Report to the Food Standards Agency

B17005 - Review of the use of irrigation water in UK agriculture and the potential risks to food safety

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Compiled for the Food Standards Agency by:

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Executive Summary

The transfer of pathogens to agricultural land and crops by contaminated irrigation water represents a significant challenge to producers, processors, and consumers since there is an established link between the application of irrigation water containing pathogens and increased frequency of pathogen isolation on produce, which may lead to disease in humans. The main risks are to ready-to-eat (RTE) crops since cooking, peeling and other processing of vegetables has been shown to reduce the risks from pathogen contamination. Hence, the focus of this report is the microbiological risk associated with irrigation of RTE crops. Priority pathogens were selected which have been associated with fresh produce, tend to be found in high loads in sewage, could potentially originate from irrigation water and are persistent under normal growing conditions. The following pathogens were selected for investigation: *Salmonella*, *Escherichia coli* O157, norovirus, rotavirus, *Listeria*, *Campylobacter, Clostridium perfringens*, *Cryptosporidium* and *Giardia*.

It should be noted that a large proportion of fruit and vegetables in the UK markets are imported. To date no foodborne outbreaks in the UK have been linked to irrigation practices but there are many examples from abroad. The reference pathogens selected for this study have a significant theoretical potential to be applied to crops in contaminated irrigation water.

Survey results indicate that the total area irrigated for all vegetables has risen since 1995, with irrigation especially widespread in the Environment Agency's (EA) Anglian region of England. Surface water is the primary water source for irrigation in England (c.54-58%), followed by groundwater (c.36-41%). Mains water, recycled water and harvested water and other minor sources account for the remainder (c.5%). There is regional variation in the water sources used for irrigation due largely to source availability and crop requirements. Limited information is available specifically on the irrigation practices for RTE crops, however, a study of outdoor salad crops indicated that 71% of the irrigated area used surface water as a source, 37% of which had been stored before use. The quality of surface waters can fluctuate considerably and is the most vulnerable to contamination. Discharges from sewage treatment works to inland waters are an important contributor of pathogens in sources that may be used for irrigation. Quality is affected by the degree of dilution at the point of discharge as well as environmental conditions, including rainfall, and land use. The relative locations of effluent discharge and abstraction

points for irrigation will clearly affect the quality of the irrigation water and the potential for subsequent contamination of crops.

The quality of irrigation water is affected by a number of factors resulting in the inactivation and reintroduction of pathogens. Primary factors affecting the survival of pathogens are temperature, sunlight, storage time of water, pH, harvest interval and protection afforded by the crop itself – moist and dark conditions have been shown to be favourable for pathogen survival – e.g. inside of lettuce head.

No data was available for the purposes of this study on the proportion of water abstracted for direct use and for storage. Water abstracted in winter is likely to be stored in reservoirs and summer abstraction is stored or used directly. Leaving aside rainfall events when sewer overflows may operate and surface runoff from farmland may occur, water abstracted during high flows in winter would generally be expected to be of better quality than that taken in summer when the flows are lower and dilution of pathogen loads is less. Storage of water allows pathogen die-off and predation, the rate of which depends on environmental factors such as temperature, sunlight and pH. However, water stored in reservoirs is also prone to contamination from wildlife unless properly protected, although protection may not be feasible for larger reservoirs. Storage time in reservoirs could therefore be an important issue in terms of irrigation water quality. The proportion of water reported as drawn from winter storage reservoirs in England in 2005, a wet year, is 30%. The use of reservoirs varies throughout the country. In one survey conducted in 2003 it was found that 37% of water used on salad crops had come from reservoirs, largely comprising of surface water.

Water management practices also play an important part in influencing the impacts of the environment. Three types of water application process are used in irrigation in the UK: overhead irrigation is predominant, surface irrigation, which is a small proportion and sub-irrigation (a method of [irrigation](#) where [water](#) is delivered to the plant root zone from below the soil surface), the extent of which is unknown. The type of irrigation methods used tends to be linked to crop type. In terms of microbiological risks to RTE crops overhead irrigation is of particular concern due to the direct application of water to aerial parts of the plant. Droplet size tends to be large for some types of equipment using this method (rainguns) which may lead to soil splash and possibly crop contamination.

Trickle irrigation (used more for perennial crops, and crops grown in greenhouses such as tomatoes, aubergine, cucumbers and sweet pepper) irrigates only the roots of the crop and not the aerial parts of the plant, possibly resulting in less contamination.

The quantity of water applied is potentially important. Over-application of water for example may result in an increase in the number of pathogenic organisms applied to the crop. Timing of irrigation and harvest interval tends to be crop specific. These are both important factors in terms of food safety, especially for RTE crops. During dry conditions irrigation tends to be more frequent; shallow rooting crops such as baby leaf brassicas, salad onions and spinach require more frequent applications, as do crops grown on soils with less water availability.

Harvest interval varies from <1 day to >10 days depending on the crops and conditions. Sunlight and temperature are primary factors for inactivation of pathogens, therefore there is a greater opportunity for die-off in plants with long harvest intervals and those grown outside and harvested in late summer provided they are not irrigated immediately prior to harvest.

Frequency of water quality monitoring varies considerably from one sample per year to monthly. Sampling may occur from the source or reservoir or at the irrigator or at nearby abstraction points. Relatively little guidance exists to advise growers about how to respond to water quality results. Indeed in some cases the results of the monitoring is available after the crop has been sold and consumed.

The availability of water for irrigation is increasingly constrained and if the general predictions of climate change are accurate the resources available will be reduced even further, resulting in possible changes to crops, production areas and irrigation techniques. Changing environmental conditions will likely result in emerging and re-emerging pathogens as issues for the future.

There are a number of issues which are discussed in this report as particularly important factors influencing pathogen loads on crops, which need to be addressed in order to control the hazards posed by pathogens in irrigation waters. These are primarily the management of the irrigation water, the method of application of the water to the crop and the harvest interval. Although risk assessment is used within the industry there is little supporting information for growers about how to carry this out, how to interpret results and what action should be taken in the light of those results. Data is lacking in some areas which would help decision-makers provide appropriate guidance to growers in order that they can undertake assessment of risk and implement appropriate management actions.

