Final report

FV 248

Assuring the microbiological quality of water used to irrigate salad crops: an assessment of the options available

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Table of Contents

GROWER SUMMARY

Headline

Although no evidence to link the irrigation of salads to disease outbreaks in the UK has been found, the industry should be seen to be taking the issue of irrigation water quality seriously. The strategy should be to take proactive measures to pre-empt the adoption of unnecessarily cautious standards within grower protocols.

Background and expected deliverables

Concerns have been expressed by some of the major supermarkets that salad vegetables may become contaminated with pathogens as a result of crop irrigation using poor quality water sources. As salads are likely to be eaten raw and will have received a minimal level of processing there are fears that consumers may be put at risk if irrigation water quality is not controlled. To assure product quality and to protect consumer confidence, some supermarkets may set stringent irrigation water quality standards in future grower protocols.

Product quality is of paramount importance to growers, processors, retailers and consumers alike. However, the salad growing industry advocates a proportionate, science-based approach to the development of grower protocols rather than the adoption of an excessively precautionary principle.

The aim of this project was to generate the baseline information needed by the industry to respond in a positive way to the concerns of retailers. The findings should help to inform the decisions and actions necessary to demonstrate and assure the quality of these products. The work should also support and contribute to the broader commercial objectives of the HDC regarding the efficient use of water.

Summary of the project and main conclusions

The following research tasks were undertaken in pursuit of the project's aim.

1. A review of literature relating to the microbiological quality of irrigation water and of salad crops.

2. A survey of current UK irrigated salad production to assess current usage and underlying trends.

3 An evaluation of the technological and economic feasibility of on-farm water treatment options.

4 An analysis and discussion of the data collected and development of recommendations for the industry.

The main conclusions of this work are:

- Irrigation water is one of many potential sources of contamination of salads. No published direct evidence has been found to link the irrigation of salads to disease outbreaks in the UK. However, there is a clear potential for this to occur.

- Published laboratory trials have shown that pathogens associated with poor quality irrigation water may survive on lettuce until harvest. Epidemiological investigations (not from UK) have indicated a link between disease and poor quality irrigation water. On occasions, some UK salad crops are probably irrigated with water of a lower microbiological standard than that recommended for comparable uses (e.g. reuse of wastewater for irrigation and bathing). The actual extent to which this occurs should be quantified and reviewed.

- The lack of guidance on irrigation water quality is a deterrent to proper water quality monitoring as most growers are unsure how they should respond to the data that is generated. This situation should be corrected as a matter of priority.

- It is reported that some of the multiple retailers in the UK favour a standard for irrigation water close to that which would meet the requirements for drinking water (i.e. absence or infrequent presence of *E. coli* in 100 ml water). Our review of standards suggests that this may be an unnecessarily cautious and expensive option.

- A grower faced with doubts about water quality appears to have four options:

    - Demonstrate existing water is of adequate quality
    - Treat existing water
    - Change water source
    - Relocate crop

  A site specific water resources study should be undertaken before assuming that treatment is necessary.

- Where water quality cannot be assured by management or sourcing strategies, treatment technologies may be considered. Of the many options, three technologies are likely to be suitable: ultra-violet (U/V) treatment, thermal treatment, and sand filters. U/V is considered to be attractive when taking all of the factors into account. Thermal treatment is the most rigorous and reliable. With heat recovery, such treatment could be viable in some cases. Sand filters offer the most farmer-friendly solution but these systems offer less assurance of water quality.

Financial benefits

There are no direct financial benefits to be gained by growers from this work. It may be prudent for growers to take proactive measures to improve monitoring procedures to pre-empt the adoption of unnecessarily cautious (and costly) standards in future grower protocols.

Action points for growers

There is likely to be increasing scrutiny of the microbiological quality of irrigation water. It is advised that growers review their monitoring strategy as a matter of priority. Regular sampling of water sources, at least monthly during the irrigation season, for faecal indicator bacteria would be a good start. The development of such a dataset would aid future decisions regarding the acceptability of particular sources.

SCIENCE SECTION

1 INTRODUCTION

Concerns have been expressed by some of the major supermarkets that salad vegetables may become contaminated with pathogens as a result of crop irrigation using poor quality water sources. As salads are generally eaten raw and will have received a minimal level of processing there are fears that consumers may be put at risk if irrigation water quality is not controlled. To assure product quality and to protect consumer confidence, some supermarkets are beginning to set stringent irrigation water quality standards in their grower protocols. Salad growers could be forced to switch to alternative, potentially more expensive water sources (e.g. public mains supply) or required to invest in on-farm water treatment plants to allay water quality concerns.

Product quality is of paramount importance to growers, processors, retailers and consumers alike. However, the industry advocates a proportionate, science-based approach to the development of grower protocols rather than the adoption of an excessively precautionary principle. In order to develop good irrigation practice in salad production a number of questions need to be addressed, including:

1 What defines water of an acceptable microbiological standard?

2 What proportion of growers produce salads using water of an acceptable microbiological quality?

3 What options are available to the other salad growers to access water of an acceptable microbiological quality?

4 How feasible are these options for salad growers?

The aim of this project was to generate the baseline information needed by the industry to respond in a positive way to the concerns of retailers. The findings should inform the decisions and actions necessary to demonstrate and assure the quality of these products. The work should also support and contribute to the broader commercial objectives of the HDC regarding the efficient use of water.

The following research tasks were undertaken in pursuit of this aim.

1 A review of literature relating to the microbiological quality of irrigation water and of salad crops.

2 A survey of current UK irrigated salad production to assess current usage and underlying trends.

3 An evaluation of the technological and economic feasibility of on-farm water treatment options.

4 An analysis and discussion of the data collected and development of recommendations for the industry.

2 IRRIGATION WATER AND THE MICROBIOLOGICAL QUALITY OF SALADS

In this section of the report, the literature relating to the microbiological quality of irrigation water and of salad crops is reviewed (research task 1).

2.1 Foodborne outbreaks of infectious intestinal disease associated with the consumption of salads, fruit and vegetables

In the UK, there is evidence that salads (as well as fruit and other vegetables) can act as a vehicle for the transmission of pathogens. For example, between 1992 and 1999, 60 outbreaks of foodborne infectious intestinal disease associated with the consumption of salads, fruit and vegetables were reported in England and Wales (O'Brien et al., 2000). Inappropriate food handling in commercial catering establishments was implicated in the majority of these cases as the cause of the outbreak. In 2000, a further six outbreaks were detected (O'Brien et al., 2001) of which two were *Salmonella* outbreaks linked to lettuce prepared in catering establishments. In a retrospective cohort study of sporadic campylobacter infection, Evans et al. (2003) found that eating salad vegetables was a risk factor (amongst others) for infection. The authors concluded that salad most likely gets cross-contaminated during food preparation.

Similar evidence can be found outside the UK. There have been a number of recent reports of disease outbreaks linked to the consumption of salads. For example, there have been reports of hepatitis A outbreaks in Pennsylvania, Tennessee, Georgia and North Carolina during 2003 that have been linked epidemiologically to green (salad) onions (Dato et al., 2003). In the outbreak in Pennsylvania, 555 people with hepatitis A had been identified - as of November 20th 2003 – of whom three had died. The genetic sequences of the outbreak strains were very similar and their origin has been traced to onion growers in Mexico. In the case of foodstuffs with a short shelf-life such as salads it can be difficult to secure samples for microbiological testing. This may be further compounded in cases such as hepatitis A where the virus has a long incubation period. Studies often rely on epidemiological studies to trace the vehicle of transmission. Some examples in which epidemiological evidence has linked consumption of salads to disease outbreaks are given in Table 1.

Table 1. Selected examples of disease outbreaks linked to salad consumption based on epidemiological studies.

Location of outbreak	Year	Pathogen	Reference
Sweden	2000/01	Hepatitis A	Nygard et al., (2001)
Germany	2000	*Cyclospora cayetanensis*	Doller et al., (2002)
U.S.A	1995	*Escherichia coli* O157:H7	Ackers et al., (1998)

2.2 Microbiological quality of salad vegetables at the point of sale in UK

The results of a study carried out in 2001 by the Local Authorities Co-ordinators of Regulatory Services (LACORS) and the Public Health Laboratory Service (PHLS) provides the most up to date information available on the microbiological quality of bagged, prepared salads on sale in the UK (Sagoo et al., 2003). A total of 3,852 bagged salad samples from retail outlets were examined for the presence of certain pathogenic bacteria and other bacterial indicators of quality. The study showed that the vast majority (99.3%) of samples were of "satisfactory" or "acceptable" quality according to PHLS microbiological guidelines (Gilbert et al., 2000). Six (0.2%) of the salad samples were classified as "unacceptable" and 20 (0.5%) as unsatisfactory.

Those salads classified as being "unacceptable" were found to contain *Salmonella* species and *Listeria monocytogenes* at concentrations > 10^2 cfu/g. Subsequently, 19 infections across England Wales were identified in which a *Salmonella* species with the same characteristics as one of those found in the bagged salads was detected (i.e. implicating the produce as a potential vehicle of infection).

The samples classified as being "unsatisfactory" contained *E. coli* and *Listeria* species (not *L. monocytogenes* in this case) at concentrations > 10^2 cfu/g. *E. coli* are considered to be indicators of faecal contamination. The presence of *Listeria* species (> 10^2 cfu/g) is used as an indicator of the potential presence of *L. monocytogenes*.

2.3 Sources of contamination

Salad vegetables may become contaminated with pathogenic microorganisms arising at various stages throughout the pre- and post-harvest system (Beuchat, 2002). Unfortunately, it is considered difficult to identify with certainty the source of microbial contamination of fresh produce (Food and Drug Administration et al., 1998). This point is illustrated by two outbreaks in the UK in 2000 of salmonellosis linked with the consumption of lettuce. In both cases it was concluded that it was impossible to trace the source of the implicated batches of lettuce due to the complexity of the supply chain (O'Brien et al., 2001).

There is strong evidence to suggest that the majority of outbreaks of infectious intestinal disease associated with the consumption of salads can be linked to poor hygienic practices in food preparation. For example, 55% of the disease outbreaks associated with the consumption of salads, fruit and vegetables between 1992-99 were linked to food prepared in hotels and restaurants (O'Brien et al., 2000). Cross-contamination and infected food handlers were identified as common sources of contamination. This underlines the fact that salads are often contaminated post-harvest.

However, there are indications in the literature that contamination can occur preharvest or at the processing or packaging stages. In their study of bagged salads, Sagoo et al. (2003) were able to trace the contamination of rocket with *Salmonella* Umbilo directly to the field lizard population living amongst the growing produce. This study suggests that contaminants originating from the field are able, on occasion, to survive decontamination processes and remain viable until the point of sale.

In a study of an outbreak of *E. coli* O157:H7 associated with lettuce consumption in Montana, USA, Ackers et al. (1998) suggested that the most likely sources of contamination were the manure used as a fertiliser; runoff from fields containing cattle faeces; and contaminated irrigation water. These suggestions remain unconfirmed however as the investigators found no evidence of *E. coli* O157:H7 in samples of lettuce, water, manure or cattle faeces 2-3 weeks after the outbreak.

Although poor quality irrigation water is often identified as a *potential* microbiological hazard for salad production, no literature has been found which establishes that it has been responsible for outbreaks of disease in the UK. In a recent report to the Food Standards Agency on water use in agriculture and food safety, Groves et al. (2002) concluded that whilst water used in agriculture may be a contributory factor in some food poisoning incidents, it is not possible to quantify the extent of the problem. Epidemiological and risk assessment studies outside of the UK, however, do indicate the existence of a quantifiable risk associated with the consumption of salads that have been irrigated with poor quality water (Blumenthal et al., 2000).

2.4 Microbiological quality of irrigation water

In their review of the use of water in UK agriculture, Groves et al. (2002) concluded that there is a lack of data on the microbiological quality of water used for irrigation. The authors of this review made several recommendations relating to the need for surveillance to *"determine the actual pathogen load of water used in agricultural processes"* and *"to quantify the pathogen loads of typical agricultural waters used for crop irrigation"*.

Currently water quality data can be found from a number of sources:

- The Environment Agency (EA) holds a long term national data set from the "Harmonised Monitoring Sites" (HMS) which includes some microbiological parameters. This monitoring programme was originally established to provide information on the loads of pollutants from rivers to the North Sea. The majority of the sampling points are on rivers. There are a small number of other sources sampled. The data are held on the Public Register and are available on request from the EA.
- The water companies routinely test sources of drinking water e.g. rivers and boreholes. There is no central database and information would have to be requested from individual companies.
- Site-specific information is collected in the course of site-specific investigations (for example research projects investigating die-off in on-farm reservoirs) or for routine monitoring of irrigation water sources by growers.

In spite of the absence of a complete national dataset on irrigation water quality, it is possible to make some broad generalisations. It would be reasonable to rank water sources in decreasing order of contamination as follows:

River → Reservoir / pond → Borehole → Mains

According to statistics for England for 2001 (Weatherhead and Danert, 2002), river water is the most important source of irrigation water accounting for over a half of the water abstracted for this purpose (Table 2).

Table 2. Source of irrigation water in England, by volume (%) (Weatherhead and Danert 2002).

Water source	Percentage (%)
Surface water	57.7
Ground water	36.4
Public mains	3.3
Rain collected	1.6
Re-used water	0.5
Other	0.5

In general terms, we would normally expect river water to have the highest levels of faecal contamination. This is because of the influence of sewage works effluent and other intermittent sources of faecal contamination, especially from livestock farms, associated with runoff following heavy rainfall. This statement should be qualified to recognise that there is a great deal of spatial and temporal variation and as such, not all river water should be considered to be significantly affected by faecal pollution. The EA's HMS dataset can be used to illustrate this point. Take for example the monitoring point at Crowland, Lincolnshire on the River Welland (NGR: TF229107). Crowland is relatively remote from major population centres and from areas of livestock production. 99 samples were taken between 1990-2001. The maximum faecal coliform count was 9000 /100 ml and the minimum 5 / 100 ml with a mean of 946 / 100 ml. It is apparent that the river water is of variable quality. To put these numbers into some kind of context 75 out of 99 samples (76%) would have passed the World Health Organisation guideline for the quality of treated wastewater for unrestricted use in agriculture (see section 2.5 on water quality standards).

Still surface waters such as on-farm reservoirs might also be expected to have a significant faecal pollution load. This may be due to pollution of the source water which may be, for example, river water abstracted during the winter period. Also, reservoirs and ponds are subject to faecal inputs from wildlife such as flocks of gulls. Faecal load may be reduced with time, however, due to the occurrence of natural die-off processes.

Groundwater from deep boreholes, which is the second most important irrigation water source (Table 2) would normally be expected to be of a very high microbiological standard – it would not be unexpected for a borehole to deliver water with a consistent absence of faecal indicator bacteria. This is a generalisation however and there are circumstances in which faecal pollution may find its way via relatively short flow paths to contaminate borehole supplies.

Finally, we should expect water delivered by a water company for public water supply to be of a consistently high microbiological standard. In the EU, drinking water must conform to the standards set out in Council Directive 98/83/EC (Council of European Communities, 1998) on the quality of water intended for human consumption, which sets a standard of 0 faecal coliforms / 100 ml. It should be noted however that mains water may become contaminated if stored in or conveyed through unhygienic materials (e.g. balancing tanks).

2.5 Irrigation water quality and other relevant standards

Microbiological water quality standards exist in different forms and may be broadly classified as follows.

2.5.1 Advisory standards

Advisory standards such as those produced by the World Health Organisation (WHO) for drinking water (World Health Organisation, 1993) are intended to be used as a basis for the development of national standards that will safeguard public health. The guideline values recommended are not mandatory and national governments are advised to consider their adoption in the context of local or national environmental, social, economic, and cultural conditions.

WHO published guidelines for the use of wastewater in agriculture in 1989 (World Health Organisation, 1989). Standards were set for microbiological indicators of faecal pollution (faecal coliform bacteria and nematode eggs) on the basis of the epidemiological evidence available at the time (Table 3). The guidelines took into account feasibility with respect to the treatment process needed to meet the standards; the risks associated with the crops to be irrigated, and the irrigation methods used.

Table 3. WHO (1989) guidelines for using treated wastewater in agriculture.

Category	Reuse conditions	Exposed group	Intestinal nematodes[b] (arithmetic mean no. of eggs per litre[c])	Faecal coliforms (geometric mean no. per 100ml[c])	Wastewater treatment expected to achieve the required microbiological guideline
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers, consumers, public	≤1	≤1000	A series of stabilization ponds designed to achieve the microbiological quality indicated or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[e]	Workers	≤1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in category B if exposure to workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by irrigation technology but not less than primary sedimentation

[a] In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account and the guidelines modified accordingly.

[b] *Ascaris* and *Trichuris* species and hookworms.

[c] During the irrigation period.

[d] A more stringent guideline limit (≤200 faecal coliforms/100ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.

