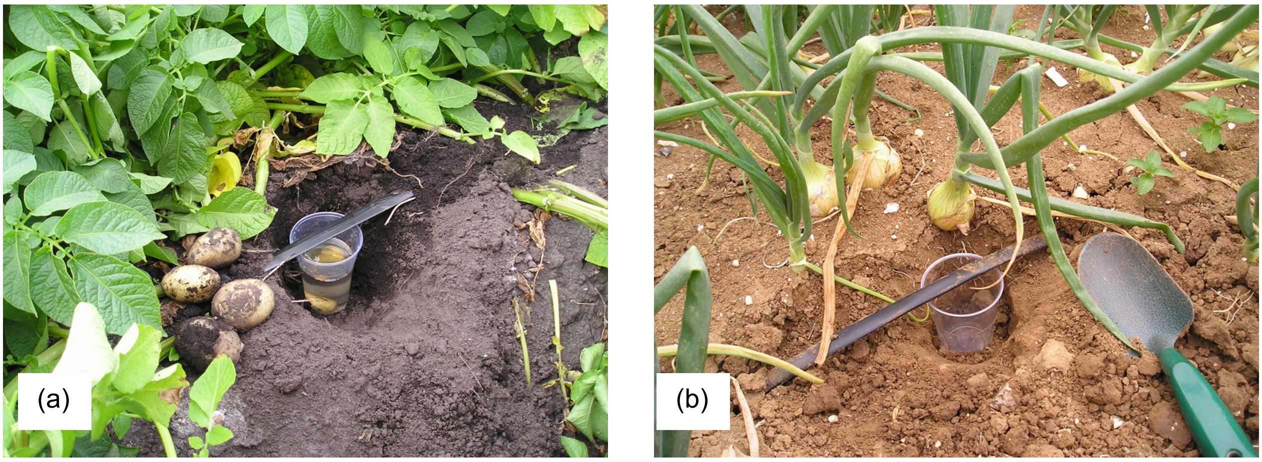
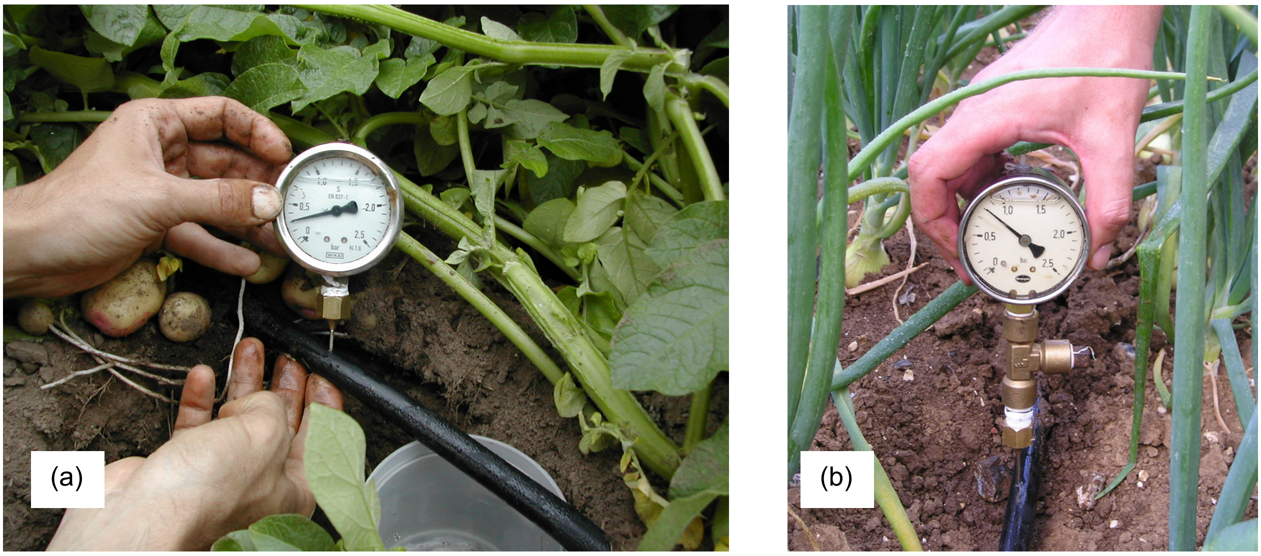


Figure 2.4: Measuring trickle irrigation water pressure on (a) potatoes and (b) onions



Various performance indicators were used to assess the performance and irrigation uniformity, including the internationally recognised Christiansen (1942) coefficient of uniformity (CU) and distribution uniformity (DU). The overall performance of each trickle irrigation system was also assessed according to an ASAE classification (1999). A summary of the performance indicators used and their definition are given in Table 2.4. The key findings from four trickle irrigation field evaluations are summarised in Table 2.5.