This report is presented in two sections. Section 1 deals with the microbiological risks associated with irrigation water. Section 2 provides information relating to irrigation practices in the UK.

Recommendations to the FSA from Section 1

- Acquire information on microbial water quality in river systems where irrigation is an established water use and make this information widely available to growers.

- Develop predictive models to help identify high risk situations regarding the quality of water used for irrigation.

- Provide guidance to growers on risk assessment processes, monitoring and interpretation of water quality used for irrigation and mitigation measures.

- Develop educational material to increase understanding of microbiological risks to irrigation waters and workshops to explain how to carry out a risk assessment.

- Identify and resolve potential conflicts with environmental policies and practice.

- Develop a single comprehensive source of good practice guidance.

Recommendations from Section 2

A number of issues need to be addressed before growers can be provided with the information they need to assess the risk from their own operations and to take appropriate management measures. This is likely to involve issues of data acquisition, development of measurable parameters and standards for water analysis, education and development of a comprehensive set of guidance. Coordination of effort between Defra, FSA, other statutory agencies and stakeholders is likely to be required. It is therefore recommended that the FSA gives consideration to the following:

Recommendation 1: the acquisition of information on microbial water quality on river systems where irrigation is an established water use

Surface water is the largest source of water used for irrigation, and is frequently abstracted from rivers for direct application without storage. In lowland areas, where most irrigation occurs, the catchments of rivers can be very large and are characterised by human settlement and more intensive forms of agriculture. Rivers are used for the outlet for most sewage effluent, and livestock farming and/or manure application to land will also be practiced in most catchments, although in varying degrees. Rivers can be characterised by fluctuating pathogen loads and growers may have little if any control over their microbiological quality.

The risk to food safety from the use of irrigation water abstracted directly from rivers is difficult to assess without water quality data representative of the level of contamination and its variability. It was clear before the start of this study that there was limited data available in the public domain on microbiological water quality relevant to waters used for irrigation. The EA monitors environmental quality for a range of parameters at a large number of sites, but microbiological data is routinely collected at only a limited number of locations. These include some of the longstanding harmonised monitoring sites and sites affecting bathing and shellfish waters. Although not necessarily available, Water Companies also collect microbiological data and routinely risk assess catchments used as drinking water sources for *Cryptosporidium.*

It is not clear whether the surface water microbiological data obtained for this study are representative of water used for irrigation. Tyrrel, however, found that data from growers, albeit limited, suggested that surface water sources would typically meet the WHO guideline limit (1989) of < 1,000 faecal coliforms/100 ml (Tyrrel *et al.,* 2006). For risks to

be estimated and proportionate guidance to be developed, further data on the quality of water used for irrigation would appear to be necessary.

Recommendation 2: the development of predictive techniques to help identify risk situations in surface waters

The fluctuating microbial loads of surface waters, with irregular spikes of uncertain magnitude, can be a problem for growers, particularly those who irrigate without the use of storage which may help to attenuate microbial loads. Defra has commissioned research on predictive techniques for peaks in microbial levels for the purposes of the Bathing Waters Directive which is now well advanced. The application of such techniques to irrigation waters could be investigated if it was considered that the risks to food safety would justify their use. Predictive techniques could allow advance warning to be given and facilitate pre-emptive action being taken by irrigators.

The development of a GIS based methodology that combines data on agricultural water abstraction (use) with data on sources of contamination could be used to provide a baseline assessment to determine and categorise irrigation water sources in terms of level of contamination (Knox (Cranfield University), *pers. comm.).* The methodology could be tested in a selected catchment where there is a dependence on surface water abstraction for irrigated production (Knox, *pers. comm.).*

Recommendation 3: arrangements for growers to access information on surface water to aid them in their risk assessments

Risk assessment of surface waters, particularly river systems, is demanding.

Growers' own monitoring data can be a useful input into their risk assessments, but an understanding of the source and its characteristics may require all the available information from wider sources to be brought together and assessed.

The EA has a comprehensive view of most aspects of water quality in England and Wales (as does SEPA in Scotland), and has assessed and classified the status of all water bodies for the purposes of the Water Framework Directive. This process has included assembling microbiological data and appraisals for bathing and shellfish waters, and relevant information may be available for risk assessments for irrigation waters.

The question arises as to how best to access the expertise residing within the environmental agencies and Drinking Water Inspectorate and any data and assessments that may be available. The question also arises as to whether the EA's water quality

monitoring processes can be adapted to better inform risk assessments for microbial parameters. For example, this could be done by including analysis for microbial parameters at a wider range of water quality monitoring points than is currently carried out.

The EA currently provides abstractors with rapid notification of upstream pollution incidents (EA, *pers.comm.*), for example after raw sewage discharges from sewer blockages, or spillages of livestock slurries. Growers could be encouraged to register for this service. However, a grower reported that when the EA was approached it declined to notify the irrigator of microbiological incidents.

Recommendation 4: the provision of information and guidance to assist growers with monitoring and interpreting results

It frequently emerged in discussions that some growers do not know how to interpret the results of their microbiological analyses to be able to assess whether water is suitable for its intended use. More guidance appears to be needed on target organisms and levels which can be regarded as acceptable, and on sampling regimes (frequency, timing, sampling point, depth etc.). There may also be a need for guidance on the use to be made of water quality monitoring data.

The significance which can be attached to water testing in assessing water quality is given considerable attention in some overseas guidance documents, with a number of reasons being given to growers to explain shortcomings in over-reliance on this. The US Food and Drug Administration (US FDA) draws attention to a number of gaps in the science upon which to base a microbial testing programme for agricultural water, adding that microbial testing may be of limited usefulness (CFSAN, 2001). Irish guidance advises that growers should focus on the adoption of good agricultural practices to control water borne hazards and use testing as a means of validating good practice (Food Safety Authority of Ireland, 2001).