[e] In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

These guidelines have been reviewed in the context of more recent epidemiological and quantitative risk assessment research (Blumenthal et al., 2000). This review concluded that for Category A reuse (also known as unrestricted irrigation), which includes the irrigation of salad vegetables, there is no evidence to suggest a need to revise the faecal coliform limit of ≤ 1000 faecal coliform bacteria / 100 ml. The authors did, however, support a revision of the nematode egg guideline from ≤1 to ≤0.1 egg/l. Although these guidelines were developed with the safe reuse of treated wastewater in agriculture in mind, they provide a useful reference point with which to compare the quality of other faecally contaminated irrigation water sources.

Aspects of the WHO guidelines have been used as a reference point for the development of national guidelines. For example, in 1991, the French Health Authorities issued the "health guidelines for reuse, after treatment, of wastewater for crop and green spaces irrigation" (Angelakis et al., 1999). The microbiological quality requirements are essentially the same as in the WHO guidelines. The French system also requires a formal process of risk assessment and management (Bontoux & Courtois, 1996).

2.5.2 Statutory standards

Statutory microbiological water quality standards are in place in the UK for drinking water and for bathing waters. There are currently no statutory standards for irrigation water quality in the UK. Statutory standards exist elsewhere in the world. For example The State of California is renowned for having some of the strictest standards governing the use of recycled water (State of California, 1978): *For irrigation onto the edible parts of food crops the recycled water must be a tertiary, recycled water that achieves the median concentration of total coliform bacteria that does not exceed a most probable number (MPN) of 2.2 per 100 millilitres utilising the bacteriological results of the last seven days for which analyses have been completed, and the number of total coliform bacteria does not exceed an MPN of 23 per 100 millilitres in more than one sample in any 30 day period*.

In their review of the main approaches to the establishment of guidelines and standards for the reuse of treated wastewater in agriculture, Blumenthal et al. (2000) conclude that this approach may be *"unnecessarily strict and could result in high costs per case of infectious disease averted"*. The use of epidemiological studies supplemented with model-based quantitative risk assessment is the preferred approach by these researchers for the process of standard setting.

2.5.3 Industry standards

Between advisory and statutory standards are what might be called *industry standards*. In the case of salad irrigation, growers may be required to meet obligations with respect to the assurance of food quality throughout production process. The use of irrigation water of a specified quality may be one of these obligations. Such agreements between producers and buyers may be set out in grower protocols and may be legally binding in contract law.

There is at present no nationally-agreed standard for the microbiological quality of water for the irrigation of salads although the pressure from retailers is tending towards a standard close to that which would meet the microbiological requirements for drinking water (with the absence or at least infrequent presence of *E. coli* being a key indicator of acceptable quality).

The development of the "Safe Sludge Matrix" (ADAS, 2001) highlights the influence that the major retailers have if they operate in a concerted way. The Matrix sets out the level of sewage sludge treatment needed prior to application to different types of crop. The Matrix has been agreed by Water UK (representing the 14 water and sewage operators) and the British Retail Consortium (representing the major retailers). It is intended that the provisions of the agreement will be incorporated into legislation in the form of the Sludge (Use in Agriculture) Regulations which are currently being revised. The emergence of this industry-level standard is significant and may be pertinent to the issue of irrigation water quality. Firstly, it demonstrates the influence that the major retailers have on the activities of other stakeholder groups (in this case water companies and food producers). Secondly, it represents a process in which industry-level standards may eventually be translated into national legislation. Thirdly, it has raised questions about whether the high level of sensitivity amongst consumers to issues of microbiological food safety is leading to over-cautious regulation that does not take a balanced view with regard to costs and benefits. Mara and Horan (2002) argue that the bacteriological requirements of the Matrix are unnecessarily strict in terms of health risk and that sludge treatment costs that will be incurred are unjustifiable.

2.6 Summary

- Salads, fruit and vegetables are the vehicle for a small number (probably <10) of reported UK outbreaks of infectious intestinal disease per year. Inadequate hygiene in catering establishments is identified as the cause of the majority of the outbreaks.
- In a recent UK survey, it was found that 99.3% of bagged salads were of a satisfactory or acceptable quality according to the PHLS. The presence of pathogenic bacteria and unsatisfactory levels of indicator bacteria in a relatively small number of salad samples were a cause for concern.
- Irrigation water is one of many potential sources of contamination of salads. There is no direct published evidence to link the irrigation of salads to disease outbreaks in the UK. Epidemiological studies in Mexico and Israel suggest disease risk in situations in which salads are irrigated with poor quality water.

- There is no systematic surveillance of irrigation water quality in the UK. From the datasets that exist, it is clear that, in general, river water is highly variable in its microbiological quality and at times could be classified as being of poor quality.
- The WHO guidelines for the safe use of treated wastewater (1989) suggest a limit of $\leq$ 1000 faecal coliform bacteria / 100 ml for salad irrigation. A recent review of available evidence has re-validated this guidance.
- There is growing pressure from the multiple retailers in the UK to encourage their suppliers (growers) to adopt a standard for irrigation water close to that which would meet the microbiological requirements for drinking water (with the absence or at least infrequent presence of *E. coli* being a key indicator of acceptable quality). This would bring UK irrigation in line with the strict standards imposed for treated wastewater reuse in California, USA.

3 IRRIGATION OF SALAD CROPS: CURRENT USAGE AND UNDERLYING TRENDS

This section provides a summary of the key findings arising from research task 2 of the project. Specifically this involved the design and implementation of a survey to evaluate the nature and composition of irrigation practices within the UK salad crop sector together with a number of on-farm visits to review salad production, irrigation management and water quality issues. Collectively, the findings have helped to inform the technology option assessment (Stage 4) and provide a basis for evaluating the extent to which existing salad irrigation practices might be considered risky. Some broader industry-wide implications that have arisen as a result of the study are also raised.

3.1 Survey of salad crop irrigation

A survey has been undertaken to provide baseline information on the nature and composition of irrigation practices within the salad crop sector in the UK. The scope of the questionnaire aimed to collect information relating to:

- salad crops grown;
- crop area/s irrigated;
- water source/s used for irrigation;
- irrigation method/s;
- minimum harvest interval;
- on-farm irrigation water storage, and;
- irrigation scheduling practices.

Growers were also asked if they were willing to participate as a 'benchmark' farm. This would provide the project team with an opportunity to discuss in more detail specific crop production, water resource and irrigation water quality issues, to help consolidate the survey findings. A copy of the irrigation survey questionnaire is given in Annex 1. The irrigation survey was targeted to all HDC registered growers involved in the production of ready to eat salad and leafy crop vegetables. A covering letter was included explaining the rationale of the survey and the project objectives. In all, 322 questionnaire were sent, using direct posting and email. Non-respondents were re-contacted and asked to complete the voluntary questionnaire. In all, 74 completed questionnaires were received, representing a 23% response rate. The survey data were processed and a database containing aggregated information was produced. A summary of the key findings is given below.

3.1.1 Crops grown

The survey focussed on 11 salad and leafy vegetable crop types, namely: lettuce, celery, Chinese leaf, endive, onion (salad), radish, watercress, spinach, rocket, culinary herbs and other baby leaf salads. A summary of the percentage of growers reported to be involved in the production of each of these crops is given in Table 4.

Table 4. Percentage of respondents growing each crop type in 2003.

Crop type	Percentage (%)
Lettuce	50
Culinary herbs	24
Spinach	20
Celery	18
Onion (salad)	18
Other baby leaf salads	16
Rocket	15
Endive	8
Watercress	7
Chinese leaf	4
Radish	4

Note: For example, 24% of all growers that responded to the survey grew culinary herbs in 2003.

The data revealed that over half (60%) of all survey respondents were growing a single salad crop; 18% grew at least two and 11% three crop types. Only a small proportion (11%) of salad growers grew four or more different crop types.

Half of all salad growers responding to the survey grew lettuce (outdoor) in 2003. Almost a fifth grew culinary herbs, spinach, celery and salad onions. As expected, watercress, Chinese leaf and radishes were only grown by a minority of growers. These data, however, relate only to the *number* of growers involved in each crop type and do not reflect the importance of each crop in terms of irrigated area (ha).

3.1.2 Irrigated areas

The survey data were analysed and used to estimate the total area irrigated in 2003, by salad crop type (Figure 1). The data confirms that lettuces are the most important crop representing half (50%) the total salad irrigated area. Spinach and salad onions are also important and together account for a further third (32%) of the total salad irrigated area.

Figure 1. Estimated irrigated area (% of total) in 2003, by crop type.

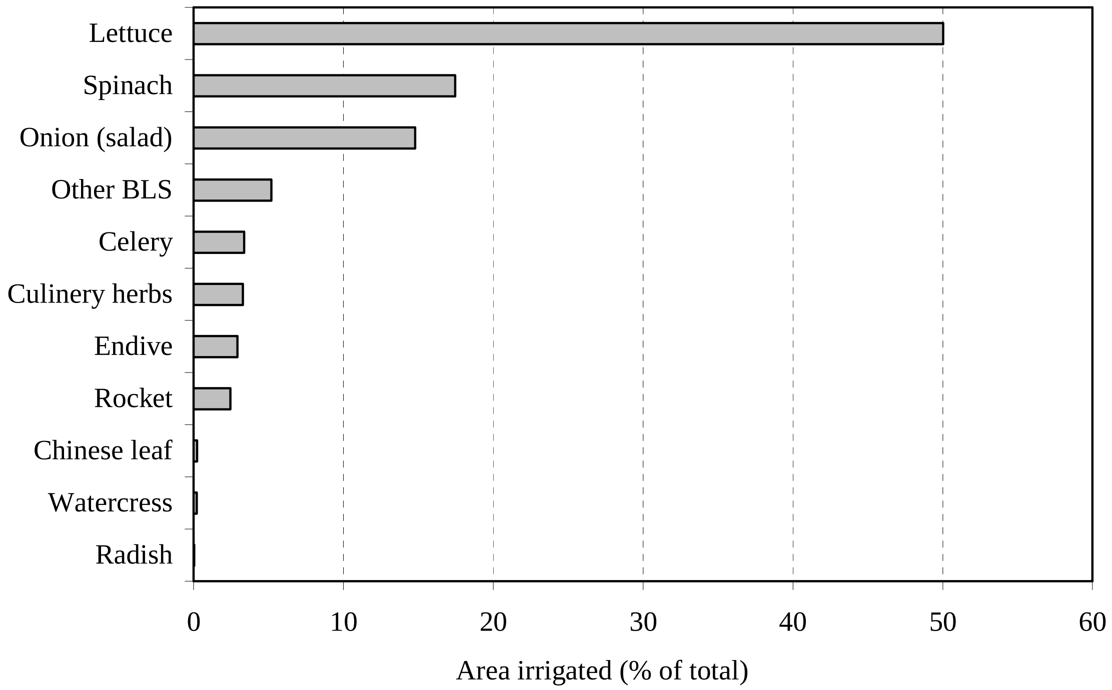
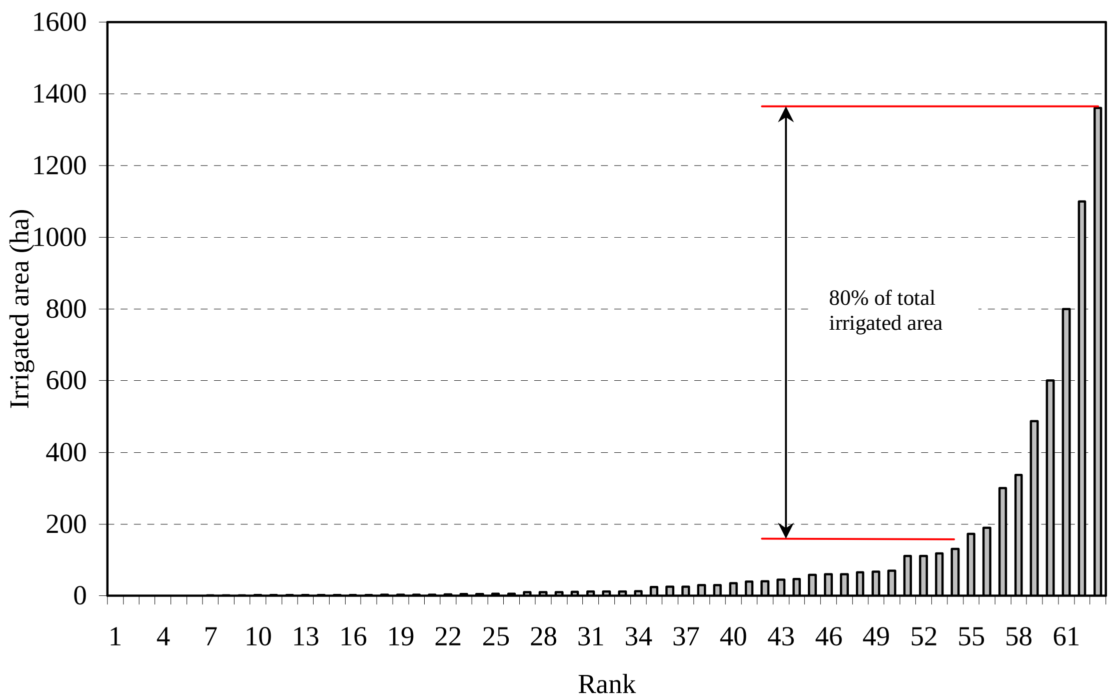


Figure 2. Total area irrigated (ha) in 2003 by each survey respondent, ranked by size.



To show the variation between individual farms in terms of total salad area irrigated (ha) was estimated and ranked (Figure 2).

Figure 2 shows the irrigated salad area of each farm ranked by area. The distribution is very skewed with a major proportion of the total salad irrigated area (>80%) being grown by only a small number of growers (<10 respondents). The remaining area represents a large number of small-scale horticultural units whose cropped areas are relatively small.

For some crops, the irrigated area reported in this study can be compared against government published horticultural cropping census statistics (Table 5).

Table 5. Comparison of Defra (2003) reported cropped areas (ha) with estimated irrigated area (ha) data reported in this survey.

Crop type	Cropped area (ha) in 2002 reported by Defra (2003)	Irrigated area (ha) in 2003 reported in the survey
Lettuce	4570	3345
Culinary herbs	1590	220
Salad onion	1320	988
Celery	640	226
Other baby leaf salad	330	347
Radish	290	2.2
Watercress	74	14
Total	**8814**	**5141**

The comparison suggests that the irrigation survey data collected in this study has accounted for approximately 60% of the total salad cropped area in the UK. It appears that all baby leaf vegetable production and approximately three quarters of all lettuce and salad onion production have been accounted for in the survey. The survey failed to gain statistically significant feedback from the radish and watercress sectors. Overall, therefore, the survey results are strongly biased towards the larger growers.

3.1.3 Irrigation application methods

The survey provided information on the irrigation application methods being used in salad crop production in the UK. A correlation between irrigation method and irrigated area, by salad crop type, has been completed (Table 6).

The data confirms that the dominant method of irrigation on salad crops are hose-reels fitted with booms, accounting for between 60-85% (by area). Notable exceptions are salad onions, culinary herbs and rocket, where sprinklers or hose-reels fitted with guns are more widely used.

It is interesting to note that despite the high value of salad crops, trickle or drip irrigation usage remains negligible. Some growers have reported trying trickle irrigation on certain row crops such as celery and other crops but with mixed success.

Table 6. Estimated split (%) between irrigation method and irrigated area, by crop type.

Crop type	Hose reel with boom	Hose reel with rain gun	Sprinkler / sprayline	Trickle or drip	Centre pivot linear move	Other	Total
Lettuce	86	9	5	0	0	0	100
Spinach	81	4	14	0	0	0	100
Onion (salad)	37	37	25	0	0	0	100
Other BLS	85	0	14	0	0	0	100
Celery	83	4	2	0	11	0	100
Culinary herbs	24	32	45	0	0	0	100
Endive	74	0	26	0	0	0	100
Rocket	39	0	60	0	1	0	100
Chinese leaf	63	0	38	0	0	0	100
Watercress	0	35	0	0	0	65	100

Note: BLS, Baby leaf salads.

3.1.4 Irrigation water sources

Using the survey data, a correlation between the sources of water used for irrigation against irrigated area, by crop type, has been completed (Table 7).

Table 7. Estimated split (%) between water source and irrigated area, by salad crop type.

Crop type	Water source					
	Surface water		Ground water		Other	
Type of abstraction	Direct	Indirect	Direct	Indirect	Public mains	Rainwater harvesting
Lettuce	46	33	8	8	5	1
Spinach	7	63	22	8	0	0
Onion (salad)	90	3	6	0	1	0
Other BLS	4	9	67	16	4	0
Celery	76	5	9	0	10	0
Culinary herbs	22	19	39	10	7	3
Endive	26	0	13	0	61	0
Rocket	2	0	50	45	3	0
Chinese leaf	0	19	0	38	25	19
Watercress	0	0	100	0	0	0

Note: indirect means via reservoir.

The data confirms that surface water accounts for between 70-90% of all water abstracted for irrigating lettuce, spinach, salad onions and celery. The use of public mains supply for irrigation is significant, particularly in certain sectors (e.g. endive, Chinese leaf and celery) although the areas of these crops and hence volumes are small in overall terms.

By re-aggregating the data, the proportion of each water source used for irrigating salad crops has been derived (Table 8).

Table 8. Estimated split (%) between water source in 2003.