Table 2.4: Performance indicators and their definition, used to assess the efficiency of irrigation

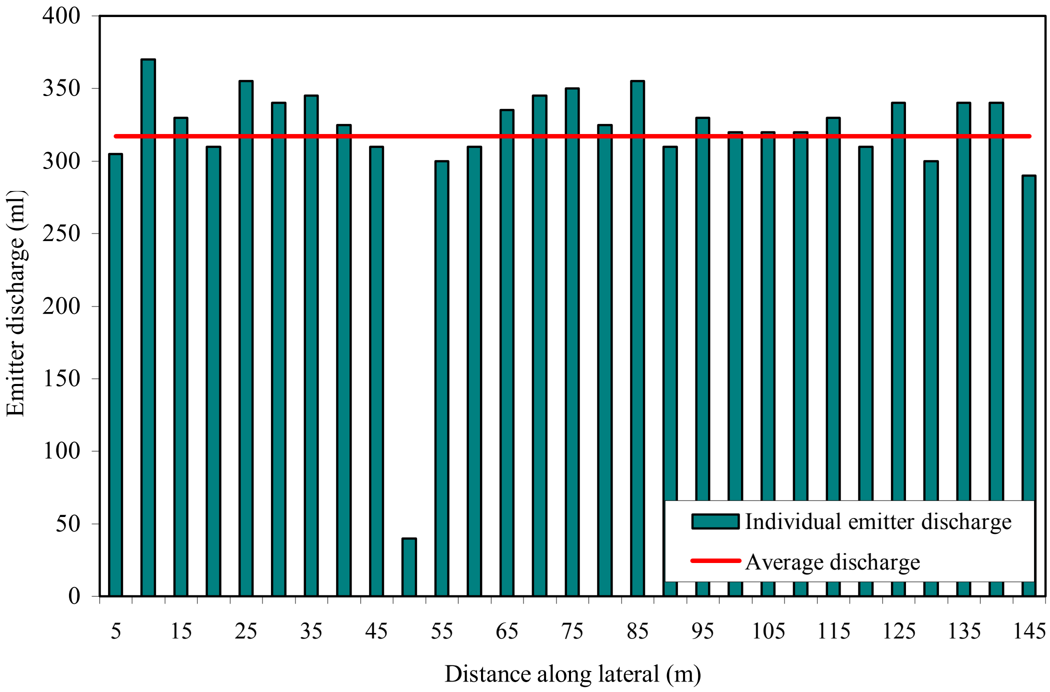
Abbreviation	Performance indicator	Definition
cv	Coefficient of variation	Defined as the ratio between the standard deviation of the sample and the average of the sample.
CU	Christiansen coefficient of uniformity (1942)	$CU = 100\%(1 - \sum x / mn)$ Where $\sum x$ is the sum of the absolute deviations from the mean (mm or ml) of all the observations, m is the mean application depth measured (mm or ml), and n is the number of observations (catch-cans).
DU	Distribution uniformity	Defined as the ratio between the average depth of water applied in the lowest quartile and the overall average depth of water applied.

Table 2.5: Summary of derived performance indicators to assess the efficiency of trickle irrigation, based on selected case studies in 2005

Performance indicator				Case studies
Site	1	2	3	4
Crop type	Potatoes	Potatoes	Onions	Hops
Water source	Borehole	Stream	Borehole	Borehole
Product type	Disposable (1 year)	Disposable (1 year)	Re-usable (3 year)	Re-usable (10 year)
Age of system	New	New	New	c15 years
Field installation	Shallow buried	Shallow buried	Shallow buried	Surface laid
Coefficient of variation (*cv* %)	56	36	52	56
Distribution uniformity (DU %)	26	52	14	12
Christiansen coefficient uniformity (CU %)	54	75	62	40
ASAE classification	Unacceptable	Unacceptable	Unacceptable	Unacceptable

To complement the field evaluations, the uniformity along single lateral lengths within each trickle irrigation system was also completed. In each case, catch-cans were laid along a randomly selected lateral on a regular spacing (usually five or 10 metres). As before, the discharge from each emitter was measured over a period of one hour. To illustrate the typical output from this procedure, the observed variations in discharge from two laterals from separate sites in 2005 are shown in Figure 2.5. A summary of derived performance indicators arising from the four trickle irrigation lateral evaluations are given in Table 2.5.