In some overseas guidance testing also has a role in triggering mitigating actions, including testing of product. One difficulty with this is the time taken to receive results from conventional laboratory analysis, and a frequent comment from growers was that, by the time test results are received, produce may have been sold and consumed. Some growers use rapid test techniques and the scope for these to be used more widely could be explored. Another aspect to be considered is that some growers report finding little correlation between product quality and irrigation water. A problem with testing surface waters in

particular is the volatility of microbial loads. This is illustrated by the EA monitoring which shows that surface water quality varies from day to day, or even hourly (Groves et al, 2002).

Recommendation 5: provision of guidance, including decision support tools, to assist growers with the process of risk assessment

It was reported that the standard of risk assessments presented for audit can be variable. Discussions with growers indicated uncertainty about both the process to follow and the factors and information to be taken into account. Growers felt they needed more guidance on how to carry out a risk assessment and thought that checklists of relevant factors, as provided in some overseas guidance, may have a useful role.

Assessing the combined effect of the various risk factors in a particular situation is a potentially complex decision and a more structured and standardised approach capable of delivering a more consistent outcome may help to reduce risk. This could for example take the form of decision trees. This would seem to fit with the widely held view that a standardised approach to risk assessment would be better than applying a single standard to the different risks arising from the range of irrigated crops and sets of conditions.

Feedback from growers is that they would be seeking an approach that is simple to use, but which would allow flexibility in their response to varying crop risks and local situations. They are very concerned that blanket measures or standards could be introduced in a "one-size-fits-all" approach across a range of crops and situations, which is perceived as likely to impose unnecessary and possibly unaffordable costs. A proportionate and targeted approach enabling effort and cost to be focused where it is needed is likely to enjoy better support from the industry.

Growers showed interest in the example of the decision tree used in Australian guidance (Department for Agriculture Fisheries and Forestry, 2004) and indicated they thought this approach may be helpful. Decision support software has been developed for Defra for use by farmers and growers for other aspects of production, such as determining the correct rates of fertiliser and manure use according to a number of variables, and is becoming established. Its use is encouraged by Defrasponsored workshops and other forms of promotion.

Recommendation 6: education on microbiological aspects of irrigation

While larger growers tend to have microbiological skills in-house, the feeling expressed was that smaller growers are not well versed in these matters and a common theme to emerge in discussions was the need for education. HDC appears to have recognised the importance of this when instituting grower workshops around the country to accompany the launch of its DVD "Keeping it Clean". On the basis of the information obtained for this study, there may be scope for further technical support and workshops, particularly if there were to be more detailed guidance on risk assessment as suggested above. Defra, for example, sponsors such events for irrigators in relation to water efficiency measures and diffuse pollution issues.

Recommendation 7: addressing crop risk on a crop-specific basis

Some observers take the view that crop categories need to be rationalised to enable effort to be more tightly focused on the highest risk crops. Growers have expressed concern that the current categorisation does not always reflect the situation on the ground. Some carrots for example are not harvested until autumn and winter and may not have been irrigated for several weeks, while most onions are dried and may be stored for up to a year.

Dealing with crops on a crop-specific basis would allow measures to be more tailored to the risks attached to different crops. The AP crop-specific protocols could provide a vehicle for this, linked to crop authors' expert knowledge of their sectors. This would require the necessary under-pinning science to be in place, which may not currently be available.

Another reason for improved targeting of crop risk is that growers in the south and east of England in particular are likely to have increasing difficulty accessing good quality water for use on higher risk crops on account of competing demands for public water supply, protection of the environment and climate change.

Recommendation 8: identifying and addressing tensions between food safety risks and environmental policies and practices

There has been increasing emphasis in national agricultural policy on the protection and encouragement of wildlife on farmland. Farming in an environmentally responsible manner and enhancing wildlife and biodiversity through positive conservation management are also important aims for some assurance schemes and retailer

schemes. However, there may be some tensions with managing food safety risks from irrigation, and some growers are aware of mixed messages being given.

On a wider policy front, there are increasing demands for the creation of wetlands on agricultural land to provide a range of benefits, including aiding with flood control, enhancing biodiversity and helping to mitigate diffuse pollution. Constructed wetlands, are being put forward by Defra as one of the more cost-effective on-farm measures for reducing pollution to meet WFD objectives (Defra, 2007). On a larger scale, the "Wetland Vision" partnership of statutory and voluntary environment organisations envisages the re-creation of extensive wetlands over a 50 year timescale. The web-site (www.wetlandvision.org.uk) shows a selection of local wetland visions, and 6 of the 23 shown are in the main irrigation region (East Anglia). Creation of wetlands could contribute to greater numbers of wildfowl being attracted into proximity with irrigated crop production, and irrigation reservoirs. Aquatic birds in particular are believed to have a negative impact on water quality.

Natural resource protection is an important part of resource protection, but in some circumstances, abstraction licence conditions may give rise to conflicts with microbial quality, for example in respect of the timing of abstraction for storage.

Recommendation 9: research on the following issues to address gaps
Attenuation in pathogen numbers on crops pre-harvest
Data is needed on the attenuation of pathogen levels in the crop, particularly in relation to RTE crops with short harvest intervals. Results from modelling undertaken as part of this study indicate that this is the most important factor in determining residual numbers of pathogens at harvest. Data on attenuation may also help to demonstrate the need for any measures to growers. (HDC project FV 292, yet to be published, may provide data for the crops being investigated).

Reservoirs
Reservoirs are likely to become increasingly prevalent as a result of the range of pressures identified in this study, particularly climate change. Data is needed on the effects of wildlife and impacts of storage on water quality, including for example the effects of different filling and residence time regimes on different water sources. Measures used overseas to reduce contamination, such as settlement ponds and vegetated treatment systems (Stuart, 2006) could also be investigated.

Methods for Treatment

Where water quality poses food safety risks from harvested produce and other mitigation measures are not available, improvement of water quality may be the principal option. The applicability of treatment technologies to a range of on-farm situations could be evaluated. Issues to be addressed could include performance, practicality and cost-effectiveness.

Recommendation 10: provision of a single comprehensive source of good practice guidance

A code of good practice or similar could provide growers with explanation and information specifically focused on minimising risks to food safety from irrigation. It could also help underpin the audit process.