Water source	**Total irrigated salad area (%)**
Surface water (direct)	42
(indirect)	29
Ground water (direct)	16
(indirect)	8
Mains water supply	5
Other	<0.5
Total	**100**

Overall, surface water accounted for almost three quarters of all water (71%) abstracted for salad crop irrigation in 2003, with most being abstracted in the summer and used direct. The use of groundwater was also important representing a further quarter of all abstraction, again mostly direct. The use of public mains supply was small and represented approximately 5% of all abstractions.

3.1.5 Minimum harvest interval

The survey provided information relating to the minimum harvest interval for each crop type, i.e. the typical minimum number of days between the last irrigation and harvest. It provides an indication of the potential risks that might be associated with using low quality water for irrigation close to harvest. The data have been aggregated into bands according to defined intervals (Table 9).

Table 9. Reported minimum harvest interval by salad crop type expressed as a percentage of total survey responses.

Crop type	Minimum harvest interval (days)				
	< 1	1	2 – 5	6 – 10	> 10
Lettuce	6	17	28	33	17
Spinach	8	8	58	17	8
Onion (salad)	17	33	42	8	0
Other BLS	8	42	25	25	0
Celery	17	33	42	8	0
Culinary herbs	7	27	53	7	7
Endive	0	40	20	20	20
Rocket	14	29	29	14	14
Chinese leaf	0	0	0	100	0
Watercress	33	0	0	0	67

Note: For example: 28% of respondents growing lettuce typically ceased irrigation 2-5 days before harvest.

The data suggests that for most crop types, the majority of growers would typically harvest their crops within 5 days of the last irrigation. For growers abstracting direct from low quality surface waters during the peak irrigation season when river flows are at their lowest, this represents the worst case in terms of the risk of pathogens contaminating the crop and surviving until harvest.

It should be noted that certain crop categories, i.e. rocket, Chinese leaf, endive and water cress the results are derived from a small sample (<10 survey respondents); the results in these instances should therefore be interpreted with caution.

3.1.6 Irrigation scheduling practices

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. The latter is a particularly important component in salad crop irrigation. Various scheduling methods are used and broadly defined under two categories, either water balance methods or direct measurement techniques. Both are considered "scientific" in their approach. There are also various "non-scientific" approaches including operator judgement, feeling soil, or crop inspection. The survey requested information relating to the salad crop area scheduled by each method, expressed as a percentage of the total area irrigated. The results are summarised in Table 10.

Table 10. Estimated split (%) between scheduling methods used in salad crop irrigation in 2003.

Scheduling method	Percentage of total salad irrigated area (%)
Water balance calculation	3
In-field moisture measurement	12
Other	85
Total	**100**

The results suggest that only 15% of the irrigated salad area is scheduled using any form of "scientific" approach. The majority of growers do not use any form of scientific scheduling, but prefer to use operator judgement, feeling the soil or walking the crop to decide on when and how much to irrigate.

The implications of such approaches to on-farm water management and the broader survey findings are discussed in detail in Section 3.3.

3.2 Benchmark farm studies

The survey received feedback from 25 growers prepared to participate as 'benchmark' farms. Ultimately, 11 sites were chosen to encompass a range of agroclimatic conditions under which irrigation would be practised as well as incorporating variation in the types of salad crops being grown. An attempt was also made to select contrasting farm business enterprises that are involved in a mixture of salad crop production systems and geographically spread across the country.

A visit to each farm was made between August and December 2003. Each visit lasted approximately 1 hour and included an informal discussion with the farm/technical manager regarding their cropping and irrigation management practices. The visits also provided an opportunity to verify the individual questionnaire data, to collect additional information on irrigation infrastructure and to gather information relating to the perceptions and attitudes of growers regarding irrigation water quality (if any). A pro-forma was used to standardise the collection of base data from each farm visit. A confidential report was produced for each benchmark farm for use by the project team. A matrix summary of the individual crop types considered is given in Table 11.

Table 11. Summary of the salad crop types grown at each benchmark farm.

Crop type	Benchmark farm										
	1	2	3	4	5	6	7	8	9	10	11
Lettuce	■	■		■	■	■	■			■	■
Spinach			■							■	■
Onion (salad)							■	■	■		■
Other baby leaf salad	■									■	■
Celery				■							■
Culinary herbs			■					■		■	
Endive	■									■	
Rocket			■							■	■
Chinese leaf											
Watercress											
Radish											■

Note: Each benchmark farm was assigned a random number for confidentiality.

The visits provided the opportunity to discuss water management issues relating to 9 of the 11 crop types of relevance to this study, with lettuces, spinach and salad onions being the dominant crops considered. The findings from the 'benchmark' farm studies and other related research are summarised below.

3.2.1 Water management

The level of irrigation water management being practised on many of the benchmark farms was generally of a high standard, particularly when compared against standards in the horticultural irrigation industry nationally. Most growers were aware of the importance and value of irrigation to their businesses and were striving to identify mechanisms for improving levels of water efficiency. However, whilst growers were aware of the benefits of improved water management, most lacked detailed knowledge on how to adopt best practices or to demonstrate efficient use.

As described earlier, the use of scientific approaches to managing water allocation between crops and fields (irrigation scheduling) was generally low. Many growers had tried such techniques but preferred to use non-scientific approaches to scheduling despite being aware of the potential yield and quality benefits. Many believed that the various scheduling methods currently available lacked sufficient sensitivity with regard to taking account of the shallow rooting characteristics of many salad crops; in most cases the preferred method for determining when to irrigate was to visually inspect the crop. Some growers reported having tried using tensiometers and other soil moisture monitoring devices to 'calibrate' their gut feelings regarding soil moisture status.

The poor uptake of irrigation scheduling in the salad sector remains a reflection of the difficulty of being able to quantify accurately (or convince growers) of the benefits that scheduling provides, particularly in dry years when many growers are usually constrained by water resources and/or equipment rather than by water management decision-making (scheduling). Most growers believe that they will derive more benefit from risking over-irrigating rather than under-irrigating. For example, in a case study in the Fens, the marginal cost of applying surface water (direct) was estimated to be £0.16/m^3 (Weatherhead *et al.*, 1997) compared against the extra net margin on say lettuces at approx £2.00/m^3 of water 'usefully applied' (Morris *et al*., 1997). On the other hand, many systems are under-designed and growers do not need scheduling to tell them to apply more water when they do not have the capacity to apply it. It is simply easier to keep irrigating at or near the capacity of the system unless extreme rainfall events occur. These reasons probably explain why there is poor take-up of scheduling in salad production especially where water resources are not limiting.

Most growers were, however, aware of the importance of scheduling with respect to the grower protocols, developed and implemented by many of the major multiples (e.g. Nature's Choice, Farm Assured, Field to Fork). Whilst irrigation scheduling is a component of these protocols, the demands on growers at present are merely to confirm that some form of irrigation scheduling (undefined) is being undertaken – the protocols themselves make no reference to any particular methods nor seek qualification of the rationale being adopted by growers for deciding which method is used. Increasing pressure on the availability of water for irrigation combined with raised public concerns regarding the environmental sustainability of abstraction will undoubtedly force the multiples to seek further reassurance from their growers that rigorous and sustainable approaches to on-farm water management (scheduling) are being practised.

3.2.2 Water resources and water quality

Many growers visited were concerned with recent changes in water resources legislation, notably the Water Act (2003) and the implications that resulting changes in abstraction licensing would have on their business in terms of securing reliable water sources in the medium term. The benchmark studies identified that there is no typical arrangement for abstraction and therefore that generalisations cannot be made. Whilst multiple abstraction points provide the grower with flexibility, they potentially require multiple treatment points unless all abstractions feed into a single delivery point. Where mobile pump-sets are being used any water treatment system would also need to be mobile, with potential implications regarding power supply for treatment.

The majority of farms visited relied on direct abstraction from surface sources (rivers and streams). This takes place during the summer months when water quality is highly variable. The farms visited with storage tended to use their summer abstraction allocation first, keeping stored winter water for use later in the season when summer flows become more unreliable. On some of the farms, the abstraction points were reported to be in close proximity to sewage outfalls but the microbiological loading at the points of abstraction was not known and not being measured. Other sources being used included public mains supply, boreholes and recycling pack-house water. As expected, the water quality associated with borehole sources were found to be of very high quality. Pack house (re-cycled) water was reported to be more variable, particularly in terms of nutrient loading.

Growers' reported perceptions and attitudes to water quality also varied significantly. On some farms water quality was not considered to be a problem. Others felt that product washing/chlorination and/or consumer hygiene should be sufficient to maintain product quality. For others there was a recognition that irrigation with surface water was potentially an issue and, if necessary would be dealt with by either switching to another water source, switching to public mains supply or as a last resort, using some form of water treatment technology. Interestingly, two of the growers visited were investigating the feasibility of on-site treatment (using UV technology) largely in response to raised concerns regarding the microbiological quality of the local river water.

3.2.3 Water distribution

On any given farm, the configuration (layout) of the irrigation water distribution system (network) will influence the viability (technical and economic) of a water quality monitoring programme and/or a water treatment system. The contamination risks associated with each type of water distribution system vary depending on a number of factors. Temporary pipe work (used for connecting from a hydrant to irrigator) would be subject to potential contamination during storage and re-assembly. The risk of serious contamination to permanently installed (underground mains) pipe work which is drained down in the winter is probably small. Covered galvanised steel tanks which are typically used for mains water storage protect the water from aerial contamination should also present a relatively low contamination risk. Questions were raised during the survey about the likelihood of biofilm development in the distribution system. Biofilms are highly likely to develop, are likely to be of limited public health significance, but may harbour coliforms and therefore could present problems of compliance if strict water quality standards are set.

The benchmark studies identified four major distribution types:

1. Source → Ring main → Irrigator (mobile or permanent).

This is the most common approach where water is abstracted direct from a source and delivered through a pressurised underground main to a field hydrant. An irrigator is then connected to the hydrant using surface laid pipes along the field margin or headland. The underground main is usually made from steel, concrete or more commonly plastic. The underground main is used during the irrigation season and then drained for winter until the following spring. It is not usual practice for such systems to be cleaned or flushed at the start of a new season unless repairs or maintenance have been undertaken.

2. Source → Reservoir → Ring main → Irrigator (mobile or permanent)

As 1 above used but with the addition of on-farm storage using either reservoirs (open) or balancing tanks (usually covered). For many growers, storage provides a guaranteed reliable source of water for summer irrigation. It does, however, necessitate double pumping and significantly raises the unit costs of irrigation, although there are economies of scale. If abstracting direct from a surface source, the typical unit costs (£ per m^3) range from £0.43 to £0.61, for an unlined and lined reservoir (20,000 m^3), respectively (Weatherhead *et al.,* 1997). The unit costs for storing water in relatively small (<20,000 m^3) lined reservoirs are similar to abstracting direct from the public mains supply. Whilst growers are actively encouraged to develop on-farm reservoirs to provide additional aquatic wildlife habitats, this ironically increases the risks of contaminating stored irrigation water from local wildlife and other aquatic fauna.

3. Source → Open dyke → Irrigator (mobile or permanent)

In a few instances (notably in the Fens) water is abstracted direct and pumped into open drainage or dyke systems. These dykes are then used to distribute the water around the farm. Mobile pump-sets are then used to abstract water and irrigate adjacent fields. These systems are cheaper to operate, because they rely on gravity for distribution, but they are more prone to microbiological contamination (e.g. from nesting birds, wild fowl etc.). Regular dredging and bank clearance is required to maintain flows and prevent blockage as well as minimising opportunities for nesting birds to colonise the water margins.

4. Source → Irrigator (mobile or permanent)

This layout is usually found on small horticultural holdings where growers irrigate by abstracting water directly from a local surface source using a mobile pump-set. The microbiological water quality risks associated with this type of distribution are dependent on the source of abstraction.

3.2.4 Water quality monitoring

All the growers visited were well aware of poor irrigation water quality being a potential hazard in salad production. A minority, however, had developed any practical strategic approach for dealing with an incident that might (negatively) impact on their salad production. The water quality monitoring practices that were encountered broadly fell into two categories. The most common approach was for the microbiological quality of the water source to be tested annually. These test results were then stored for reference but had no specific operational role. In some cases more regular sampling and analysis was being conducted with the data then being reviewed periodically. It was apparent that the majority of growers conducting water quality sampling were unclear as to how to respond operationally to any deteriorations in water quality. Only on a few farms was a programme of regular monitoring throughout the irrigation season being undertaken. In the case of two of the eleven growers visited it was possible to identify a process of regular review and pragmatic action being taken in response to observed changes in water quality. For most growers, collecting water quality data represented an additional activity that simply had to be undertaken to conform to grower protocol requirements. When discussing water quality monitoring, the following issues/questions were raised by growers:

- Which microorganisms should be tested for presence/absence in the irrigation water?
- What frequency of water quality monitoring is required? (daily, weekly, monthly, annual)
- Where should water sampling take place? (at the point/s of abstraction or at the point of delivery)
- Should all sources of water be tested or only those perceived to be higher risk?
- How should the results be collated and interpreted?
- What standard of irrigation water quality is acceptable?
- What actions should be undertaken if a standard is not met?
- Sampling is not real-time, so how should a grower deal with a water quality reading retrospectively?

These questions raised by the bench mark farms underline the fact that there remains very limited information or practical guidance available to growers to assist them in making rational decisions with regard to monitoring and managing irrigation water quality (e.g. ADAS, 2003). In order to raise standards of practice and awareness, growers will need to identify and collect relevant information in support of developing best management practices. The concept of collecting data on irrigation water <u>use</u> is not widely practised. This is because many growers are not exactly sure of what should be measured and why. The same is true with regard to monitoring irrigation water <u>quality</u>. Whilst some benchmark growers had recently begun to collect water use data, this was most often in response to concerns regarding abstraction licence renewal. In this context, new legislation (Water Act, 2003) which places greater emphasis on abstractors to demonstrate ‘reasonable need’ and efficient use might prove a useful driver for promoting greater awareness of other on-farm issues (e.g. irrigation water quality). For example, incorporating new frameworks or best practice guidelines to assist growers in measuring and monitoring water quality would be timely, particularly if placed in the context of helping to improve standards of on-farm irrigation water management.

It was also apparent that the attitudes of some growers to water quality stemmed from the various protocol pressures being exerted by the major multiples; this ranged from no apparent pressure, to a requirement that some form of monitoring needed to be carried out (although this might only mean one sample per year). It was evident that some protocols were moving towards a requirement where a stringent regular sampling approach would need to be demonstrated; the objective being that this would help keep the processor/retailer informed on trends in irrigation water quality and would help to establish remedial plans if sudden reductions in quality occurred.

It was widely believed amongst the growers visited that a drinking water equivalent standard was unjustifiable both in terms of the perceived public health benefits and economic viability. Most growers agreed, however, that some industry standard (however defined) was clearly required. Such an approach that could be practically implemented and managed and based on pragmatic guidelines would be welcomed by the majority of growers involved in the production of high quality produce for the retail and processing markets.

3.3 Summary

- Based on a survey of growers in 2003, lettuces represented the most important salad crop accounting for half the total irrigated area.
- The salad crop industry is dominated by a small number of large commercial growers (<10) who collectively are responsible for growing in excess of 80% of the total cropped area.
- The dominant method of irrigation on salad crops are hose-reels fitted with booms accounting for between 60-85% of the total area irrigated. Irrigation methods that lead to direct contact between the irrigation water and the edible part of the crop are therefore dominant.
- Direct abstraction of surface water accounted for almost three quarters of all water (71%) used for salad crop irrigation in 2003. Surface water is the irrigation source that is most vulnerable to faecal pollution. Public mains represents only 5%.
- A significant proportion of irrigated salad crops are harvested within 5 days of the last irrigation event. This has implications for the opportunity for pathogen die-off processes to occur.
- It is estimated that only 15% of the salad irrigated area is scheduled using a scientific approach (e.g. water balance or soil moisture measurement).

- Growers perceptions and attitudes to irrigation water quality and the associated risks to public health varied widely. Many growers contacted undertook only an annual check on the microbiological quality of their water. Only in a few instances did growers monitor water quality on a regular basis both at the source and point of application. Only in exceptional cases were pragmatic and practical steps being taken in response to observed changes in water quality. Most cited lack of knowledge on what to measure and why (no industry accepted standard to compare against) as their underlying reasons for limited water quality monitoring.

- Most growers believed that a drinking water equivalent standard was unjustifiable both in terms of the perceived public health benefits and economic viability. Most felt that an industry standard or agreed framework for water quality monitoring was clearly required.

4 TREATMENT OPTIONS FOR IRRIGATION WATER

4.1 Introduction

4.1.1 Which method? The approach used in selection

In this section, a wide range of water treatment techniques will be reviewed and a shortlist of the three most suitable methods for horticulture set out. To achieve this firstly requires a definition of what is meant by *treatment* and then the listing of the appropriate criteria by which the related performance is assessed. Furthermore, there are a series of other factors including cost and farm practicality that must also be considered. A dozen distinct treatment options are then briefly described and considered in the light of these criteria and the results illustrated in a simplified table. Many options are quickly found to be lacking in one or more key areas and these are thus put to one side. The remaining shortlist is scrutinised in greater depth in the penultimate section and ranked in order. This final list is presented in the conclusions (section 4.5).