Figure 2.5: Examples of measured discharge (ml) along single trickle irrigation laterals



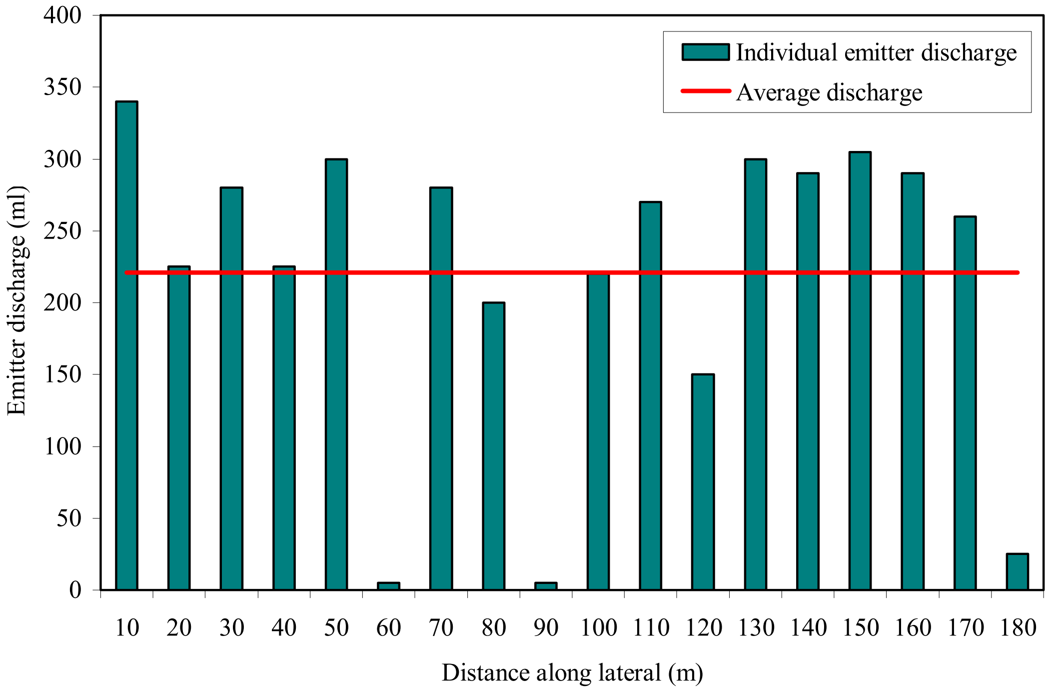


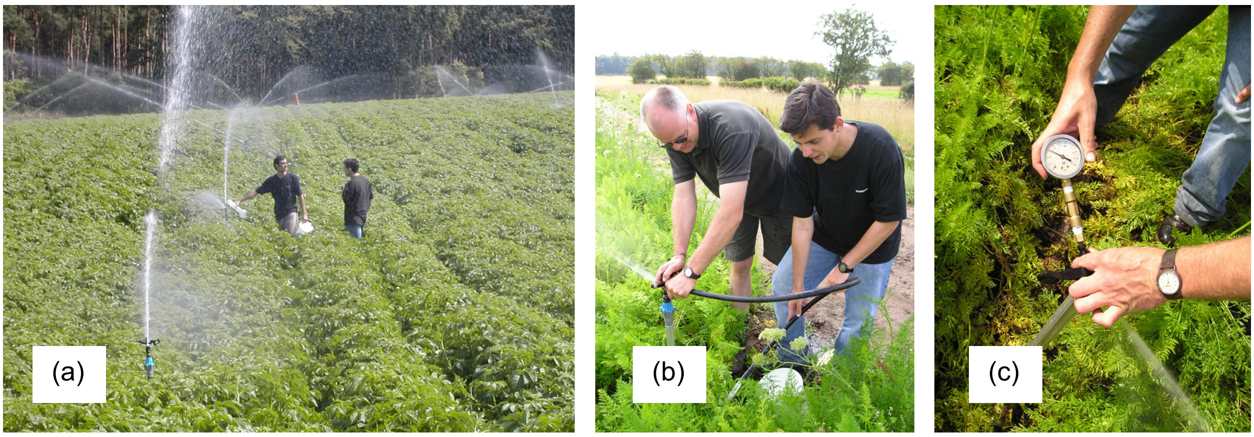
Table 2.6: Summary of derived performance indicators for single trickle irrigation laterals, based on selected case studies in 2005