Issues to be covered could for example include:

- explanation of microbial issues and methods of management

- source protection

- water management to improve quality

- sampling and interpretation

- good housekeeping measures

- monitoring for effectiveness of corrective measures

Mitigation measures to address particular problems could also be included in guidance (as is the case in the current Air Code (Code of Good Agricultural Practice for the Protection of Air) (MAFF, 1998).))

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Abbreviations

AP	Assured Produce
BOD	Biochemical Oxygen Demand
BSE	bovine spongiform encephalopathy
C of U	Coefficient of Uniformity
CAMS	Catchment Abstraction Management Strategy
CAP	Common Agricultural Policy
CCFRA	Campden and Chorleywood Food Research Association
CFA	Chilled Foods Association
CFP	critical failure points
cfu	colony forming unit
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CSO	Combined sewer overflows
Defra	Department for Environment, Food and Rural Affairs
DWF	dry weather flow
EA	Environment Agency
EPA	Environmental Protection Agency
EU	European Union
FCV	Feline calicivirus
FDA	Food and Drug Administration
FPC	Fresh Produce Consortium
FSA	Food Standards Agency
HACCP	Hazard Analysis and Critical Control Point
HDC	Horticultural Development Council
HEV	Hepatitis E virus
HPA	Health Protection Agency

LACORS	Local Authorities Coordinators of Regulatory Services
Ln	Natural logarithm
Log_{10}	Base 10 logarithm
M&S	Marks and Spencer's
MAFF	Ministry of Agriculture, Fisheries and Food
MPN	Most probable number
NFU	National Farmers' Union
NLV	Norwalk like viruses
PCR	Polymerase Chain Reaction
pdu	PCR detectable units
pe	Population equivalents
PHLS	Public Health Laboratory Service
PSA	Public service agreement
QMRA	Quantitative microbial risk assessment
RNA	Ribonucleic acid
ROI	Republic of Ireland
RPA	Risk Policy Analysts
RSA	Restoring Sustainable Abstraction
RTE	Ready-to-eat
SAC	Scottish Agricultural College
SACs	Special Areas of/for Conservation
SEPA	Scottish Environmental Protection Agency
SPAs	Special Protection Areas
SRSV	Small round structured viruses
SSSIs	Sites of Special Scientific Interest
T_{90}	Time for 90% reduction
US	United States

UV   Ultraviolet

VTEC   Verocytotoxin-producing *E. coli*

WFD   Water Framework Directive

WHO   World Health Organisation

WwTW   Wastewater treatment works

Section 1 - Microbial risk associated with irrigation water

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Chapter 1 Introduction

Many fruits and vegetables are eaten raw, often with minimal processing by the consumer to reduce potential surface contamination. Thus, there is a risk of the consumer being exposed to pathogens that have contaminated the product during its growth and preparation for sale.

The risk of transmission of microbial pathogens through water contaminated by farm waste run-off has been considered by a number of FSA-funded projects (e.g. FSA B05006/7, B17001). These projects showed that many water supplies, such as rivers and ponds, were susceptible to contamination by infectious agents in run-off from land (FSA B17001). However, this is not the only potential source of contamination of water resources used for irrigation. Point sources of contamination, such as discharges from sewage treatment works may also be significant.

The contamination of water resources from the spreading of farm slurries onto agricultural land has been identified as a route for transmission of microbial pathogens (DH 221, FSA B17001), including *Escherichia coli* O157 (BBSRC D12282), with the greatest risk of transmission being during the first 24 hours after spreading (SEERAD UAB/007/99).

Use of contaminated irrigation water is a possible route for the introduction of pathogens to the wider environment and also to the food-chain (FSA B17001). The risk from contaminated irrigation water is considered greatest for ready-to-eat (RTE) crops, such as salads, and lower for those crops which would be cooked, peeled or otherwise processed before consumption. The focus of this project is the potential risk to RTE crops from irrigation water.

The dispersal of pathogens to agricultural land and crops by contaminated irrigation water represents a significant challenge for producers and processors of fresh produce. Since the general trend in the UK suggests that the amount of water needed to irrigate crops is expected to increase in the future, due to predicted climatic change and the pressure from retailers to produce crops of a higher quality standard, it is important for the protection of public health that the routes of transmission of pathogens by irrigation are fully understood.

Soil, irrigation water, and processing water are potential sources of bacterial contamination. Pathogens such as *Listeria monocytogenes*, *Clostridium botulinum*, and *Bacillus cereus* are naturally present in some soil, and have been detected on fresh produce (Beuchat *et al.*, 1997). Irrigation water contaminated with untreated sewage,

manures, or contaminated wash water is a potential route of contamination of fresh produce with bacteria, parasites and viruses (Beuchat *et al.*, 1997; Solomon *et al.*, 2002b; Wachtel *et al.*, 2002). Washing of harvested produce, such as bagged salads, with hyperchlorinated water may reduce populations of some pathogenic and other microorganisms on fresh produce but cannot eliminate them (Beuchat *et al.*, 1997).

The limited process controls available to prevent product contamination and transmission of pathogens, should contamination occur, means for fresh produce, the greatest risk of foodborne illness is associated with uncooked fruit and vegetables, whilst at the same time there is an increased shift of the public towards consumption of these foods and therefore increased exposure.

Understanding the risk factors leading to contamination of irrigation water, in combination with the health outcome after infection, will allow an appraisal of the significance of pathogens. The source of the pathogen, including the potential reservoir, and the pathogen loadings in the source and the water body are of importance in assessing the risk posed by the water body that these pathogens are found in. If the water body is used for irrigation, this potentially has significance for food safety. In addition, the risks associated with the method of application of the irrigation water, including the timing of irrigation should be considered.

Aim and Scope

The aim of the study was to assess the risks to public health from different irrigation practices used in agriculture. The results are presented in two sections.