4.1.2 The purpose of treatment

A large number of treatment options exist, many of which can improve the quality of water used for crop irrigation. The initial selection of a subset of techniques (section 4.3) to be considered in further detail was based on two key criteria:

(a) the achievement of at least *some* reduction of the microbial load that may be present, and;

(b) the broad *suitability* of such technology in the horticultural industry.

The driving force behind this is the need to demonstrate the quality of horticultural produce on the basis of the control of identified microbiological hazards. The concept of “clean produce” is taken as both accepted and implemented but this does not necessarily imply an adequate microbiological standard. The presence (or the risk of the presence) of a range of microorganisms that can cause ill health to consumers is of increasing concern to producers, retailers and, not least of all, to the consumers themselves. In epidemiological studies, various sources of contamination in the process running from “farm/field to fork” have been identified along with the related critical control points. Central amongst these is the quality of the water used of irrigation which for the most part is applied via the air as a jet; in consequence, the leaf will regularly come in contact with the water applied. For salad crops such as lettuce where it is the leaf that is eaten, this can present a high risk to food safety.

The quality of the water used for irrigation and its *actual* impact on the level of microbiological contamination on the produce (or the perceived or measured risk of such) will vary from farm to farm.

The hazard itself will depend on the source water and the type of crop irrigated. The strategy is thus firstly one of water *management* to attain a certain standard - such measures might include control/choice of water source, storage (and protection of reservoirs) and timing/method of application. If such approaches can not reliably achieve the required standard, then the second (and invariably more costly) approach is the use of *treatment technology* to achieve the same. Clearly, in the case where treatment is being used, it must then be effective in attaining the required water quality.

The cost implied in the use of water treatment technology will make it the last option in most cases but it may be attractive in some special cases for other reasons. These may be expected where there are water supply problems; treatment may then enable a previously unsuitable source to be considered. In this case, additional treatment requirements may apply such as the removal of suspended matter or (in the case of brackish water) the removal of dissolved salts as well.

4.2 Selecting criteria for process assessment

4.2.1 The importance of defining a treatment standard

Although the presence of a health hazard can be readily identified (and even quantified in terms of risk in some cases) converting this to a meaningful set standard is difficult. There is always the danger of choosing standards that may imply a substantial input of effort but may be inappropriate or, in some cases, even ineffective. Nonetheless, without any sort of target, objective comparison of different methods and/or the determination of an acceptable level of effectiveness is impossible. A standard is thus necessary even if only to decide on the best technology.

4.2.2 Methods of evaluation of process performance

The are two possible scenarios that will be considered:

(a) ***continuous microbial load***: where there exists measurable levels of bacteria in the irrigation water. Such determinations as total viable count (TVC) might be an example and one can envisage setting limits such as 10^3 counts per ml or setting minimal reduction in numbers such as 3 $\log_{10}$ units.

(b) ***intermittent pathogen hazard:*** where there would normally be no measurable level of specific bacteria of concern. This may be due to either (i) the presence of low (but still hazardous) levels that are below the *threshold of detection* or (ii) the intermittent presence of otherwise measurable levels of bacteria. In either case, the performance of the technique can only be satisfactorily demonstrated in specific laboratory trials. If protection against such possible (albeit rare) contamination is important, a high level of confidence in the treatment technique used would be very important.

Outside the laboratory environment, monitoring can only be done with respect to those organisms that are likely to be present in the source water. Even frequent random sampling (once a month or more) is no guarantee of protection in the event of the infrequent presence of pathogens in the water. As an example, one might consider the nature of cattle shedding *E. coli* O157 in their manure: reported measurements (e.g. Besser et al., 1997) demonstrate the intermittent pattern with long periods with little or no such bacteria present. Only when shedding occurs and when there are accidental spillages, is there the risk of contaminating surface water. Incidents such as that of Walkerton in Canada (Goss, 2002) that resulted in fatalities following water contamination are mercifully very rare; monitoring for *E. coli* would ***not*** have prevented this. However, even in the event of more commonly present bacteria such as *Salmonella* (from wild animals and birds) or *Campylobacter*, their presence in irrigated water is unlikely to be frequent enough or at high enough levels to allow detection through normal monitoring schemes. Appropriate treatment strategies to deal with this are thus based on the ability of destroying any such bacteria *if and when they are present*; effectively operating as an "insurance policy".

The preferred selection criteria can be based upon reported effectiveness against pathogens of concern (i.e. those leading to food poisoning) in specific laboratory trials. In response to such challenges, an acceptable target performance will be the reliable reduction of numbers by ***4 or more*** ***log_{10} units*** which has been used as a measure of effective microbe destruction (e.g. Turner et al., 1998 and 1999). It is likely that much lower doses than that used in the challenge will still be harmful (and indeed that high concentrations would not occur naturally anyway). However, the concept is put forward that the level of decontamination would be similar irrespective of the starting concentrations; thus a reduction of four log_{10} units, if demonstrated in the measurable range, can be equally expected even if starting at much lower concentrations.

In the absence of reported data on the effectiveness of any given technique on the pathogens of concern, data on similar microbes or indicator organisms is taken. General indicators such as total coliforms (for faecal matter) or TVC remain most useful as a means of monitoring (where numbers are regularly present in the source water) rather than as a method of establishing performance.

Other indicators of performance can be derived from laboratory results such as physical indicators. For example, if it is shown in studies that an adequate reduction is achieved by heating to 60 ^{o}C and holding at such a temperature for 5 minutes, the monitoring of such parameters will be a valid alternative to direct microbiological assays (Turner and Burton, 1997).

4.2.3 Using mains water as a benchmark

Increasingly in the food industry, there is the policy of citing "potable water" as the acceptable standard for a wide range of duties. It is reasoned that any water deemed of sufficient quality to be consumed without suffering ill effect will be inevitably adequate for a wide range of food duties. Such a quality may not unreasonably be considered excessive in terms of that water used for irrigating salad crops but it does define an upper limit of the quality of applied water.

"Mains water" is normally taken to meet the requirements of potable water. However, the microbiological standards applied in the monitoring of such water do not automatically confer the status of potability on any water source. For example, service water used in an electronics factory may meet such standards but it would not make it fit to drink. Clearly, the *source* of water is an important consideration as well - that taken from deep bore holes would not be expected to carry the same risk of pathogens as for river water. Nonetheless, mains water is a useful standard in that it defines a potable grade of water that is available at around £0.5 / m^3. Any process that suggests costs greatly in excess of £0.5 / m^3 of supplied water will thus be given a low score.

4.2.4 Suitability of treatment technology for use in horticulture

Treatment methods that can reduce pathogen numbers in water must also be "appropriate" for use in horticulture. This is described by a series of ***secondary criteria***.

1. *Investment costs* - at the top of any list is bound to be the investment cost required. This is for the simple reason that (in most cases), this will represent an "up front" cost to be raised by the farmer himself. Grants and/or some financial support from processors or government are unlikely. Investment will include purchase of the equipment, installation costs (including site preparation) and training. Auxiliary items such as additional pipelines, pumps and the provision of services to a remote location may be part of the exercise. Costs can vary widely depending on the daily volume of water treated and the process type.

2. *Cost per tonne of water treated* - this is the running cost and typically includes any charge for services as well as maintenance (typically 5-10% of the equipment cost) and labour costs *incurred*. The total cost that is applied to the water processed must include an appropriate capital element reflecting the investment made. There are many ways of accounting for this - one useful indicator is to estimate the life of the plant (e.g. 10-20 years) and divide by the anticipated volume of water processed in the period. An interest charge also needs to be included.

If the market value of the product is brought into the equation, the cost of the water supplied can be expressed as a % of product value; the impact of a further treatment cost then becomes clear. The following are used as a reference point. Variation in all of these figures is expected and adjustment should be made as appropriate. Figures marked with an asterisk are based on published statistics for 2002 (Defra, 2003):

1. Lettuce (all types) represents the largest proportion of irrigated outdoor salad crops in the UK; 4,800 hectares were grown in 2002*

2. Mean lettuce yield in 2002 was 23 tonnes per hectare with a mean farm gate price of £610 per tonne (equivalent to £14,030 per hectare)*

3. Irrigation varies widely. A mean value of 300 mm is used here. This is equivalent to 3000 tonnes (or m^3) per hectare per year.

4. Peak flow is even more difficult to determine: based on point 3 and assuming even irrigation restricted to 50 warm dry days in summer, flowrates from source can be expected of 60 tonnes (or m^3) per day per hectare (2500 litres per hour per hectare).

5. Based on points 2 and 3, the mean water usage for lettuce is deduced as 130 tonnes (or m^3) of water per tonne of lettuce produced.

The price of mains water is taken as £0.5 / m^3; this is considered the maximum. The cost of the water supplied (excluding irrigation costs) at this price (point 5) is thus £65 - this to produce lettuce with a farm gate price of £610. This is thus equivalent to 11% of the value of the produce. To set this into context, it is perhaps also of note that irrigation costs for water abstracted from borehole or river are estimated as £0.4-£0.7 per tonne (m^3) depending on the equipment and location (Weatherhead et al., 1997).

3. *Labour demands on farm staff* - the running costs of the plant will be reduced if the range of duties to keep it running are both few and fit into farming practice. Equipment needing specialist inputs will incur the related costs. Even if not specialist, any treatment regime that demands frequent attention or is likely to greatly interfere with the normal operation at the farm will not be welcome.

4. *Reliability problems*

(a) equipment failure - as the main consequence of inadequate treatment is an enhanced risk to food quality, unreliability is a serious drawback. Furthermore, poor performance (i.e.

in terms of the protection against microbe contamination) may not be apparent unless there is also an obvious mechanical failure. In both cases, the virtue of sound technology is clear.

(b) inadvertent equipment misuse - less apparent are design weaknesses that can allow equipment to be wrongly used or easily damaged. Notwithstanding the general observance of reasonable care, technical options that can easily be misused represent a drawback. Critical processes that need precise actions at certain times are clearly not attractive to the farm situation. It might be reasonably expected that any equipment intended for farm use ought to be able to take minor physical knocks without suffering operational problems.

5. *Environmental issues* - it is not impossible for a treatment process intended for improving quality to also be the cause of unwanted environmental consequences. There might be waste product implications such as the generation of filter sludges or spent absorbent that will need disposal. There may be the direct hazard such as from the use of chemicals. In either case, the presence of such factors will reduce the attractiveness of the option.

6. *Operation factors* - there are also other considerations that relate to how the equipment is to be used and how long it takes to be set up. These include design features such as whether the technology represents a fixed or mobile facility or whether the treatment unit is best operated as a single (centralised) unit or as several local units. The significance of this will be partly determined with farm size but also with the distribution of the fields requiring irrigation.

7. *System capacity* - the final criterion for the assessment of treatment options lies with the amounts of water used and the peak flow rates needed. Clearly larger volumes imply a greater overall treatment cost but of greater relevance will be the amount of water per tonne of a given product. This will depend upon: (a) rainfall; (b) crop type; (c) soil type (re retention of water) and (d) irrigation system used.

The significance of peak flow lies with the size of equipment required and therein the investment cost. Wide variations imply larger equipment that the mean flow rate would imply. The use of reservoirs or other storage can reduce this effect but, if uncovered, these too can be a source of further contamination (after treatment) from wild animals and birds.

4.3 Possible treatment methods for irrigation water

4.3.1 Introduction - initial screening of options

The many treatment methods fall roughly into four categories: (a) those based on direct disinfection (both chemical and irradiation types); (b) those based on a filtration principle; (c) those using a biological process and (d) those using heat application. Each method is considered in turn based upon the seven criteria described above along with performance as defined by the two scenarios in the previous section. Table 12 below summarises the key information. In many cases, treatment techniques are defined "unsuitable" because of a particular weakness in one or more areas. It does not follow that other strengths can negate such shortcomings; the temptation to look at aggregate scoring at this stage is thus resisted.

Table 12. Summary of evaluation of each treatment option based on performance based on (a) a criteria of reducing the numbers of normally present indicator organisms and (b), responding to the infrequent presence of specific high-risk pathogens . The suitability of the technique is given in terms of the system parameters as defined in section 2. Scoring is relative with one star denoting poorest and three the best. A black dot indicates an assessment that effectively rules the method out of further consideration.

Process	**Performance score**		**System considerations**						
	Normally present microbes	Intermittent high-risk pathogens	Investment	Treatment cost	Labour demands	Robust-ness	Environ-mental	Operation	Capacity
U/V radiation	**	**	**	***	**	***	***	**	**
Ozonation	***	**	*	**	**	***	•	**	**
Chemicals	**	*	***	**	***	**	•	***	***
Filtration modules	*	•	**	**	**	**	***	**	*
Deep bed filtration	**	*	**	***	***	**	***	***	***
Membrane systems	***	***	*	**	**	•	***	**	*
Flocculation	*	•	*	**	**	**	**	**	*
Packed bed	*	•	**	**	**	*	***	**	*
Wetlands	*	•	**	***	***	*	***	***	**
Thermal treatment	***	***	**	**	**	***	**	**	**
Thermophilic aeration	**	*	*	*	**	**	**	*	**
Storage methods	**	•	**	***	***	**	***	**	**

4.3.2 U/V irradiation methods

Irradiation by U/V represents a simple disinfection approach that is already well used in the water supply industry, sewage treatment and also in swimming pool water quality control. In fact, it now represents the most common method of the disinfection of treated wastewater in the UK with more than 100 plants using the technology (Thair, 2002). Of special note is that U/V has already been used in trials on some UK horticultural farms.

The principle is simple: the water is pumped through a cylindrical module that contains a bundle of U/V lamps. Larger systems can be set up in ducts or channels. Lamps are usually of the form of long tubes that are orientated in the direction of flow. They can be of variable power up to 100 watts or so but then the tendency is to then use two or more lamps equally spaced within the module. In this way the penetration distance for the light is minimised. In recent years, more powerful lamps have been developed to overcome the main limitation of turbidity in the process water. Power supply (excluding pumping) is solely that to illuminate the lamp.

An adequate retention time is important (20 to 30 seconds) which along with lamp power, determines capacity. A typical 100W module might be expected to handle 3-4000 litres per hour which is equivalent to a peak irrigation water flow rate needed for 1 or 2 hectares of crop (section 1.5). Larger capacity units are available or several of modules can be operated in parallel. Small U/V units are relatively cheap to buy, install and run. They are also relatively maintenance free with the periodic cleaning of the elements and replacement after 4000 to 8000 hours (equivalent to 6-12 months continuous operation).

Assessment

The main drawback of U/V is variable performance especially if there is any turbidity in the water. Even where promising results exist for clean water, this can be all but lost if the supply becomes cloudy which is a possibility for any surface abstracted water. For this reason, some U/V units are linked to filtration modules or a similar clarification step. A second concern is the variable performance of the method: whilst good reduction in overall microbe numbers (three logs and more in some systems) has been demonstrated, there is also evidence that some bacteria are resistant to the treatment (Thair, 2002). However, the general simplicity of the process and the ease in which it can be deployed makes it worthy of further consideration. It is of note that the Environment Agency include this as one of their permitted methods for disinfection of wastewaters prior to discharge to controlled waters (EA, 2002). Thair (2002) in his review on the subject for UKWIR (The UK Water Research Ltd) also put U/V forward as the best technology for the disinfection of such wastewaters. ***Short-listed.***

4.3.3 The use of ozone

Ozone technology is well established in the water industry both for the purification of drinking water and for wastewater disinfection where it is commonly used worldwide (although increasingly less so in the UK). The concept is one of injection of the gas into the process water (0.5 to 1%) at one point, retention in a pressurised vessel (10-15 minutes) and the removal of any unused chemical at a ventilation stage. The treatment module is often little more than a holding vessel set in the water pipeline; perhaps with retention baffles and mixing elements. However, the main apparatus lies with the ozone generator itself that sits alongside and also with a separate U/V unit to destroy any unused ozone emitting from the process and the treated water. The technique is effective in the destruction of a wide range of bacteria and viruses.

Assessment

The technology is relatively simple and it can be expected to be very effective. However, it does have the clear drawback of representing a toxic system with many hazards to the user and those nearby. Control of such systems is also very strict with maximum emissions below 1 ppm stipulated. The method has the additional problem of potentially producing a range of toxic by-products from its reaction with any organic matter present. For these reasons, its use is now being restricted in some countries including the UK where it should not be used for waters with a high organic content (over 30 ppm). The presence of a large amount of organic matter would also substantially increase the consumption of the gas There is increasingly concern about the possible by-products of such treatment and the impact on these on the environment. The process itself can represent a large capital investment with equipment (especially the generator and off-gas destruction unit) and maintenance by specialists will be necessary. In conclusion, this is not considered suitable technology for the horticulture industry. ***Not short-listed***.