Performance indicator				Case studies
Site	1	2	3	4
Coefficient of variation (*cv* %)	52	18	47	50
Distribution uniformity (DU %)	50	84	35	27
Christiansen coefficient uniformity (CU %)	56	92	82	50
ASAE classification	Unacceptable	Very good	Poor	Unacceptable

2.3.2 Overhead irrigation

Similarly, an international (ASAE) standard was adopted for evaluating the overhead irrigation systems. In this study, results from a field evaluation of a sprinkler irrigation system (Figure 2.6) together with data collected by Lacey (2005) relating to the field evaluation of a hose-reel rain gun system on carrots (Figure 2.7) are presented. As before, two key performance indicators were used to assess irrigation uniformity, namely the Christiansen (1941) coefficient of uniformity (CU) and the distribution uniformity (DU).

Figure 2.6: Measuring (a) uniformity, (b) discharge and (c) water pressure under sprinkler irrigation in 2005



Hydraulic evaluation of the sprinkler system was based on assessment of the irrigation uniformity within a selected area, using catch-cans to collect the discharge from four overlapping sprinklers. A suitable area between four sprinklers was selected and a grid of catch-cans laid on a 3 m x 3 m grid spacing. In all, a grid of 80 catch-cans was laid out. The irrigation system was then pressurised and operated for one hour. The volume of water collected from each catch-can was measured and the results statistically analysed.

For the rain gun, a regularly spaced transect of catch-cans was placed across the field perpendicular to the direction of each gun pull (Figure 2.7). The volume of water collected from each catch-can (and local wind speed and direction) was measured.

Figure 2.7: Field evaluation of uniformity under hose-reel rain gun irrigation (Lacey, 2005)

To illustrate the typical output from an evaluation of a hose-reel rain gun, the observed variations in irrigation application across a field for two separate irrigation events in 2005 are shown in Figure 2.8. The actual variations in irrigation application from the scheduled (design) depth across the field can be seen, although the overall uniformity for both transects is still good (CU 83 and 70 per cent). A summary of performance indicators for the sprinkler and rain gun system evaluations are given in Table 2.7 and 2.8 respectively.

Table 2.7: Summary of derived performance indicators to assess the uniformity of sprinkler irrigation used on carrots, based on a selected case study in 2005

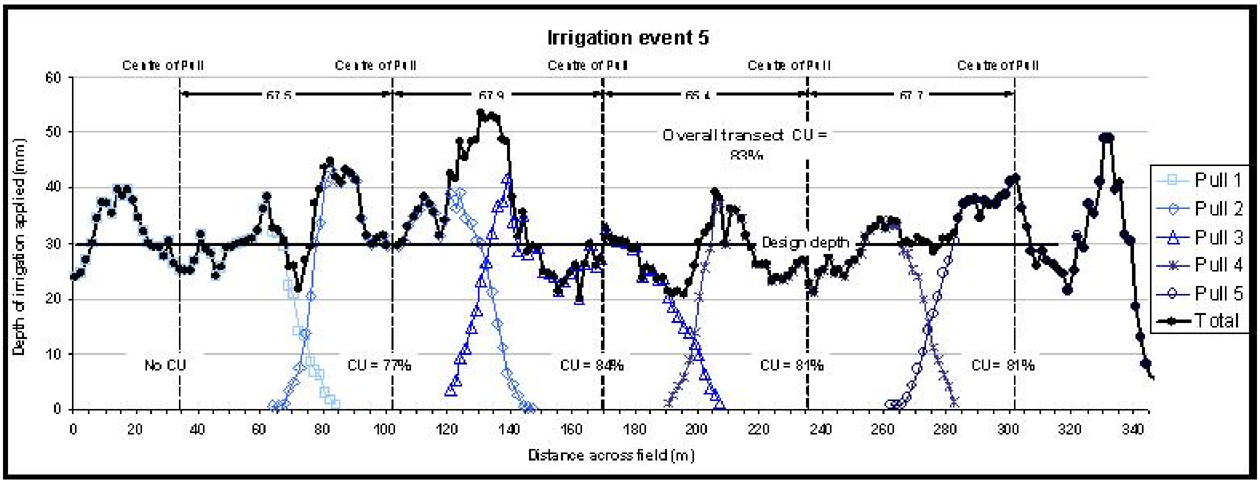
Performance indicator	
Age of system	New
Coefficient of variation (c*v* %)	30
Distribution uniformity (DU %)	67
Christiansen coefficient of uniformity (CU %)	77