The first section identifies:

- The key pathogens causing foodborne illness and their modes of transmission (Chapter 2)

- The characteristics of the pathogens that control survival and mobility in the environment (Chapter 3)

- Data to assess, and the tools available to predict, the quality of water used for irrigation (Chapter 4)

- The relative risks from different irrigation practices (Chapter 5)

The second section identifies:

- The irrigation practices and water sources currently used in the UK, and how they may impact the level of contamination of crops (Chapters 1 and 2)

- The potential future changes to agricultural water use due to environmental legislation and climate change (Chapter 3)

- Available guidance and legislation to control the risks from irrigation (Chapter 4)

This report identifies whether there is a need for further guidance on irrigation to the industry to reduce risks associated with fresh produce, whether sufficient data exists to control risks from irrigation and suggests areas for further research required to achieve a reduction in risks. The scope of this report, illustrated in Figure 1.1, encompasses the contamination of fresh produce at harvest, resulting from contaminated irrigation water.
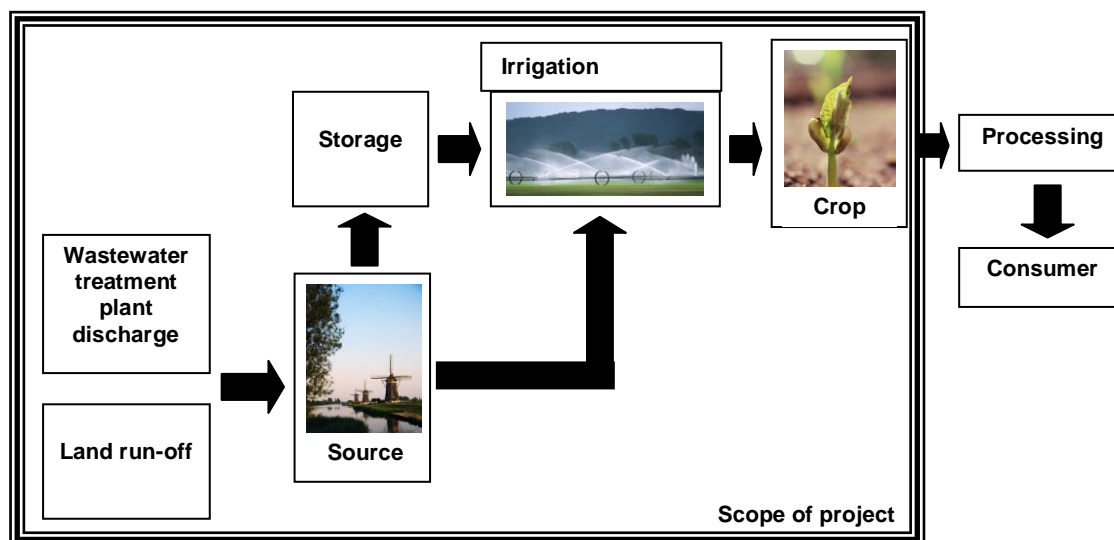
Figure 1.1 Diagram highlighting the scope of this project within the food supply chain for fresh produce

Chapter 2 Identifying Priority Pathogens

2.1 Introduction

Foodborne disease is of major concern to governments, the food industry and the public. This chapter provides an overview of foodborne disease outbreaks in the UK and internationally over the last decade, focusing on outbreaks attributed to fresh produce. Priority pathogens were identified based on these outbreaks, pathogen prevalence and their use as model organisms for risk assessment modelling purposes. A summary of these priority pathogens is provided.

2.2 Foodborne disease outbreaks

In the UK, foodborne disease surveillance is co-ordinated by the Health Protection Agency (HPA). However, it is recognised that the data collected by surveillance is subject to bias for several reasons: mild cases of illness are not reported or investigated; viral and parasitic protozoa are rarely tested for; variation in reporting practices between clinicians exist; speed of reporting by laboratories varies; and negative results from laboratories are not reported to HPA. As a result, under-reporting of disease is to be assumed, and may be significant.

It has been estimated that between 1996 and 2000 there were over 1.7 million cases of foodborne intestinal disease per year in England and Wales (Adak *et al*., 2005), resulting in almost 22,000 hospital admissions and approximately 680 deaths. During this time the major pathogens responsible for indigenous foodborne disease were *Campylobacter* (337,655 cases), *Clostridium perfringens* (168,436 cases), *Yersinia* spp. (129,338 cases), non-typhoidal salmonellae (73,193 cases), and norovirus (61,584 cases). There were 839,000 cases for which the pathogen was unknown. This study also illustrated the seriousness of foodborne illness with 209 deaths attributed to non-typhoidal salmonellae, 177 deaths attributed to *C. perfringens*, 80 deaths from *Campylobacter*, 78 from *Listeria* and 85 from unknown pathogens. Fruit and vegetables accounted for 49,600 cases of foodborne illness per year (3%), including 14 deaths. The lowest disease risk was for cooked vegetables, at 0.11 cases/million servings and 0.45 hospitalisations per billion servings. Fruit also had a low disease risk at 2 cases/million servings and 15 hospitalisations (in comparison to 5,869 cases/million servings for shellfish). Sixty seven thousand cases of foodborne disease (4%), including 14 deaths, were attributed to food contaminated by infected food handlers. Between 1992 and 2000, salad vegetables and fruit were the cause of 5.5% of foodborne outbreaks of infectious intestinal disease in the

UK reported to the PHLS (now HPA) (Long *et al.*, 2002), with salmonellas (41.0%) and noroviruses (15.7%) the most frequently reported pathogens.

The studies described above used ascertainment ratios, calculated by the Infectious Intestinal Disease Study (Food Standards Agency, 2000), to adjust for the number of cases of disease that go unreported to provide an estimate of total foodborne illness.

By contrast, there is limited data on the geographical source of produce leading to disease outbreaks, making it hard to identify what proportion is derived from UK produce. For outbreaks associated with nationally distributed fruit and vegetables, detection becomes particularly problematic. Furthermore, the origin of the contamination is also difficult to identify, e.g. whether contamination is due to poor irrigation water quality or poor hygienic practices during production and packaging.