4.3.4 The potential role of chemical disinfectants

Other than ozone, there are a number of disinfectant chemicals that one may be tempted to try in an attempt to reduce microbe numbers in abstracted water. These include chlorine, peracetic acid (PAA), chlorine dioxide, hydrogen peroxide and various alkalis. The benefit is clear; a very simple low cost system to install - little more than a dosing pump and perhaps a section of pipe containing mixing elements. The main drawback is that virtually all of these chemicals represent a hazard to both the operator and the environment. Furthermore, the consumption of chemical can be considerable. Taking chlorine as an example: a supply concentrate of 10% strength and an application level of 100 ppm implies one litre of concentrate per 1000 litres of water treated. As with ozone, the amount required will increase with the concentration of organic matter present. The dose may be less for other chemicals but it is worth noting that there must be a destructive effect on the microorganisms; it would follow that a lower dose will imply a more hazardous chemical.

The performance of these chemicals is variable and, in most cases reduced by the presence of organic matter. Chlorine has been the most widely used disinfectant in the food, water and wastewater industries but it is increasingly been discouraged. In the UK, it is a no longer permitted additive to the water used in meat processing and its use in wastewater disinfection is discouraged by the Environment Agency owing to the possible presence of a number of toxic by-products. Peracetic acid is less hazardous but it is also less effective and unlike chlorine there is little evidence of its use in water treatment. Processes based on raising the pH (e.g. lime addition) have been explored in the context of effluent treatment but the cost of materials is high and disinfection is poor (Thair, 2002). More powerful chemicals such as chlorine dioxide and mixed oxidants have been researched - they do offer a reduction of microbe numbers at a lower dose but they carry the drawback of presenting a negative environmental impact and a hazard to the operator.

Assessment

Virtually all chemical disinfectants that could be added to process water represent a hazard to the operator and the environment and (not least of all) to the crop itself. The Environment Agency increasingly discourages the use of chemicals in treated wastewater that is to be released to controlled waters (Thairs, 2002). Most of all is the variable effectiveness in reducing microbe numbers reported for the use of chlorine and many other chemical additives - this is especially so if there is organic matter present. Thus the use of disinfectants is ***not short-listed.***

4.3.5 Filtration modules

Filtration technology is divided into systems based on modules and larger deep bed systems (section 4.3.6). The key feature of module systems is the need to squeeze a lot of filtration into a small volume. Units tend to consist of one or more filtration cartridges in a steel holding vessel. Cartridges can be disposable or re-usable after a cleaning stage. In either case, a large surface area is provided by elaborate pleating of the filter medium. Flow is nearly always *through* the media leading to the inevitability of blockage in time. A turbid water will clearly shorten the operational life of the filter - initially, this will lead to a rise in pressure as the filtered layer of debris builds up. Eventually, the back pressure exceeds the system limit and the operation stops; in larger systems, flow is automatically switched to a parallel module whilst regeneration occurs.

The nature of any filter medium is to initially retain particles larger than the pore size; with time, the formation of a deposited layer (filter cake), results in the removal of smaller particles also. A finer medium will take out smaller particles but at the penalty of both higher pressure drops and lower throughputs. The increased pressure drop translates to greater pumping energy along the simple correlation: pump energy equals volume flow rate multiplied by pressure drop.

The effectiveness of filters in removing some bacteria is almost assured in all cases in that many such organisms exist in flocs rather than individually. Thus, any filtration that clarifies down to 100 microns or less can be expected to achieve a reduction in bacteria numbers although the organism itself is typically only 1-2 microns in size. Total removal would need filters with a pore size approaching this value but the penalty in lost throughput would be prohibitive. Alternatively, there is the option of filter presses that allow easier cleaning. In this case, the use of filter aids (a fine inert substance to aid separation) would only ensure a good separation. The small size of viral particles would make their removal by any such filter module unlikely. It follows that the role of a filter unit would be to improve the general quality of the water rather than provide any crop protection against infrequent but hazardous pathogens.

Assessment

Despite the poor performance of filters used to remove bacteria, there remains the clear attraction of simply technology that can readily fit into an existing irrigation system. Running costs will be low amounting to the periodic replacement of filter media and additional pumping energy. There are drawbacks in the risk of filter failure (and the subsequent release of a plug of bacterial filtrate into the treated water but this can often be picked up if pressure difference is monitored. Overall, the poor performance of this technology rules it out as a method to disinfect irrigation water and it is thus not considered further as a single method. However, it may be suited for clarifying irrigation water ahead of other processes such as U/V and hence it is ***not short-listed*** but should be considered for the purpose of pre-treatment.

4.3.6 Deep bed filtration

Deep bed sand filters are often used for removing turbidity from drinking water: they can also be used for the final (tertiary) treatment of wastewater but this is limited to those with a very low level of suspended matter. There are many configurations and operating regimes including rapid, slow (downflow) and upflow filters. Flow is usually in the vertical direction with bed depths of 1 to 2 metres. Rapid flow units require daily backwashing to maintain porosity; retention of bacteria is likely to be minimal unless a very large bed depth is used. Slow sand filters, as the name suggests, have a much lower capacity (2 to 3 m^3/day per m^2 of area - White, 1987) but retention is better and cleaning is less frequent. Upflow filters overcome the porosity problem caused of using sands with a wide particle size range - some stratification will occur and the whole bed will become active in the separation process rather than just the top few centimetres.

Unlike the filter unit (section 4.3.5), pressure drop is rarely a problem as a very large area is involved. The working principle is that of retardation (rather than true filtration) of suspended matter (including bacterial flocs) by the sand particles as the water passes through the bed. As with the filter cartridge (or filter press), the medium (sand in this case) will become progressively fouled with the suspended fines that are removed. In the case of a deep bed filter, the mechanism is slightly different as a degree of migration of the entrained particles can be expected rather akin to chromatography. Thus with the passage of time, the limit of the filter is determined not only by the loss of throughput but also by the emerging of debris from the bottom. Back pressure is not a problem as the system is largely open. Periodic cleaning of the bed becomes a necessity; its size (running into many 100's of m^2) makes total replacement of the media impractical. The usual method is backwashing with the removed cloudy water discarded. However, some chemical sterilisation may also be needed to ensure that any entrained bacteria do not contaminate the first of the next batch of water passed through for treatment.

Assessment

Sand filtration systems clearly imply a large earth-moving investment although costs are not particularly high and some tasks could be done by farm staff. It is important to manage the bed in a disciplined manner (with periodic back washing) but operation duties are not demanding and running costs are not particularly high. The main drawback is variable performance and the risk penetration of bacteria especially as the media becomes old. Warm weather can lead to biomass growth and fouling by wild animals is always a risk if not covered. This is potentially a suitable technology for irrigation water treatment if there can be a commitment to a consistent operation regime. Further studies may be necessary but the simplicity of such systems make them an option to consider further: ***short-listed***.

4.3.7 Membrane filtration methods

Unlike filter systems, membranes can physically stop bacteria from passing through into the treated water stream. The degree of effectiveness does of course depend on the mean pore size of the membrane but this can easily be sub-micron (micro-filtration) or even smaller (ultra-filtration) the latter extending to the removal of some viral particles. The tightest membranes (nano-filtration and reverse osmosis) can also remove dissolved matter and it potentially can upgrade brackish water. However, unless this is a particular problem, the penalty of using such high filtration (low through-puts and high pressures) seldom justifies such a process.

Membrane systems are already well established in the water supply industry where the removal of bacteria is of special importance. They are also increasingly being used in the treatment of wastewaters for the same reason but this is limited to those with a low level of suspended solids.

Units are often constructed as modules not unlike filter units but there is a big difference in the operation mode. Most (if not all) membrane systems operate by *cross flow* rather than *through flow*. In other words, the feed water flows along a tube (for example) with the membrane lining the wall;

the treated water is squeezed through by the applied pressure. Some membrane fouling can be expected but to a large extent, suspended matter (including bacteria) is transferred out of the system with the waste concentrate. This latter is a second difference with conventional filters: inevitably, some of the feed water must be rejected with its enhanced load of debris for careful disposal. However, with re-circulation, and a source water that is low in suspended matter, 99%+ of the abstracted water should pass through.

Membrane systems broadly fall into two categories: *pressurised* and *submerged.* The former has been in use for longer and involves the concept of pumping water into a system lined with membranes as for reverse osmosis plants for example. A lower cost option is the submerged membrane type which has been largely developed for the sewage treatment industry. This uses membranes arranged in vertical panels submerged in a rectangular vessel where secondary treatment takes place. The panels are typically around 1-10 m^2 each and grouped together to make a block that almost fills the vessel; air is bubbled up from the base and both serves to stimulate the biological activity and to keep the membranes clear of fouling. The water is drawn through by a pump but the suction would be modest (below 0.2 Bar) compared to that of a pressurised system; permeate rates are reduced as a consequence, typically 25 litres per hour per m^2 of membrane (Choi et al., 2003) leading to the need for relatively large units. For example in existing wastewater treatment plants in the UK, 3,000 to 20,000 such membrane panels are used (Thair, 2002) to handle continuous throughputs of 100 to 300 m^3 per hour of sewage effluent.

Evaluation

Membrane systems are more costly than conventional filter systems and some might say they are less robust as well. Reported performance from sewage treatment plants using submerged membranes indicate a failure of 1% the modules in 2-4 years of operation since new (Thairs, 2002). However, the operational life is given as 7-10 years suggesting that a much higher level of replacement can be expected in the next few years. The cost of a unit which could deliver 20-100 litres per hour is typically £50-£100 suggesting an investment of £5-10,000 for the 2,500 litres/hour peak flow to irrigate one hectare (section 4.2.4). However, the cost of the installation will be much larger involving a treatment vessel fitted with aeration equipment, pumps and instrumentation which would increase this cost by a factor of three or four. As an indication, a new sewage treatment plant processing 25 m^3 per hour might be expected to cost between £300,000 and £500,000. The costs for a pressurised membrane system handling the same flow rates are normally higher.

Compared to standard filtration equipment, losses through pumping are generally lower for submerged membrane systems but higher for pressurised units. The efficiency in terms of clarification and especially microbe removal are much better with the best results for pressurised membrane units fitted with ultrafiltration membranes. Throughput in this case can be modest though leading to the need for a large number of modules. The pressurised units are also more vulnerable to blockage and need more frequent cleaning.

In conclusion, membrane technology (both submerged and pressurised) can definitely achieve a substantial microbe reduction and the submerged membrane option is well suited to the treatment processes for wastewater where there is also a recoverable cost. However, this technology brings a series of drawbacks when used to treat irrigation water for horticulture: it is relatively costly to install and maintain, it requires periodic specialist attention and it is vulnerable to failure. It is quite possible that the continuing improvements (especially those driven by the water industry) will enable such technology to be used on the farm in the future. Nonetheless, for the present, it remains unsuitable for use in horticulture. ***Not short-listed.***

4.3.8 Flocculation and sedimentation techniques

An alternative to direct filtration are systems based on flocculation. This is commonplace in wastewater treatment systems but the use for water already of a high purity is limited. Inevitably, any such clarification is most suitable for the most turbid of irrigation water sources. Natural settlement (gravity) will be slow owing to the nature of fine organic matter which is both easily stabilised in water and which has a density close to that of water. Adding flocculants to the water can induce settlement e.g. by the action of strong ionic solutions on the electric fields that stabilise the suspended particle. Such technology is already well established in the wastewater treatment industry.

Further acceleration of the settlement process can be achieved by the use of hydrocyclones which require the water to be pumped through at a high flow rate. This latter point at least would fit with the high volumes irrigated and the hydrocyclone itself is relatively simple to make (although hard to design). Centrifuges can also achieve accelerated settlement but they are relatively expensive and throughputs are low.

Assessment

A well designed clarification system relying on settlement can be expected to achieve some reduction in pathogen numbers but this will inevitably be limited. Unlike filtration techniques, there is no physical barrier to the passage of bacteria and any that are not settled out will pass through with the treated water. Little or no effect on viral numbers can be expected. Clarification may have a useful role as a pre-treatment step for turbid water ahead of U/V or filtration but by itself it is not a sufficient technology for dealing with the presence of pathogens in irrigation water: ***not short-listed***.

4.3.9 Trickling tower and packed bed technology

Aerobic biological treatments can be expected to reduce the numbers of bacteria on account of (a) the presence of oxygen (hostile to strict anaerobes), (b) the presence of competitive bacteria and (c) retention of the bacteria in the forming biomass. There is no shortage of published data that demonstrates the reduction in the numbers of pathogens as the result of aerobic treatment (for bacteria - Heinonen-Tanski, 1998; Venglovsky and Placha, 1999; Wekerle and Albrecht, 1983) but in many cases, this applies to wastewaters and stronger effluents where a great deal of activity can be induced along with a raised temperature from the heat of reaction. The very low level of nutrients in abstracted waters makes any attempt to aerate in-vessel ineffective owing primarily to wash-out problems. The alternative is that of using a packed bed where the microbes are held on support material; the water then flows over and the relatively modest oxygen demand is met by natural percolation. The approach again well established in the water industry and the technology can be very simple.

Packed beds used in trickle filters (also known as bio-filters) can be made from a variety of materials ranging from broken rock or gravel to specialised packing products offering a high surface to volume ratio. Cheaper packing options tend to lead to a larger treatment bed to ensure a sufficient contact time; recycling is preferably avoided as the treated and feed water then becomes mixed. However, it is then important to ensure that the percolation rate is not excessive - retention times ought to be in excess of an hour - which implies both low application rates and a good depth of bed. This in turn determines the overall volume of the bed for a given throughput of water.

Assessment

The limitation of biological filters lies with the ease with which feed water can “by-pass” the system from excessive flow, channelling or from leaks. The biofilm itself must be careful maintained - drying out of the bed must be avoided at any time. The method is unlikely reduce numbers of all bacteria with little effect anticipated with any oxygen-tolerant bacteria. Lastly, the relative capacity of such technology is small (to enable reasonable residence times for biological activity) - excessive flow rates lead to flooding on the packing and a loss of treatment. In conclusion, the technology is not expected to transfer well to the treatment of irrigation water. ***Not short-listed***.

4.3.10 Reed bed and wetland systems

Reed beds, soil filters and other wetland systems also rely on aerobic activity to be effective. Unlike biofilters, there is also the additional benefit of a degree of filtration although, in time, this can cause its own problems as the bed becomes progressively blocked. The technology has been primarily developed to treat dilute wastewaters to enable (in some cases) discharge to rivers. Some entrainment of bacteria in the root-gravel system can be expected akin to sand filters but the risk of channelling is greater in the more open structure implied. Some reduction of bacteria as the result of competition can also be expected but it is uncertain whether a consistent and adequate reduction can be obtained. Furthermore, with the passage of time, elution of bacteria from the discharge end of the bed may occur. Any treatment dependant on microbiological activity can be expected to fall over the winter period.

Reed beds and wetlands in general fall into two main type: horizontal and vertical flow. As the names imply, the former involves a flow along the bed from one end to the other. For effluents this is usually replaced by the preferred vertical flow bed where the entire surface is flooded and water percolates down to collection drains underneath. For effluents this is an advantage as it avoids subjecting the entry point to a consistent high concentration of pollutants. This is not the case for abstracted water: in this case, the short percolation distance implied by the vertical design is a drawback and the horizontal configuration is preferred. Nonetheless, unless the abstracted water is very poor in quality and caries a high organic load, the real benefits of reed beds is largely under-utilised and the system represents an over-elaborate solution to the problem.

Assessment

In his review of disinfection systems, Thairs (2002) does shortlist wetland systems (including reedbeds) despite the reported variable performance. This may have been influenced by the combination of the large number of units now in use and the environmental green image they have. However, where such systems are being used to solely deal with a microbial (or potential microbial) risk, one has to accept the principal shortcomings of the reported performance which falls well short of the 4 $\log_{10}$ units reduction possible with other systems. Some work does indicate 1 or 2 $\log_{10}$ units reductions for specific bacteria (e.g. faecal coliforms - US EPA 2000a and 2000b) but even such modest achievements are likely to vary with the season. Thairs admits that reedbeds do not achieve a consistent reduction of indicator bacteria to low levels in the case of treated wastewaters. There is very little data to suggest that reedbeds have any effect at all on viruses.

The central problem is that the necessary open structure of wetland systems (to enable air penetration) reduces the filtration effect that might be achieved as in the case of deep bed sand filters. In its place is a mechanism that relies on an ill-defined and poorly understood interaction with naturally-occurring benign bacteria. If reliable performance can be demonstrated, wetlands may yet have a role in the upgrading of irrigation water but for the moment it is ***not short-listed***.

4.3.11 Thermal treatment

At first glance, thermal treatment may seem an expensive option that would rule it out of any further consideration. Indeed in his review of disinfection techniques, Thairs (2002) fails to even give it a mention. This would indeed be the case but for the option of heat recovery which enables much lower operation costs. Assuming fuel costs of 5p per kWh, heating a tonne (m^3) of water from 20 to 70 ^oC would cost around £2.90 (equivalent to 58 kWh). Heat of combustion of oil or gas (if available) is cheaper at around 3p per kWh suggesting £1.70 per tonne; with 90% heat recovery, this falls to £0.17 per tonne. With a relatively non-fouling medium such as irrigation water, greater heat recovery is readily possible implying an even lower running cost. Equipment costs are relatively small amounting to a heat exchanger system and some form of heat generator

Thermal treatment thus involves a heating stage, a retention stage and a cooling stage. The heat/cooling operations are carried out in an heat exchanger which can be of the compact PHE (plate heat exchanger) type. The size of this unit increases with the amount of heat recovery sought and there is a case for optimisation. The retention stage is also of great importance; the elapsed time often needs only be in the order of minutes if temperature is high enough. However, a larger vessel is often implied to overcome the inevitable back mixing and channelling and up to two hours may be implied in some designs.