Table 2.8: Summary of derived performance indicators to assess the uniformity of rain gun irrigation used on carrots. Based on the evaluation of eight transects by Lacey (2005).

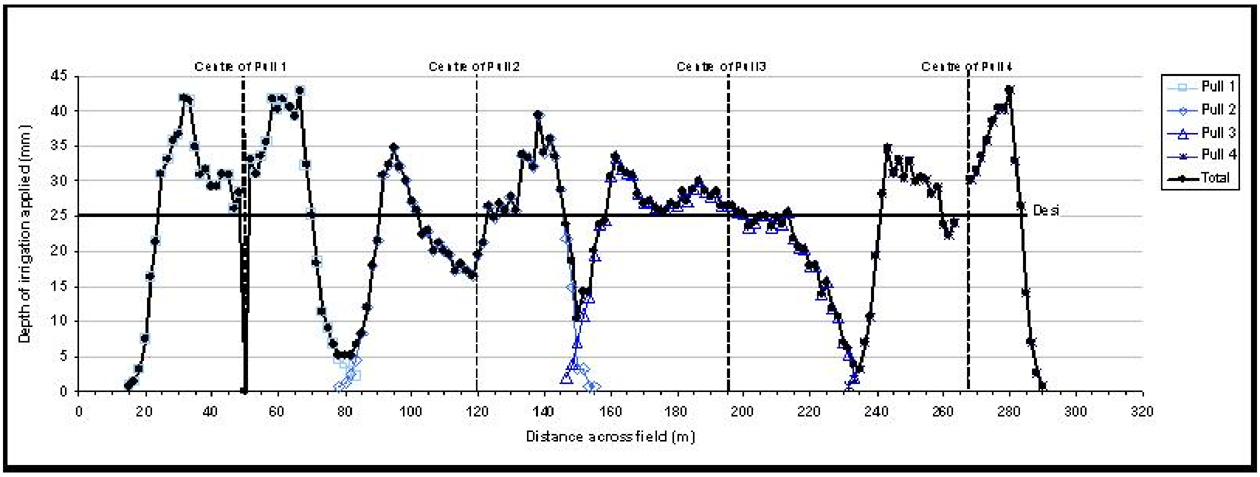
Performance indicator	Transect across field								
	1	2	3	4	5	6	7	8	Mean
C*v (%)*	37	39	35	22	23	31	39	23	31
DU (%)	55	45	58	77	73	67	57	76	64
CU (%)	72	69	76	82	82	77	72	83	77

Figure 2.8: Sample outputs from an evaluation of a hose-reel rain gun system operating on carrots under a typical (a) low and (b) high wind speed condition (Lacey, 2005)

(a) Low wind speed conditions. Overall uniformity (CU 83 per cent).



(a) High wind speed conditions. Overall uniformity (CU 69 per cent)



Field evaluations to assess the performance (uniformity) of each type of irrigation system (trickle, sprinklers, rain gun) revealed some important points, particularly the difficulty of comparing the relative performance of individual systems. A brief summary of the key findings relating to each system is given below.