Further information on the outbreaks of disease in England and Wales between 1995 and 2005 associated with consumption of fruit and salad vegetables was attained from the HPA. Table 2.1 summarises the outbreaks by specific pathogens. It is not known whether any of these are imported foodstuffs or originated in England and Wales. Almost half of these outbreaks (46%) were reported in the months of June to August. Further information on studies linking the consumption of fresh produce irrigated with contaminated water has been summarised by the World Health Organisation (WHO, 2006).

Table 2.1 Foodborne general outbreaks of infectious intestinal diseases associated with salad vegetables and fruit, England and Wales 1995 - 2005 (Health Protection Agency Centre for Infections Environmental and Enteric Diseases Department, August 2006; full data: Appendix 1.1)

Organism	No. outbreaks	No. affected	No. positive
Bacillus	4	45	0
Campylobacter	5	102	53
Cl. perfringens	5	122	59
E. coli	1	37	24
E. coli O157	2	14	14
Mixed aetiology	1	30	0
Norovirus	9	463	41
Salmonella	28	1354	1024
Unknown	12	240	0
Grand Total	**67**	**2407**	**1215**

2.3 Priority Pathogens

Foodborne pathogens that are frequently associated with fresh produce originate from the intestines of humans, animals and birds and are excreted in their faeces. Contamination of fruit and salad vegetables with pathogenic organisms can occur directly or indirectly via animals or insects, soil, water, dirty equipment, and human handling. In this report we have focused on a selection of 'priority pathogens' for irrigation waters (Table 2.2). The pathogens that were chosen are of priority for three reasons:

- they tend to be found in high loads in sewage and livestock manure. Research has shown that pathogens such as verocytotoxin-producing *E. coli* (VTEC), *Salmonella*, *Listeria* and *Campylobacter* are present in up to one third of livestock manure (FSA B05003/4). Faecal matter can contaminate crops through polluted and inadequately treated waters used for irrigation or processing, through use as a soil fertiliser in fields or by animals defecating close to produce fields or processing areas;

- they pose a high level of threat to the community in terms of severity of health impact, current prevalence of infection and infectivity;

- their ability to be used as 'model' pathogens for risk assessment, i.e. pathogens that are present in irrigation water that are persistent and mobile under conditions associated with crop growth.

The pathogens discussed are: *Salmonella*, *E. coli* O157, norovirus, rotavirus, *Listeria, Campylobacter, Clostridium perfringens, Giardia* and *Cryptosporidium*. A summary of the epidemiological properties of selected pathogens is given in Table 2.4.

It is important to note that contamination of fresh produce is not considered a major route of transmission for any of the pathogens discussed here. Fresh produce, and in particular contamination from irrigation of RTE crops, is a small component of the total illness load. However, significant and serious outbreaks have occurred from fresh produce that have been linked to the irrigation of crops with contaminated water.

2.3.1 Bacteria

Salmonella

Salmonellae are the most common agents of infectious intestinal disease in the UK from fruit and salad vegetable outbreaks (Long *et al.*, 2002). It has been reported that they cause around 10,000 cases of infection in the UK annually (Wheeler *et al.*, 1999).

All *Salmonella* infections begin with the ingestion of organisms in contaminated food or water. The principal clinical syndromes are enteric (typhoid) fever and gastroenteritis. Enteric fever is a protracted systemic illness that results from infection with the exclusively human pathogens, *S. typhi* and *S. paratyphi*. Without treatment, mortality is 10% – 15%. In contrast, the many non-typhoidal *Salmonella* strains, such as *S. enteriditis* and *S. typhimurium*, infect a wide range of animal hosts, including poultry, cattle, and pigs. A study in the USA showed that the prevalence of *Salmonella* in animal faeces has been reported at 3.8% (Callaway *et al.*, 2006), with irrigation water containing manure shown to

be a source of *S. enterica* on vegetables (Islam *et al.*, 2004). Concentrations of *Salmonella* in sewage have been reported to range between 930 and 110,000 per litre (average 22,000) (Koivunen *et al.*, 2003).

Table 2.2 Summary of priority pathogens

Type	Pathogen	Reason for inclusion	Notes
Bacteria	*Campylobacter*	The most common cause of foodborne illness in England and Wales. Consumption of contaminated food of animal origin, particularly poultry, is largely responsible for infection, but *Campylobacter enteritis* has also been associated with lettuce or salads. Does not grow on food.	Principal reservoir: animals Therefore a threat to water quality via excretion from cattle.
	Salmonella	Second most common cause of UK foodborne outbreaks. Can multiply on food if not cooked/ stored at correct temperature.	Principal reservoir: animal. Survives well in water and in soils.
	E. coli O157	Infections traditionally associated with animal products, but outbreaks associated with salad vegetables, fruit juices and water, have been reported with increasing frequency. Important because of the severe health outcomes it causes, low infectious dose and high mortality.	Principal reservoir: livestock. Water and foodborne.
	Clostridium perfringens	A common source of food poisoning but mainly from inadequate cooking and refrigerating of meat. Because the bacteria also live in the soil, contamination from unwashed vegetables is also possible.	Principal reservoirs: animals and environment. Included in this report as the spores of the organism persist in soil, sediments, and areas subject to human or animal faecal pollution.
	Listeria	*Listeria monocytogenes* is widely distributed on raw fruits and vegetables. Can cause severe symptoms. Is ubiquitous in the environment and resistant to environmental stress.	Principal reservoir: animals and environment. Faecal contamination of water and soil (possibly via land application of sewage or sewage effluents) could lead to contamination of fruits, vegetables. Primarily associated with post-harvest contamination.
Virus	Norovirus	Second main agent in UK foodborne outbreaks. Highly infectious. Persistent. Most food-related outbreaks may be explained by faecal or vomit contamination of RTE foods by ill food handlers during harvesting, transport, preparation or serving. Very large outbreaks of norovirus infection have been linked to fruits, berries and salads.	Principal reservoir: human. Norovirus very commonly found in sewage. Contamination of water and soil could lead to contamination of fruits, vegetables.
	Rotavirus	Highly infectious.	Principal reservoir: humans. Predominantly transmitted by faecal-oral route and may contaminate surface water and ground water.
Protozoa	*Giardia Cryptosporidium*	Although there are not many recorded outbreaks of cryptosporidiosis or Giardiasis from salad, fruit and vegetables large outbreaks are associated with water.	Principal reservoir: animals.