Laboratory and pilot scale trials have demonstrated that most viruses and bacteria can be destroyed by temperatures below 100 ^oC (and sometimes below 70 ^oC as implied in pasteurisation) with little more than a few minutes retention (Turner et al., 1998 and 1999). For a flow rate of 5000 litres per hour, this implies a vessel as small as a few hundred litres and a PHE of similar size. The whole package could fit on the back of a trailer. The main requirement would be a supply of fuel. Realistically, gas and electricity are unlikely to be available and an oil-fired boiler is implied.

Assessment

The lack of complete packages "off the shelf" or working systems may be a barrier to the uptake of this sort of technology but the various components (heat exchangers, boilers etc) are readily available. Thermal treatment remains a relatively sophisticated method but the versatility of the approach makes it a rigorous method for use especially where the hazards are particularly high. Unlike many alternative approaches, the treatment does offer an *assured* treatment in that so long as prescribed temperatures are achieved and maintained, elimination of bacteria will be achieved. Thus it is put forward for further consideration; ***short-listed***.

4.3.12 Thermophilic aeration

The benefit of thermal aeration lies with an environment that is doubly hostile to a wide range of pathogens from the presence of elevated temperatures and of oxygen. The presence of ammonia (common in many organic effluents) will further enhance the process. The reduction in many pathogens has thus been shown by many such treatment systems but this has been almost exclusively concerned with wastewater effluents with large amounts of organic matter present (eg: a BOD_5 or five day biological oxygen demand over 1000 ppm). The significance of this lies with the heat of reaction generated from the aerobic decomposition of such material. For abstracted water , it is the absence of such exothermic activity that makes the adoption of the methodology difficult. If the technology is used, external heating would be necessary: as with thermal treatment some heat could be recovered but losses would be greater owing to the need for a long residence time (over 24 hours) to sustain any form of natural bacterial activity. In reality, it would prove better to run this as a non-biological process with the application of heat plus a steady stream of air to maintain a high dissolved oxygen level. The process thus comes down to a variation on thermal treatment.

Assessment

Thermophilic aeration tends to bring the problems of thermal treatment with few of the benefits. Unless it is likely that strict anaerobes of particular concern will be present, the value of this option will not be realised. It is thus not considered suitable for irrigation water; ***not short-listed.***

4.3.13 Storage strategies

For completeness, storage is included although is not strictly a treatment. There are many processes that can occur in a well managed storage regime, given enough time. The numbers of many microbes can be expected to fall with time especially if this runs into weeks or months rather than days. The causes of this include the natural decline of those bacteria that are strict anaerobes (the stored water often being aerobic), the effect of ultraviolet light on the surface layers and settlement of the flocs. The last mechanism raises a danger of an enhanced bacteria load if reservoirs are run very low or if the take off point is deep. This risk is worsened by the development of anaerobic sludges where concentrated numbers of some bacteria can survive or even increase in numbers.

Covered stores should be free from the contamination from wild animals, especially from droppings but any benefit from the U/V in natural sunlight will be lost.

Many farms already have reservoirs as part of their management plan - the numbers and size have been increasing for over 30 years. By 1997 the number of farm reservoirs in the England and Wales exceeded 3000 representing a total capacity of 64 million m^3; this was equivalent to a quarter of the volume of water abstracted annually (Weatherhead et al., 1997). However, the actual volume used was much less indicating that farmers tend to use such stores as an insurance policy rather than to increase the volumes of winter abstraction. It is far more common to use water soon after abstraction rather than to store it for an extended period then irrigate.

The benefit of separate storage of water of different grades is noted. Where there is a range of irrigated crops, there is a clear advantage in using the poorer water on the less vulnerable crops and keeping the better water for special use. The alternative strategy of blending is possible where there is an adequate supply of high quality water to mix with a poorer supply.

For farms planning to install new reservoirs dedicated to providing a minimum storage [treatment] option, investment costs can be expected of £40,000 to £80,000 for capacities of 20,000 and 100,000 cubic metres respectively (Weatherhead et al., 1997). This is unlined; lined reservoirs will cost 50% or so more. Converting this to a running cost (allowing for a repayment over 20 years at 6% and adding in maintenance costs) implies £0.2 / m^3 per year for a 20,000 unlined reservoir falling to half this amount for one of 100,000 m^3. The implied cost for treatment by, say 6 month storage thus can be expected as around £0.05-£0.1 / m^3.

However, it is likely that storage will not in itself be sufficient to improve water deemed to be of poor microbiological quality. The increasing importance of reservoirs in the management of water does mean that they will be available to help maintain quality. It is not a replacement for a treatment system if required. ***Not short-listed*** as a treatment technique.

4.4 Shortlist of practical techniques

4.4.1 Selected options

There are three main treatment options put forward as the result of this review based on the criteria set out in section 4.2. These are (in order of suitability - best first):

1. Treatment by ultraviolet radiation.

2. Thermal decontamination.

3. Deep bed filtration.

Each of these is discussed in more detail below. The other seven methods outlined in section 4.3 are not necessarily “rejected” but they are considered as having one or more serious drawbacks in the role of up-grading irrigation water. Storage remains a management option but it is not likely to be sufficient by itself if specific pathogen hazards exist.

4.4.2 Treatment by ultraviolet radiation

Performance - continuous microbial load (**) It is quite possible that a new U/V system treating a clean water and operated well within the specified capacity of the unit will consistently achieve a four log reduction for a wide range of common microbes. Reported results from the disinfection of treated sewage waste indicate more than four log_{10} units of reduction for total and faecal coliforms but no more than two log_{10} units for salmonellas (Thairs; 2002). The main limitation is with the inevitable loss of performance as the light elements become fouled or at times when the turbidity of the water increases - treatment monitoring is difficult.

Performance - intermittent pathogen hazard (**) The indications are that a well-designed U/V system would achieve some reduction when confronted with the intermittent presence of other pathogens. It may equally be expected that the performance may be variable with some bacteria able to resist treatment. The main reason for a degree of uncertainty lies with the loss of treatment should turbidity increase.

Investment costs (**) Thairs (2002) implies an investment cost of a rather high £200 to £300,000 for a U/V unit set up at a sewage treatment plant handling 5 l/s (18 m^3 per hour which would meet the irrigation requirement for 7 hectares of salad crop - see section 4.2.4). A problem with any treatment system is that (unlike a sewage plant) it would only be used for part of the year. Thus over 100 days of irrigation 43,000 m^3 of water would be processed by the unit implying a capital charge alone of over £0.5 /m^3. Cheaper units are available though and will need to be if this technology is to be used.

Cost per tonne of water treated (***) One of the main strengths of U/V is the low running cost which amounts to the energy to power light elements and possibly the pump as well (although the latter can be expected to be needed anyway). Additional costs related to the periodic replacement of the lamps and servicing. Collectively, unit cost is unlikely to exceed £0.1 / m^3 of water treated.

Labour demands on farm staff (**) On the one hand, a U/V plant can be expected to require relatively little attention and that which is needed can be largely covered by automatic processes. On the other hand, periodic maintenance will be required and this will be largely fall to specialist labour although trained farm staff may be able to fulfil some of the duties.

Reliability problems (a) equipment failure, (b) inadvertent equipment misuse (***) U/V systems are remarkably reliable with lamp failure being the main problem. Many systems will include warning of such failures but unless there are relatively few lamps in a plant this should not prevent continuing operation at a reduced flow rate. The main risk for misuse lies with the temptation to increase flow rates beyond that specified. In most cases, this will not damage the equipment although the level of treatment will be reduced.

Environmental issues (***) A great strength of U/V treatment is its limited (detrimental) effect on the environment. The water once treated should contain no residual evidence of the process. However, it is noted that some concerns have been raised on the possibility of the production small amounts of toxic compounds from the reaction of organic matter in the presence of high doses of U/V light. Little or no evidence has been produced to substantiate this fear.

Operation factors (**) An important consideration of any treatment technology is that it will need to be operated intermittently. It thus follows that they should be easy to turn on and off and to run. This is likely to be the case with U/V although it might be recommended to recycle the water for the first 10-20 minutes whilst the system settles down. Once running, the system should require little attention but periodic checks (especially to monitor lamp condition) will be necessary.

System capacity (**) U/V plants have been built to handle throughputs of over 500 m^3/h but the scale of economy is limited by a modular design - more flow rate tends to be met by more U/V lamps and flow paths can not be allowed to exceed many centimetres. The largest plants amount to civil engineering projects built on site but smaller units can be coupled into existing flow lines without a large degree of disruption.

4.4.3 Thermal decontamination

Performance - continuous microbial load (***) The destruction of bacteria by the application of heat has been well demonstrated in various studies on pasteurisation and sterilisation. Some bacteria can resist temperatures up to (and in excess of) 100 ^oC but this is only possible if it can form cysts of some similar structure. In plate heat exchangers, application of heat can be done very quickly (raising the temperature from ambient to 60 ^oC+ in a matter of seconds) thus preventing such defensive mechanisms from operating. Reduction in numbers by four $\log_{10}$ units can be readily achieved for a wide range of organisms: residence time is rarely more than an hour and temperatures can be as low as 50 ^oC. For example: *Salmonella* - 30 minutes at 70 ^oC (Bruce et al., 1990); similar conditions destroy intestinal parasite eggs such as *Ascaris suum* and *Taenia saginata* (Strauch and Berg, 1980) and a wide range of viruses are destroyed by exposure for 5 minutes at 60 ^oC (Turner et al., 1998).

Performance - intermittent pathogen hazard (***) The strength of thermal treatment is that it can be easily modified to deal with a wide range of pathogens. Temperatures up to and in excess of 100 ^oC (with pressure) can be readily achieved although heat losses will increase thus implying a more expensive process. It is very likely that the treatment will be equally effective if challenged with an occasional contamination by serious pathogen. For any specified type, a time-temperature survival (or destruction) curve can be established in a laboratory relatively easily.

Investment costs (**) Treatment systems will consist of five parts - a heat source (e.g. an oil-fired boiler), a heat exchanger, a retention tank, pumps and instrumentation. As a benchmark, the costing of a mobile thermal unit handling 20 tonnes per hour of animal slurry potentially contaminated with virus is used: the total figure was £375,000 (Burton et al., 1999). However, the treatment of water will be both less demanding than animal slurry (e.g. enabling the use of cheaper plate heat exchangers) and less critical (thus avoiding the requirement for high biosecurity). The mobility is also unlikely to be necessary. Taking the flow rate of 18 tonnes per hour cited for the U/V option above, this would imply a cost of an installed package to thermally treat irrigation water of around £100,000 to £200,000. A 20 year plant life can be expected if periodic refurbishment of the boiler is allowed for.

Cost per tonne of water treated (**) Despite the general perception of a costly process, thermal treatment can be relatively cheap so long as a high level of heat recovery is ensured. At 90% and with oil heating, a running cost of £0.17 / m^3 is implied for treatments to 70 ^oC. More heat recovery is possible but at the expense of a larger heat exchanger. As a rule, doubling the heat recovery (e.g. for 80 to 90% or from 90 to 95%) will double the size of the heat exchanger and half the heating costs.

Labour demands on farm staff (**) This is very similar to the U/V option in that relatively little attention will be required but some of this will be from an outside specialist. This will include regular servicing of the boiler and cleaning of the heat exchanger. As with the U/V option it is noted that there is a specific operator hazard (this time in the way of high temperatures) which will make training an essential requirement.

Reliability problems (a) equipment failure, (b) inadvertent equipment misuse (***) Unique amongst all the treatments is the possibility of ensuring near certainty of treatment by the relatively simple monitoring of temperature and flow rate. Water quality will not affect the treatment other than influencing the rate of fouling which (if a problem) will again reveal itself by the failure to meet target temperatures. If temperatures are maintained that have been established as those required, treatment is assured. The main consequence of misuse is an inadequate treatment which will not normally damage the plant; e.g. running with excessive water flow rates. Equipment failure (other than pumps or boiler) is most likely to arise from the progressive fouling of the heat exchanger. This will have two possible consequences: a lower heat recovery and/or insufficient thermal treatment. In either case, the problem can be rectified by accepting a lower flow rate. In reality, all heat exchangers exhibit this characteristic: when new (clean), they will easily exceed their design specification. As they foul over the following weeks or months, they will lose performance and meet the design specification. Beyond this point, they will fall short of the specification and either flow rates or temperatures must be reduced. In effect, this is the point when a cleaning operation must be carried out.

Environmental issues (**) It is highly unlikely that the mere application of heat at pasteurisation temperatures will lead to the production of any toxins in the treated water. The only impact on the environment is a low level of heat in the water that is a few degrees warmer than the temperature of the abstracted water. Heat pollution can be an issue and thermal treatment clearly carries such risks but no more so that the heating of buildings (for example) or the burning of waste or fuel in the normal farm operations. Clearly though, a poorly-run treatment system could have some detrimental effects on the environment but this will certainly be noticed on the high fuel costs at the first stage.

Operation factors (**) Because the system involves running a boiler, set start up and shut down regimes must be followed which in themselves require training. The time of this exercise and to allow settling down (warming up to operation temperatures) may add up to 20 minutes or more. Automatic procedures can be expected to reduce this operation. Frequent in-line cleaning procedures may be followed (e.g. once a week) to extend the period before the heat exchanger must be de-scaled - a potentially costly operation requiring specialist help.

System capacity (**) Systems can be designed for a wide range of throughputs up to several hundred m^3 of water a day; there will also be a substantial scale of economy in using larger (rather than extra) heat exchangers, boilers etc. Once specified though, a system can not readily be extended to handle higher capacities (other than by duplication): this is especially the case for the boiler and retention vessel. Enlarging a plate heat exchanger is easier and can be done by adding extra plates although this is a task for a specialist. Over-designing a system to leave some spare capacity is readily possible and without a large extra investment cost. Running costs closely follow flow rates.

4.4.4 Deep bed filtration

Performance - continuous microbial load (**) Of the three techniques listed, sand filtration offers the poorest and most variable performance. Results with reed beds do suggest that reductions of one or two log_{10} units for faecal coliforms are possible and one might reasonably expect better performance with sand filters (and without the seasonal effects). Vega et al. (2002) report a 2 log_{10} reduction with viral pathogens but little change when challenging their sand filters with *Salmonella*. Logan et al. (2001) reported that sand filters would remove the oocysts of *Cryptosporidium* if fine sand (d_{50} = 0.3mm) is used. Lukasik et al. (1999) did find a 3 log_{10} reduction in *E. coli* but only after modifying the sand to incorporate ferric and aluminium hydroxide. Consistent data is generally lacking which may reflect the wide range of operating systems possible for sand filters. Some reassurance of performance would be necessary before committing to this treatment approach.

Performance - intermittent pathogen hazard (*) If slow sand filters are used, retention times can run into hours for the liquid phase and days for the entrained bacteria - some loss of pathogen numbers may then be expected as the result of the prevailing conditions (*cf* storage). One might thus expect some effect on the occasional presence of more serious pathogens. However, there is no guarantee that some such organisms will not pass through and if this were to be a crucial aspect for treatment, the level of confidence in the protection offered would be low.

Investment costs (**) The uncertain performance of sand filters in removing pathogens is partly balanced by the simple nature of the installation and the relatively low costs involved. The technology is much simpler than either U/V or thermal treatment. In essence, the installation in its simplest form involves a clay-lined pit filled with sand on a thin layer of gravel on the base (where removal pipes are located). As a design guide, maximum flow rates for the slow sand filters (offering the most complete treatment) one m^2 of bed area (of 1-2m depth) will handle 2-3 m^3/day of water. It would follow that a 100-200 m^2 sand bed will handle the 18 m^3/hour water flow rate used in the examples for U/V and thermal treatments. The bed may be made larger to provide some extra assurance of removal of microbial material but costs are still unlikely to exceed £50,000 - most of which covers earthworks rather than materials.

Cost per tonne of water treated (***) Running costs for a sand filter will be little more than that for pumping. A larger element will be maintenance including the topping up and/or replacing the sand but even so, it is unlikely to be more than a few pence per m^3 of treated water.

Labour demands on farm staff (***) Once set up, it is likely that most of the relatively few duties in running the sand filter can be covered by farm staff with limited training.

Reliability problems (a) equipment failure, (b) inadvertent equipment misuse (**) Accepting the uncertainties of the process as described above, the relatively simple operation leaves little scope for further problems as the result of misuse. If backwash cycles are included, these can be mismanaged with disruption to the bed and an overflow of contaminated water. However, the situation ought to be recoverable with little lasting damage to the system. The bigger concern lies with the uncertainty of the extent of treatment achieved at any one time.

Environmental issues (***) There are no environmental impacts of note expected from the use of sand filters. New sand beds may impart a small amount of salinity on the first irrigation water to be passed through.