The field data showed that the uniformity of trickle can be highly variable. The (field level) uniformity of the new trickle irrigation systems studied ranged from 54 to 75 per cent, with 40 per cent measured under a relatively old system (around 15 years). For trickle irrigation, a reference value of 15 per cent for the coefficient of variation (*cv*) is recommended by Keller and Bliesner (1990); however, for all the trickle systems investigated here, calculated cv values ranged from 36 to 56 per cent, even for new installations. However, despite the generally low overall level of uniformity observed at field level, assessment at single laterals in each trickle system confirmed that uniformity can be very high. Uniformities for single laterals ranged from 56 to 92 per cent, with 50 per cent for the older system. Calculated cv values ranged from 18 to 52 per cent.

Clearly, maintaining a high level of uniformity under trickle depends on a number of factors, of which a high degree of in-field management is probably the most important. Correct installation, good filtration and regular flushing to avoid emitter blockage are also important. Failure to maintain any of these operational aspects as part of the system's management inevitably results in a rapid decline in trickle performance, with direct impacts on water application uniformity. The findings of this study on in-field performance of trickle irrigation are consistent with other studies reported internationally.

Evaluation of the sprinkler irrigation system showed that the uniformity of water application could be very high, with a measured CU of 77 per cent. This was considered “very good” compared to a reference value of 80 per cent considered to be “good” as recommended by Keller and Bliesner (1990). Similarly, the distribution uniformity (DU) of 67 per cent was reasonable compared to the reference value defined by Keller and Bliesner (1990). However, this result was based on only a single test; repeat evaluations across a range of sprinkler systems under variable wind conditions should be undertaken to provide a more representative assessment of performance. Notwithstanding this, the field data showed that these new types of sprinkler, which are not currently widespread in the UK, can potentially provide a high level of irrigation uniformity, particularly when correctly designed and where sprinkler spacings are appropriate for the crop and local conditions (topography, climate, soils). High wind speeds are likely to affect uniformity, because the finer sprays produced by these systems are more susceptible to wind drift.

An extensive evaluation of irrigation uniformity under a hose-reel rain gun system by Lacey (2005) found that the average uniformity (CU) of a hose-reel working at near optimal pressure was 77 per cent, ranging from 69 to 83 per cent depending on ambient wind conditions. These values demonstrate that hose-reel rain guns can provide a very high level of uniformity, but only when the equipment is correctly set (including lane spacing, pressure, trajectory, sector angle) and where wind conditions are not excessive. Failure to operate these systems at the correct operating pressure (undoubtedly the most common problem), combined with irrigating under windy conditions, can dramatically reduce their performance and uniformity. The range of equipment and management factors that influence the irrigation efficiency of rain guns is currently the focus of research by Lacey (2006). This research will, in due course, provide significant new information to help assess the efficiency of overhead irrigation.

3 Discussion

3.1 Irrigation efficiency

In order to compare irrigation systems, a range of indicators to assess their performance has been widely used internationally. These have generally been termed *efficiencies,* for intuitive appeal (Burt *et al*., 1997). Unfortunately, in many cases the term *irrigation efficiency* has been used, 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). 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 most often when adopted as synonymous with irrigation performance (Pereira *et al*., 2002).

Whilst there is a significant volume of published research on the efficiency of individual irrigation systems for a wide range of crops, there is very little published information comparing trickle with rain gun irrigation on crops under UK weather conditions (low evapotranspiration and significant rainfall). Most studies relate to the USA and for crops not grown in the UK (such as cotton, sorghum). Many papers have compared 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 promoted, often by government as well as the trickle industry. Compared to 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. However, our initial findings confirm that whilst trickle irrigation is *potentially* more efficient than overhead irrigation, in practice its *actual* efficiency (defined in terms of application uniformity) is lower than overhead irrigation. The levels of uniformity measured under trickle therefore depend as much on the level of on-farm water management being practised as on the crop being grown.

In Australia, a number of farm trials have compared trickle against other irrigation methods 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 studies have reported direct water savings attributable to trickle. In one comparative study of trickle on tomatoes, it was reported that the skills of the grower 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 increases 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, and would encourage water use to move to higher value crops. 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 bring improvements in efficiency and water savings.

3.2 Water audits and abstraction licensing

As discussed previously, there is widespread confusion regarding the many performance indicators that could be used to assess efficiency, Most refer only to a particular stage of the irrigation process (such as application efficiency), or are too general to be useful. A wider definition has been assumed across most other water uses: using the lowest reasonable amount of water to achieve the desired goal. The Environment Agency has suggested the following definition: "*Efficient use of water means using the right amount of water in the right place at the right time*" (Environment Agency, 2005). It is against this definition that water audits should be targeted.