Of particular concern is the increasing detection of *Salmonella* isolates displaying resistance to key antimicrobials, such as the recent global epidemic spread of multidrug-resistant *S. Typhimurium* DT104 (Butaye *et al.*, 2006).

E. coli O157

E. coli is an enteric organism and comprises the majority of the normal flora of the gut. More than 400 different serotypes of *E. coli* produce verocytotoxin, and most of these have been linked to human illness (Molbak *et al.*, 2004). *E. coli* O157:H7 is the most commonly identified VTEC serotype in the UK, although non-O157 VTEC are much more common in most continental European countries and Australia (Molbak *et al.*, 2004). The organism is now recognised as an important cause of food and waterborne illness in developed and some developing countries.

E. coli O157:H7 causes relatively few cases of illness: between 1,100 and 1,400 each year in the UK (Hilton, 2002). The incidence peaks in the summer months and is more common in young children (Molbak and Scheutz, 2004). Due to the severe disease symptoms, high mortality and low infectious dose, *E. coli* O157:H7 is of concern.

E. coli O157:H7 has been isolated from fresh produce, including bean sprouts, cantaloupes, radish sprouts, alfalfa sprouts, apples, leaf lettuce (Ackers *et al.*, 1998; Hillborn *et al.*, 1999) and a large outbreak was recently reported in the US from spinach (Anon, 2006). In 2000, a waterborne outbreak of *E. coli* O157 in Canada resulted in serious illness in over 2,300 people and seven deaths (O'Connor, 2002).

Livestock, such as cattle are a major reservoir of *E. coli* O157:H7. It has also been isolated in sheep, goats, pigs and chickens and other domestic and wild animals (WHO, 2004b). It has been reported that 16% of cattle (Jones, 1999) in endemic areas, such as the UK, carry the pathogen and that *E. coli* O157 may be present in more than half of the cattle herds (Molbak *et al.*, 2004). It is thought that production practices such as feeding practice and crowding may contribute to the emergence of *E. coli* O157:H7 in cattle (Molbak *et al.*, 2004). Excretion by cattle may persist for 2 to 4 months and appears to be seasonal with excretion highest in the spring and late summer, and in young weaned cattle. This seasonal trend reflects the start of the peak in reported human cases of *E. coli* O157:H7. *E. coli* O157:H7 can survive in cattle faeces up to 7 weeks, in non-aerated cattle manure for more than a year and in cattle slurry less than 10 days (Jones, 1999).

The mechanisms by which *E. coli* O157:H7 is introduced onto crops are not fully understood; nevertheless, it has been reported that common vehicles include flood

irrigation with water contaminated with cattle faeces, contaminated surface water subsequently used for irrigation or when field grown crops are fertilised with improperly treated manure (Ackers *et al.*, 1998; Hillborn *et al.*, 1999)

A number of *E. coli* O157:H7 outbreaks in the USA and elsewhere have been linked to contaminated water (Anon, 1999). Cattle in an adjacent field were implicated as the source of *E. coli* O157:H7 during a multi-state outbreak in the USA associated with the consumption of mesclun lettuce in 1996 (Hillborn *et al.*, 1999). The authors speculated that contaminated water was used to irrigate the lettuce fields. Furthermore, studies have demonstrated the ability of the pathogen to survive for extended periods in water (Wang *et al.*, 1998; Chalmers *et al.*, 2000).

Campylobacter

The consumption of contaminated food, untreated water or rainwater has been implicated as risk factors for *Campylobacter* infection (Schorr *et al.*, 1994; Stenstrom *et al.*, 1994; Eberhart-Phillips *et al.*, 1997; Furtado *et al.*, 1998; Jones, 2001). *Campylobacter* infections associated with properly disinfected public water supplies are rare in the UK (G. Stanfield, Pers. Comm.), although *Campylobacter* has been a cause of outbreaks from private water supplies in England and Wales (Said *et al.*, 2003). The organism has been isolated from rivers (Arvantidou *et al.*, 1996; Obiri-Danso *et al.*, 1999), lakes (Arvantidou *et al.*, 1996) and groundwater (Savill *et al.*, 2001) as well as drinking water (Vogt *et al.*, 1982; Alary *et al.*, 1990; Savill *et al.*, 2001). The occurrence of the organisms in surface waters has proved to be strongly dependent on rainfall, water temperature and the presence of waterfowl (WHO, 2004b). This widespread occurrence of *Campylobacter* in water represents a risk of the organism being present in untreated irrigation water.

Although *Campylobacter* is the most common foodborne pathogen in England and Wales (Hilton, 2002), few foodborne outbreaks from fruit and salad vegetables have been attributed to *Campylobacter* (Stanley *et al.*, 2003). Nevertheless, because the organism is ubiquitous in the environment, it is reasonable to assume that irrigation, from time to time, will introduce *Campylobacter* onto crops. The low infectious dose of *Campylobacter* (<500 cells) translates this contamination into a risk of infection.

Although species identification is difficult it is generally considered that *C. jejuni* accounts for 80-90% of all cases of campylobacteriosis, and 5-10% are due to *C. coli*, when the diagnosis is based on selective media (Nachamkin *et al.*, 2000).

Listeria

Listeria is the causative agent of listeriosis. The first confirmed cases of foodborne listeriosis occurred in 1981, at a maternity hospital in Halifax, Nova Scotia, Canada, where contaminated coleslaw was served to patients (Schlech *et al.*, 1983). Subsequent studies have shown that elderly, pregnant, newborn and immunocompromised populations are more susceptible to listeriosis (Gandhi, 2007).