Operation factors (***) Unlike reed beds or wetlands, there is no management problems with reeds or some other herbage. Likewise one would not expect a loss of performance with season although the persistence of some viruses is greater in colder weather. Operation is thus not expected to make large demands on staff - start up and shut down ought to be quick with just a few minutes necessary to enable settling down at the beginning. Initial water drawn from the bed ought to be recycled during this time. One consideration is the need to periodically backwash the beds to remove accumulated debris. The frequency of this operation depends upon the design of the bed and quality of water passed through. Slow sand filters can be left for several months at a time and cleaning may be limited to the ends of the season.

System capacity (***) A great strength of sand bed treatment is the wide range of flow rates that they can be operated at (but not exceeding the maximum capacity). Oversizing facilities does not bring a large investment penalty. However, if a sand filter did need to be enlarged, it would probably be more worthwhile to build a second unit alongside rather than disrupt an existing established bed by extending.

4.5 Main conclusions and recommendations

1 Three techniques out of eleven are considered to be particularly suitable for the up-grading of irrigation water. The main selection criterion is the ability to reliably reduce the level of bacteria (continuously or intermittently present) by at least two $\log_{10}$ units and preferably as much as four $\log_{10}$ units. The short-listed options also meet criteria of cost, robustness and relatively low labour demand .

2 The main candidate is the use of U/V technology. The main limitation of the wider deployment of such treatment is that of turbidity in the water which is rarely a serious problem for abstracted water for irrigation. It is a simple well-proven concept that is increasingly used in the wastewater industry for disinfecting large volumes of water prior to discharge to controlled waters. The demands of irrigation water is arguably even higher as the applied water directly contacts the crop which will ultimately be consumed. However, the consistent reduction of microbe numbers achieved along with the versatility of the technique and the ease which it fits into the horticultural industry makes it a strong choice. It is not surprising that some farms are already looking at this approach to treat their water. The main limitation may yet lie with the relatively large investment cost and running costs that include an electrical supply to power the lamps.

3 Thermal treatment may yet prove to be a better option than U/V on the basis that it could be a cheaper process and the level of treatment can be both more reliable and more complete.

Electrical requirements are modest (mostly pumping and instrumentation) but there will be a significant consumption of fuel (presumably oil). A great deal depends on the value ascribed to attaining a very high quality of water; there would need to be a definite and serious microbiological risk identified with the abstracted water to make this the better option.

4 Of the three options taken forward to a short list, deep bed sand filters represent the most uncertain technology. It is well established in the water supply industry as a method of treatment but it is rarely tested against the presence of pathogens and data is lacking. The removal of microbes can be expected to be better than wetlands on the basis that they are designed as filter systems from the outset. They are also a cheap technology that includes little sophistication. Many of the tasks in setting up and operating such units could be fulfilled by non-specialist staff with minimal training. If proven to be effective, it represents the most likely technique to be used on the farm where the main drawback of land area demand is unlikely to be a problem.

5 DISCUSSION

5.1 Irrigation water as a food safety hazard

Poor quality irrigation water is one of a number of possible sources of contamination of salad crops. It is probably not the most important however. In cases where illness is caused by the consumption of salads it is not always possible to establish the source of contamination. On those occasions when a contamination source can be found, it is often traced to the poor hygienic practices of food handlers.

There is no clear evidence that poor quality water used for the irrigation of salads has been responsible for outbreaks of disease in the UK. There may be two explanations for this absence of a link which are discussed below.

1. Salad production and processing methods greatly reduce the exposure of consumers to pathogens.

The risk of salads becoming contaminated with pathogens depends on the level of pathogen presence in the irrigation water. In comparison to the concentration of faecal indicator bacteria, we would expect the pathogen content of irrigation water to be low and therefore that contamination risk would also be low. Unfortunately, there is relatively little information available on the pathogen content of UK irrigation water (as opposed to faecal indicator bacteria concentrations) with which to test this assertion. There have been very few published studies on the link between irrigation water quality and salad contamination. In studies of vegetable irrigation in Nigeria, Okafo et al., (2003) found that there was an apparent association between the pathogen load of streams used for irrigation and the frequency of detection of pathogens on the vegetables. In growth chamber experiments, Solomon et al. (2003) found that lettuce plants irrigated with water that had been artificially contaminated with 10^4 *E. coli* O157:H7 / ml contained high levels of the pathogen at harvest. They also found that plants irrigated with 10^2 *E. coli* O157:H7 / ml on day 1 of the experiment were microbiologically positive up to 17 days after irrigation. Solomon et al. (2002) found that *E. coli* O157:H7 in irrigation water could be internalised and recovered from the inner tissues of lettuce plants. An issue in interpreting these studies is that the experimental pathogen concentrations in the water are very high and may be unrepresentative of irrigation water in the UK. It is also possible that the greenhouse conditions favoured persistence (when compared to growth outdoors). As previously mentioned, lack of a good dataset on pathogen levels in UK irrigation water hampers such a comparison. It should also be noted that there is likely to be a higher pathogen:coliform ratio in parts of the world where the prevalence gastrointestinal disease is higher. For instance, we might expect that faecally-contaminated water in Mexico might have a higher pathogen load than faecally-contaminated water in the UK. Those organisations that import salads during the winter months from overseas should consider this hazard carefully – especially in the light of the hepatitis A outbreak in the United States in 2003.

For the purpose of developing this hypothetical argument, let us assume that occasionally, water containing pathogens is used to irrigate salad vegetables (*n.b.* the survey shows that most salads are irrigated in a way that allows the water to contact directly the edible part of the crop – see Table 6). If irrigation-derived pathogen contamination of salads can occur albeit probably at low levels in the UK, the next question is whether the consumer is likely to be exposed to them. Normally we would predict that faecal pathogen numbers would decline in the field as a result of various environmental stresses. The rate of die-off varies depending upon the pathogen and the environmental conditions. Some pathogens such as *E. coli* O157:H7 are capable of surviving for days or even weeks in water, soil and on surfaces (Maule, 2000). In general however, we may assume that as the interval between irrigation and consumption lengthens, the opportunity for die-off becomes greater and the risk of exposure will diminish (*n.b.* the survey reveals that this interval can vary significantly - see Table 9).

Finally, salad processing is another barrier to exposure. The degree to which salads are processed ranges from "cut, trim and bag" for whole-head lettuce through to the production of ready to eat bagged salads which have been disinfected using chlorine. In both of these cases (if good practice is applied) we could reasonably expect the processing to reduce contaminant load through the removal of outer leaves or through the effect of anti-microbial chemicals (*n.b.* disinfection methods provide no guarantee of complete decontamination (Beuchat, 1999)).

A scientific argument can therefore, be made in support of the hypothesis that aspects of salad production and processing reduce the exposure of consumers to pathogens. The key elements are:

- Irrigation water may contain a low pathogen load normally.
- Faecal pathogens tend to die-off during the interval between irrigation and consumption.
- Salad processing is likely to further reduce the contaminant load.

This argument could perhaps be further strengthened by reference to growers' databases on product quality which, we presume, demonstrate that irrigated vegetables do not have a serious pathogen problem prior to distribution.

However, none of these arguments are conclusive as: there is no good dataset on pathogen levels in UK irrigation water; there is insufficient knowledge of pathogen die-off to allow accurate predictions to be made; and the fact that even the most stringent salad decontamination regime does not provide a guarantee of product safety.

2. Salads contaminated with pathogens derived from irrigation water do occasionally cause disease but that it is difficult to establish a causal link.

Salads are occasionally vehicles of disease transmission. In those instances where the source of contamination has not been found, it is possible that irrigation water could have been responsible. With reference to the previous argument, the worst case scenario is:

- Irrigation water containing a high pathogen content – perhaps as a result of atypical contamination of source waters from slurry runoff or sewer overflows.
- No or little opportunity for pathogen die-off between irrigation and consumption.
- Limited decontamination associated with processing.

These conditions would increase the risk of exposure. Other factors that could contribute to the "worst case" would be contamination with a pathogen with a relatively low infective dose and the exposure of immunocompromised consumers.

Because of the short shelf-life of salads and the transient nature of source water quality, it may simply not be possible to trace the contamination source back to irrigation water. Similarly, it is hard to disprove an accusation that irrigation water is to blame because the level of monitoring that would be needed would be prohibitively expensive.

It is quite possible that both of these explanations hold true, i.e. that salads are generally of a high sanitary quality but that on very rare occasions, pathogens derived from poor quality irrigation water cause disease. The next proactive, proportionate step would be for the industry to be able to demonstrate that the issue of poor quality water is being investigated and that good practices are being developed. These ideas are further developed in the following sections.

5.2 Defining high quality irrigation water – the issues

This research was, in part, prompted by concerns that the multiple retailers have with respect to the risks associated with irrigated salads. We had originally intended to discuss these concerns in detail with retailer's representatives. Because of the commercial sensitivity of this subject and the on-going negotiations on the detail of the M&S Farm to Fork protocol, it was agreed that there would be no discussions between the research team and the multiple retailers. It would be sensible to review the conclusions and recommendations of this work when the M&S Farm to Fork protocol is finalised.

It has been reported to us that the retailer's view is that salads should be irrigated with water of a similar standard to mains water. Such a view would accord with the aforementioned strict standards in place in the State of California, U.S.A. Requiring salads to be irrigated with water meeting the EU drinking water standard, for example, might be an attractive option for the retailers as it would provide additional confidence in the production process. The fundamental question is: would such a high standard represent an appropriate balance between the additional costs of production and the benefits in terms of public health? Another, more practical question is whether every aspect of the EU drinking water standard would have to be met or just the aspects related to coliforms?

Risk assessment models have been used to assess the costs and benefits of standards. Shuval et al. (1997) developed a preliminary risk assessment approach for evaluating wastewater reuse standards for agriculture. In this study the risks were calculated of falling ill from ingesting hepatitis A and rotavirus associated with lettuce and cucumber irrigated with wastewater which met the WHO guidelines (1000 faecal coliforms / 100 ml). The results suggested that the annual risk of succumbing to hepatitis A was of the order of 10^{-6} to 10^{-7} This risk rose by three orders of magnitude if raw wastewater was used for irrigation. The findings of quantitative risk assessment studies coupled with epidemiological evidence led Blumenthal et al. (2000) to conclude that there was no evidence of "*a need to change the WHO guideline limit on exposure of ≤ 1000 faecal coliform bacteria / 100 ml for irrigation of vegetable and salad crops eaten uncooked*" Interestingly, in the paper by Blumenthal et al. (2000) there is a report of a study in which onions were irrigated with river water containing partially treated sewage and with an average of 10 000 faecal coliforms per 100 ml. In this case, enteroviruses were found on the onions at harvest, and consumption of onions led to a twofold increase in diarrhoeal disease. It was concluded that *"the risk of enteric infection is significant but low when the [WHO] guideline is exceeded by a factor of 10"*. This indicates a need for an upper limit of acceptability for irrigation water.

So, how does irrigation water quality in the UK salad sector measure up against the types of standards and guidelines advocated in the U.S.A. and by the WHO? We were able to acquire a limited but useful collection of water quality data from the benchmark farm visits and other supporting data from the questionnaire survey. The survey indicates that approximately 5% of the UK salad irrigated area is supplied by mains water. We would expect this water to conform to the EU drinking water standard at the point at which it is delivered to the grower. However, there are opportunities for quality to deteriorate on farm as a result of storage in open reservoirs or unhygienic balancing tanks, or contact with unhygienic pipework. We would expect such irrigation water to remain of a high standard relative to surface water sources but it may not meet drinking water standards unless the level of hygiene in the growers' storage and distribution systems is equivalent to that achieved by the water supply company. 16% of the UK salad irrigated area is supplied by groundwater. Groundwater has the potential to meet very high microbiological standards. Groundwater data provided by one grower demonstrated that the source would meet microbiological drinking water standards without the need for treatment. >70% of the UK salad irrigated area is supplied by surface water either directly or indirectly via storage. Surface waters are more likely to contain faecal microorganisms. The limited data acquired from growers suggests that surface water sources would typically meet the WHO guideline limit of ≤ 1000 faecal coliform bacteria / 100 ml. It would be rare for a surface water source to meet the drinking water standard of 95% of samples achieving 0 faecal coliform bacteria / 100 ml however. In summary, although a comprehensive dataset for source water quality does not exist, we can reasonably conclude that the majority of growers do not irrigate with water that would conform to the EU drinking water standard. Furthermore, we conclude that the majority of growers utilise water that is faecally-contaminated, but that typical faecal coliform concentrations are ≤ 1000 / 100 ml (and normally considerably less than this according to the data available).

Progress towards a standard based on the absence of faecal indicators may be attractive to retailers but may be considered disproportionate. In their review of the WHO guidelines for the microbiological quality of treated wastewater used in agriculture, Blumenthal et al. (2000) concluded an "*approach based on the absence of faecal indicator organisms in the wastewater is an unnecessarily conservative and expensive instrument for public health protection*". It should be emphasised that these guidelines are specifically related to treated wastewater, but as the chronic faecal pollution of UK rivers is caused by sewage treatment works discharges, these guidelines remain relevant. In the related field of bathing water quality, similar concerns have been raised regarding proposals to tighten the microbiological standards encompassed within the EU bathing water directive (76/160/EEC). The European Commission's draft proposal is for a mandatory standard of 500 *E. coli* / 100 ml and 200 enterococci / 100 ml (as 95 percentile values). The current mandatory value is 10 000 total coliforms per 100 ml and 2 000 *E. coli* / 100 ml. Defra have queried the epidemiological basis for the proposed revision, its cost-effectiveness, and "*whether protecting the public from bathing-related illness should be a high public health priority*" (Defra, 2002). Any proposal to introduce an irrigation water quality standard based on the absence of faecal indicators could also be considered disproportionate in the context of other sources of faecal pollution in-field. The soil in which salads are grown typically contain measurable numbers of faecal bacteria (Lang *et al*., 2002) . Similarly, birds and wild animals make regular inputs of faecal matter into the fields in which salads are grown. In the context of a natural, open-air production system, a zero faecal indicator standard for irrigation water seems out of place.

One option for the industry is to argue for a "business as usual" approach based on the argument that there is no concrete evidence that there is a problem with current practice. This position may be hard to defend. In general the approach to pathogen risk management for harvester hygiene is more rigorous than that typically in place for irrigation water quality monitoring and management.

Available evidence suggests that contamination as a result of human handling presents the principal threat to the microbiological quality of product contamination and therefore the measures being taken are proportionate and credible. The gulf between these measures and those taken to document irrigation water quality could, however, be interpreted as an indication that water quality is a low priority. The salad industry's bargaining position could be enhanced, for example, by adopting a code of practice that sets out minimum requirements for water quality monitoring for instance.

5.3 Towards a solution – a proposed framework for water quality monitoring and management

The lack of appropriate guidance on irrigation water quality partly means that growers are not of a mind to invest in monitoring as they are unsure of how to deal with microbiological data. There is a strong argument for developing industry guidelines on microbiological quality. Existing quality criteria such as the WHO wastewater reuse guidelines and the EU bathing water standards could be used to guide the process. One possible starting point would be the development of a series of thresholds to indicate good, moderate, and poor water quality (Figure 3).

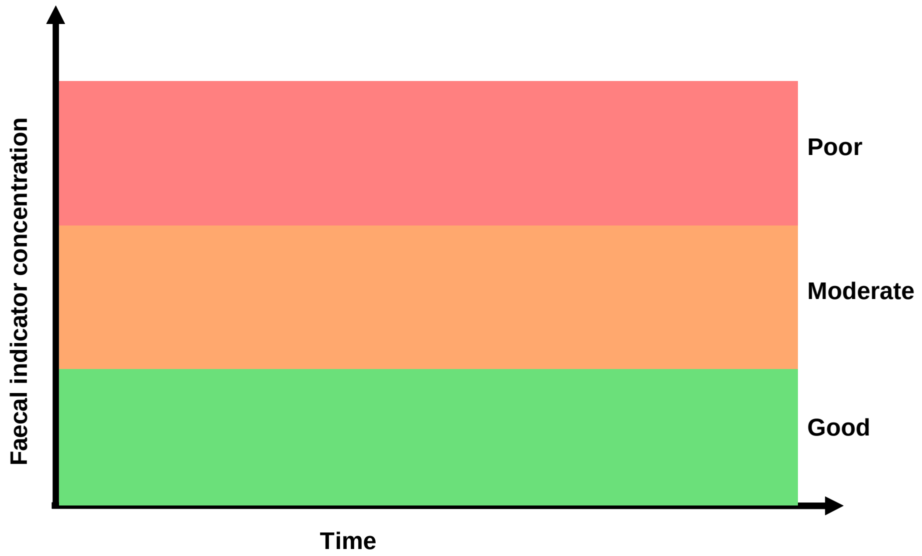


Figure 3. A template for representing water quality monitoring data for a single or multiple irrigation seasons using thresholds as a guide to acceptability

Such a scheme could be piloted with a limited number of growers to assess the practicality and implications. The key issue arising from such an approach is how to respond to the data. Figure 4 illustrates one scenario. In this case, the water quality is normally of a good standard with occasional dips. The response of this may be to investigate the glitches when they occur, ascertain if they are avoidable, inform the supplier, but to continue production in the normal way.