This definition is narrower than "best use", which implies re-allocating water from low value uses to high value uses. It is assumed that this will occur under economic forces either within each business or by trading between abstractors. Each licence is assessed individually on whether the intended purpose is reasonable (Test 2), and then on whether the water is being used efficiently for that purpose (Test 3). However, it would be reasonable to accept that the definition of "the right amount" should reflect the marginal benefit obtained from the irrigation.

The work described in the previous chapter has demonstrated the difficulty of defining a simple audit procedure to determine a single value demonstrating efficiency. Any procedure must cope with different crops, irrigated for different objectives, with different equipment, under different circumstances. However, audits are invaluable in helping irrigation staff identify areas of inefficiency, and the results could form the basis of a report to the Environment Agency showing that the applicant is aiming to attain efficiency.

The audit could first collect data needed for Tests 2 and 3, including (i) crop type/s and area; (ii) contractual requirements/irrigation objectives; (iii) soil type/s; (iv) preceding weather; and (v) records of previous irrigation water use.

The audit could then address factors such as (i) water abstraction and storage efficiency; (ii) distribution efficiency – minimising leakage and wastage from filters; (iii) type and use of equipment appropriate for the crop and conditions; and (iv) irrigation scheduling being undertaken and the results being used appropriately.

It is suggested that audit procedures be kept within the competence of a typical applicant as far as possible; only for high and very high risk situations should more complex analysis be required. This will help keep audit costs reasonable.

For large irrigators, much of this data is already being collected, through for example crop assurance schemes (grower protocols). An important consideration in designing an efficient audit should be to avoid duplication of effort, ensuring data can be used for both the assurance schemes and the audit, rather than specifying slightly different datasets.

Finally, some concerns have been expressed about confidence in the outputs, and importantly "who audits the auditor". However, restricting audits to independent auditors would be very expensive and possibly counterproductive; many of the benefits of water audits are obtained when undertaken by irrigation staff themselves. Here, a comparison may be appropriate with the auditing of Good Agricultural and Environmental Conditions (GAEC) under the single farm payment scheme, and to the auditing of crop assurance schemes, both mainly undertaken by farmers themselves.

4 Conclusions

A water auditing method was developed and tested on commercial farms using potatoes as a representative field-scale crop. The impact of different irrigation strategies on soil moisture was monitored in three irrigation systems (trickle, sprinkler and rain gun). Supplementary data relating to crop productivity was combined with information on the annualised costs of irrigation, to estimate the marginal value of irrigation (over and above rain-fed production) for maincrop potatoes. This provided useful information for farmer decision-making with respect to identifying operational and management issues to improve irrigation system performance, water productivity and for investing in new technology or infrastructure.

The study provided new data on the actual performance of overhead and micro systems. This will help to inform the water regulatory authority and the industry on how individual farmers might use water auditing as an operational tool to demonstrate efficient use of water as part of their abstraction licence (permit) renewal process.

The research will help improve our understanding of irrigation system performance. Clearly, if meaningful comparisons between different irrigation systems (such as trickle versus sprinkler) are be made, it is essential that those who undertake such work and the stakeholders for whom the results will be important (such as 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 confirmed the practical difficulties of assessing application efficiency, and risks in using it as an indicator of best use. If efficiency assessments are required legally for abstraction licensing control, they should be more closely related to marginal irrigation water use efficiency and/or economic benefits (value) of the water being used. However, these definitions can themselves become subjective in defining costs and benefits, and can omit non-economic issues, such as rural development and fairness.

The Environment Agency has a duty to promote the efficient use of water by abstractors. It also aims to promote sustainability, including rural businesses and employment. The best way to achieve both goals is to work with the irrigation industry, helping irrigators to use their water efficiently, and with others, for example ensuring that the requirements of assurance schemes match those of the water audits. The regulatory “stick” of non-renewal remains the ultimate sanction, but should not normally be relevant.

A notable output of the trial audits was confirmation that irrigation costs can be £0.50 per m^3 and higher. It is often suggested that “irrigators waste water because it is too cheap”, referring to abstraction charges only. The value of water to irrigators can be very much higher still. Clearly at these real costs and values, irrigators themselves have a financial incentive to be efficient. Working together will benefit both parties.

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