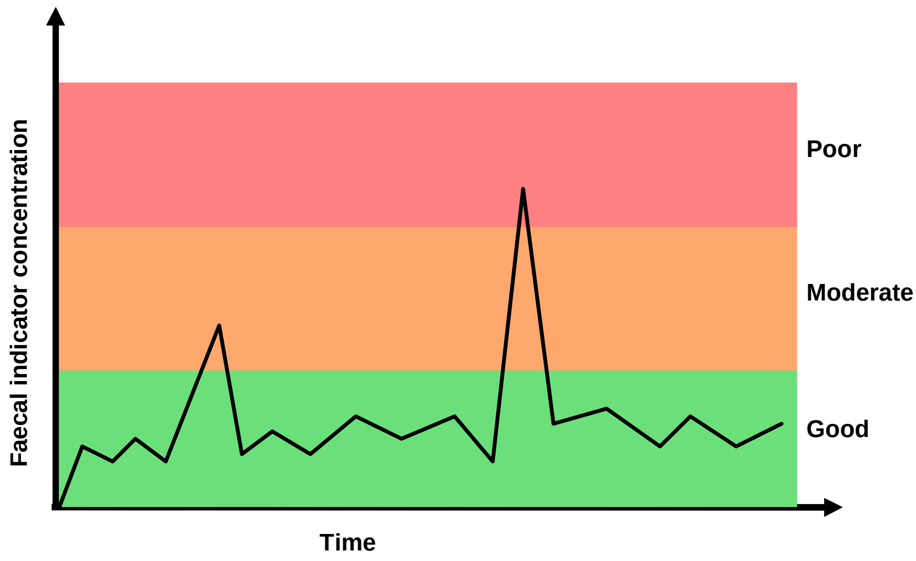


Figure 4. Illustration of hypothetical water quality monitoring data in which water quality is generally good but with occasional reductions in quality.

Figure 5 illustrates a scenario in which water quality is typically moderate but sometimes poor. The response of this may be to investigate the cause of the problem and to consider alternative sources of good quality water.

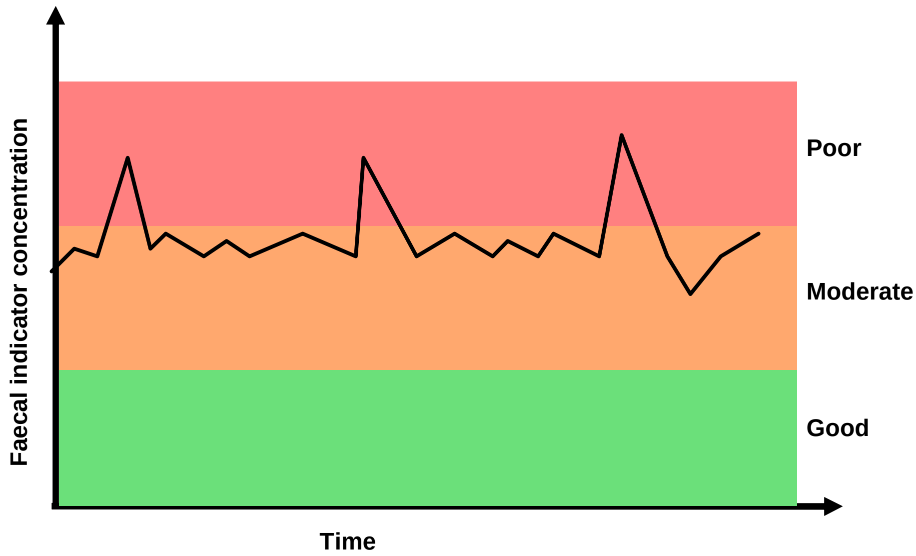


Figure 5. Illustration of hypothetical water quality monitoring data in which water quality is generally not good.

Figure 6 illustrates the value of trend monitoring. The source water quality is deteriorating and requires prompt action to investigate the problem and to identify possible solutions.

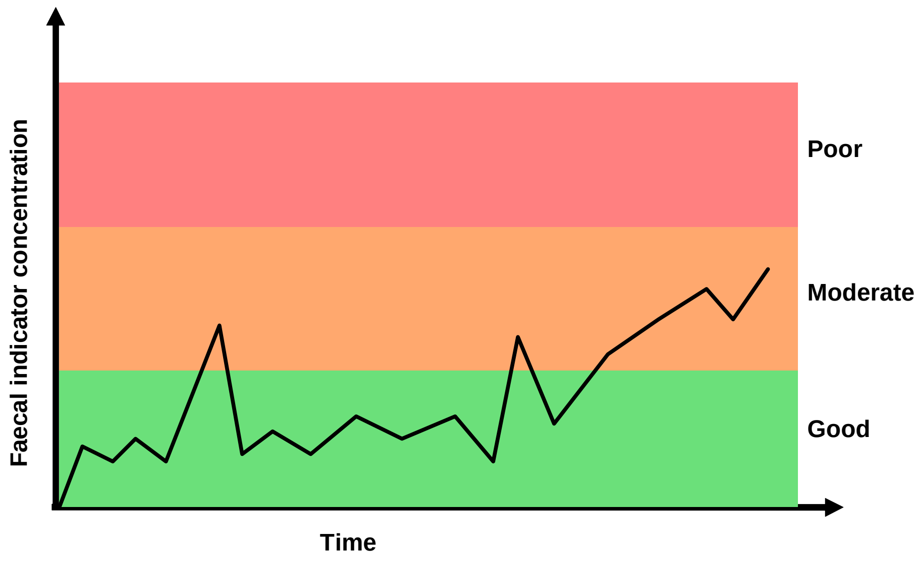


Figure 6. Illustration of hypothetical water quality monitoring data in which water quality is generally good but demonstrating a trend towards poor quality.

The focus should not just be on microbiological standards. Complementary management approaches such as HACCP and good practice in irrigation system hygiene should be considered.

5.4 Options available for accessing high quality water for irrigation

A grower faced with doubts about water quality appears to have four options:

- Demonstrate existing water is of adequate quality
- Treat existing water
- Change water source
- Relocate crop

In all cases, improving irrigation efficiency, e.g. by changing to precision methods such as trickle (drip), will theoretically reduce the volumes required and hence the cost of water and/or treatment. As water costs increase, higher expenditure on water saving technology and better management becomes more justifiable financially.

Demonstrate existing water is of adequate quality

An approved programme of monitoring is a pre-requisite. This must be able to quantify all the likely problem contaminants, and be repeated frequently enough to identify short-term problems. The results must then be assessed and classified against agreed quality criteria. Finally, a plan of action must be in place in case of non-compliance.

Mains water is increasingly being suggested as the standard for comparing quality. However, this standard may be unnecessarily extreme. Furthermore, some of the other drinking water standards, such as taste, colour, turbidity, and odour are of little direct relevance in terms of irrigation suitability. Conversely, some chemicals which are restricted in mains water, such as nitrates, can be positively beneficial in irrigation water, replacing some artificial fertiliser. Hence some groundwater sources rejected for mains supply would be ideal for salad irrigation.

However no alternative standards yet exist. It would seem sensible for the industry to work towards its own set of agreed guidelines and criteria.

Treat existing water

Treatment options have been discussed in detail previously. Cost, reliability and flexibility are likely to be important factors, but the optimum choice is likely to depend as much on the irrigation method, farm layout, management level and the overall business plan as on pure technical performance.

Again, a monitoring/assessment/action plan is essential. Clearly, a defined acceptable quality is a pre-requisite for treatment selection and operation.

Change to alternative water source

There are a range of alternative water sources (see Table 13) each of variable quality (see Figure 7) and which could still need treating to varying degrees. Most growers will have only a few of the options on their site, and may not have access to all of those.

Almost all abstractions from surface or groundwater now require a licence and will be subject to environmental restrictions. In many catchments new licences are unavailable, particularly for summer abstraction. Water and/or abstraction licences can still sometimes be purchased from neighbours or from other users in the same catchment. The Water Act (2003) makes this simpler, e.g. by removing the point of use stipulation from new licences and by simplifying licence trading, though environmental constraints will limit opportunities. Reservoir storage allows the use of higher winter flows, which are more widely available.

Using a combination of sources increases reliability and can reduce costs, e.g. supplementing mains supply by rainwater harvesting. However, it may be necessary to restrict some crops to the higher quality source, and use the existing water elsewhere. This would have cost implications for pipe systems and storage.

There are significant benefits from combining with neighbours, to obtain economies of scale and the increased reliability of multiple sources.

Relocate crop to alternative site

Land rental or land purchase offers options to move the crop to the water rather than the reverse. Annually renting new land with water already appears to be widespread for producers of some horticultural crops needing long rotations, e.g. carrots. Moving permanently may be a necessary longer-term response for some growers.

Table 13. Water source options.

Summer abstraction of surface water

If an abstraction licence can be obtained, surface water (i.e. from rivers, streams and lakes) is usually the cheapest and simplest option. However, summer surface water is likely to be the poorest quality micro-biologically. Many rivers carry sewage effluent, and this is diluted least at times of low flow. Most streams and rivers are affected by diffuse pollution from agricultural land. Runoff after summer thunderstorms often carries pollution from livestock.

Winter abstraction of surface water with on-farm storage

Winter flows are generally better quality than summer flows (though they may contain more silt), with higher dilution factors. Rejecting the first winter flows can be helpful. Storage in the reservoir may also allow some quality improvements, though further pollution can be caused by wildlife, particularly gulls. Covered reservoirs are likely to be prohibitively expensive for the large volumes required for winter storage. The lower winter abstraction charges will not offset the storage costs (see Weatherhead et al., 1997). However, winter abstraction is more reliable, and the grower will know whether the reservoir is full well before planting, thus reducing risk.

Groundwater abstraction

Groundwater can be of high quality, and is generally more consistent over time than surface waters. Boreholes minimise contamination more than wells. Springs require careful protection but can also provide high quality water (as shown by bottled spring water). The costs of drilling the boreholes can make groundwater a more expensive option initially, but it may be preferable in the long term.

Rainwater harvesting

Harvesting rainwater runoff off roofs can provide a valuable water source, particularly for glass houses. Storage is necessary to cope with dry periods. The trade-off between roof/crop area ratio, storage volume and reliability can be modelled (see Weatherhead et al. ., 1997), but a back-up source is usually needed. The rainwater itself is of high quality, but pollution can occur from for example bird droppings. Some growers have also expressed worries about herbicide sprays from surrounding farmland being blown onto the roofs.

Water can also be harvested off concrete and tarmac areas (beware of oil/petrol/diesel pollution from vehicles), off clay soils, or from land-drains (the law on this is unclear). It may even sometimes make commercial sense to construct new collection areas.

Re-use

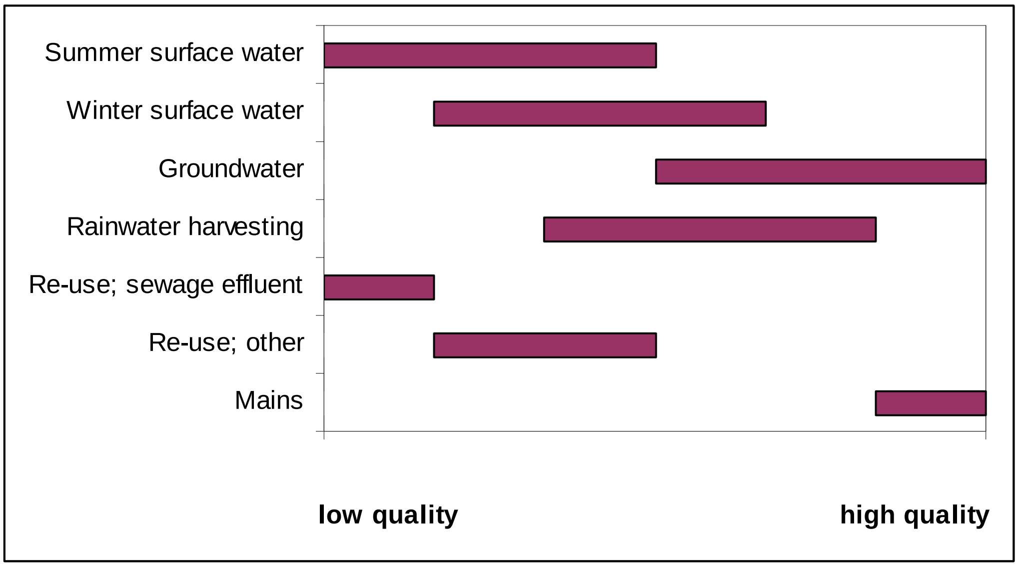
Water used for purposes such as crop washing can often be re-used for irrigation, avoiding discharge costs as well as providing a free water resource. Quality and treatment requirements clearly depend on the prior use.

Re-use of sewage effluent is practised in many parts of the world. Direct re-use is not yet used for any irrigation in the UK (to the best of our knowledge), though indirect re-use of effluent discharge via streams and rivers is commonplace. Salad crops are the least suitable irrigation crop using this source.

Mains water

Mains water is expensive (typically £0.5-0.8 /m^3), and is often not available in the quantities required. Most farms are at the end of long supply pipes, often of small diameter. Typically abstraction is limited to night-time only, and storage may be required for meeting peak demand. Water companies are not required to supply water to businesses (unlike households), and customers only requiring water in dry summers are not necessarily welcomed.

Figure 7. Indicative ranges of water quality for irrigation



Note: indicative only; some sources will lie outside these ranges.

6 FURTHER RESEARCH

Three lines of further research are recommended as a result of this study.

6.1 The development of guidance on irrigation water quality monitoring, assessment and management

There is a need for guidance for growers on the microbiological monitoring of irrigation water i.e. what to measure, where to measure it, and how often. Growers also need guidance on how to respond to the different water quality scenarios set out in section 5.4. A collaborative research project is proposed which would have the ultimate aim of the development of new industry guidelines. Such a project would have the additional outcome of generating a meaningful database on water quality used for salad irrigation in the UK. The project would have the following principal components:

- The development of an interim classification system for the microbiological water quality of irrigation water together with compliance criteria.
- The development of an interim monitoring plan for growers.
- The development of interim guidance on how growers should respond operationally to different water quality scenarios.
- A trial of the interim classification system and monitoring guidance, involving several growers.
- An analysis of the findings leading to the development of finalised guidelines to growers.

6.2 Small-scale/on-farm demonstration of selected treatment technologies

The current project has been predominantly desk-based underpinned by a grower survey and a number of on-farm visits. The range of potential treatment technologies available to salad enterprises has been evaluated and a short-list drawn up. However, a major gap will still exist in actual grower uptake without there being some form of practical demonstration and comparative in-field testing of the various options, under conditions that growers can relate to. This type of work would be undertaken in conjunction with selected water treatment technology companies in order to road test and develop equipment that fits the treatment needs, affordability and other criteria of the salad crop sector.

6.3 Implementing best practice in irrigation water management

Feedback from many of the benchmark farmers coupled with the findings of the irrigation survey confirmed that there is significant scope to improve existing standards of on-farm water management.

Demonstrating sustainable water management practices and particularly the efficient use of water will become increasingly important. Using less water will reduce the problem and cost of finding high quality water and/or treating that water. The gap in knowledge relates to the provision of some form of framework or package that could help growers demonstrate best management practices. It is proposed that a decision support package could be developed to help growers improve their current approaches to irrigation scheduling (essential for demonstrating efficient use of water to the multiples via the grower protocols) whilst also collating the necessary information to support the renewal of abstraction licenses for irrigation (addressing the Environment Agency's duty to assess reasonable need and best use of water under the new Water Act 2003).

7 CONCLUSIONS

- Irrigation water is one of many potential sources of contamination of salads. No published direct evidence has been found to link the irrigation of salads to disease outbreaks in the UK. However, there is a clear potential for this to occur.

- Laboratory trials have shown that pathogens associated with poor quality irrigation water may survive until harvest. Epidemiological investigations (not from UK) have indicated a link between disease and poor quality water. On occasions, some UK salad crops are probably irrigated with water of a lower microbiological standard than that recommended for comparable uses (e.g. reuse of wastewater for irrigation and bathing). The actual extent to which this occurs should be quantified and reviewed.

- The lack of guidance on irrigation water quality is a deterrent to proper water quality monitoring as growers are unsure how they might respond to the data generated. This situation should be corrected as a matter of priority.

- It is reported that some of the multiple retailers in the UK favour a standard for irrigation water close to that which would meet the requirements for drinking water (i.e. absence or infrequent presence of *E. coli* in 100 ml water). Our review of standards would suggest that this may be unnecessarily cautious and expensive.

- A grower faced with doubts about water quality appears to have four options:

    - Demonstrate existing water is of adequate quality
    - Treat existing water
    - Change water source
    - Relocate crop

  A site specific water resources study should be undertaken before assuming that treatment is necessary.

- Where water quality cannot be assured by management or sourcing strategies, treatment technologies may be considered. Of the many options, three technologies are likely to be suitable: U/V treatment, thermal treatment, and sand filters. U/V is considered to be attractive when taking all of the factors into account. Thermal treatment is the most rigorous and reliable.

With heat recovery, such treatment could be viable in some cases. Sand filters offer the most farmer-friendly solution but these systems offer less assurance of water quality.

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9 ANNEX - QUESTIONNAIRE