Although there are very few documented outbreaks demonstrating a link between this organism and produce (Schlech *et al.*, 1983; Aureli *et al.*, 2000), *L. monocytogenes* does raise concern among producers. *L. monocytogenes* was found to be capable of growth and persistence on several types of produce following its introduction to germinating seeds (Jablasone *et al.*, 2005). *L. monocytogenes* has been found in a variety of foods, such as milk and dairy products, meat and meat products, and radishes, carrot, cabbage, lettuce and potato (Nguyen-the *et al.*, 1994; Rocourt *et al.*, 1997). Furthermore, several studies have demonstrated that minimally processed vegetables can support the growth of this pathogen once it becomes established on the food surface (Nguyen-the *et al.*, 1994; Farber *et al.*, 1998; Li *et al.*, 2002). In contrast, Babic *et al* (1997) made the interesting observation that native microorganisms on spinach inhibited the growth of *L. monocytogenes*.

Clostridium perfringens

Clostridium perfringens is widely distributed in the environment and foods, and forms part of the normal gut flora in humans and animals. Spores of *Cl. perfringens* are extremely resistant to environmental stresses and, during slow cooling and unrefrigerated storage, germinate to form vegetative cells. However, there have been no reports of food poisoning outbreaks attributed to the transmission of *Clostridium* spores in irrigation waters and cases linked to the consumption of raw vegetables are rare (Groves *et al.*, 2002). Nevertheless, *Bacillus* spp (also a spore forming bacteria) have been implicated in diseases caused by contaminated seed spouts (Taormina *et al.*, 1999).

2.3.2 Viruses

The role of viruses in foodborne disease linked to fresh produce has been reported by Seymour and Appleton (2001). The most frequently reported foodborne viral infections are viral gastroenteritis and hepatitis A, both of which have been associated with the consumption of fresh fruit and vegetables (Seymour *et al.*, 2001). For different reasons, the disease statistics for both syndromes are likely to be misleading. Whereas the generally mild nature of viral gastroenteritis means that the incidence will be underreported

for the reasons discussed above, the severe nature of viral hepatitis leads to higher levels of reporting, but the long incubation period makes individual cases difficult to associate with a food source.

Enteric viruses only replicate in the host (Toze, 1997), and therefore their presence on crops is likely to be as a result of faecal contamination. After replication in the gastrointestinal tract, viruses are shed in high numbers and may contaminate surface water, groundwater, drinking water and food (Estes *et al.*, 2000; Parshionikar *et al.*, 2003). Crop contamination can occur during growth or harvesting from contact with polluted water used for irrigation and inadequately treated sewage sludge used for fertilisation (Metcalf *et al.*, 1995). Secondary infection is by person-to-person transmission, aerosolised vomitus, fomites, and infected food handlers (Sair *et al.*, 2002). The most important viruses causing gastroenteritis are rotavirus, norovirus, astrovirus and adenovirus types 40 and 41. Norovirus is the most frequently implicated virus in foodborne outbreaks, although it is not always possible to determine whether illness is from a foodborne source or by person-to-person transmission. Adenovirus has not been associated with foodborne transmission (Seymour *et al.*, 2001). As the viruses of interest have low infectious doses, poor personal hygiene is an important route through which viruses can directly reach food.

Hepatitis A is typically associated with contaminated seafood; however, other foodborne routes of transmission have been reported. O'Brien (2000) recorded 202 cases in one outbreak in the USA linked to the consumption of commercially distributed lettuce. Outbreaks associated with fresh produce, primarily soft fruits (strawberries) and salads (Iceberg lettuce and diced tomatoes) have been reported in other countries (Seymour *et al.*, 2001). Hepatitis A virus, therefore, should be considered as a potential risk to fresh produce, although the literature evidence appears to show that the main risk of infection in the UK is through produce imported from countries with a high incidence of hepatitis A.

Norovirus

Noroviruses, also known as small round structured viruses (SRSV), or Norwalk-like virus (NLV), are ubiquitous human pathogens that cause epidemics of acute viral gastroenteritis in people of all ages. The disease is self-limiting. Noroviruses are highly infectious, notably via the faecal-oral route or by aerosols generated by vomiting. Hence, there is a high rate of secondary infection which increases the difficulty in determining where the illness is foodborne or transmitted person-to-person. The concentration of noroviruses in raw sewage in the Netherlands have been reported to be 5,111 to 850,000 pdu per L (Lodder

et al., 2005), with an average concentration over twelve months of 10^5 pdu per L (van den Berg *et al.*, 2005).

The virus has been associated with food- and waterborne outbreaks (Koopmans *et al.*, 2000; Lopman *et al.*, 2002). Outbreaks of norovirus have been epidemiologically linked to fresh produce, such as washed salad, imported frozen raspberries, coleslaw, green salads, fresh cut fruits and potato salad (Seymour *et al.*, 2001).

Rotavirus

Rotavirus is a common cause of severe diarrhoea among children, resulting in the deaths of one million children, annually, worldwide (Seymour *et al.*, 2001). The disease is characterized by vomiting and watery diarrhoea for three to eight days, and fever and abdominal pain occur frequently. The primary mode of transmission is faecal-oral, although low titres of virus in respiratory tract secretions and other body fluids have been reported. Because the virus is stable in the environment, transmission can occur through ingestion of contaminated water or food and contact with contaminated surfaces. In countries with a temperate climate, the disease has a winter seasonal pattern, with annual epidemics occurring from November to April (Hunter, 1997).

2.3.3 Protozoa

Animal faeces represent a major source of zoonotic protozoa, such *Cryptosporidium* and *Giardia.*

The *Giardia* parasite lives in the intestine of infected humans or animals. Millions of cysts can be released in a bowel movement from an infected human or animal, leading to widespread contamination in soil, food, water, or surfaces (Hunter, 1997).

Cryptosporidium is a single-celled intestinal parasite which can cause severe diarrhoeal diseases. It reaches the gastrointestinal tract via ingestion of the oocysts. The life-cycle of the parasite is completed within one host. Cryptosporidiosis is often self-limited but its severity and duration of the disease varies from individual to individual. Asymptomatic infections are possible and can be a source of transmission to others. Cryptosporidiosis can be transmitted directly via person-to-person contact (at home, in nursery schools, etc.) or indirectly via ingestion of recreational water, contaminated foodstuffs and drinking-water (Hunter, 1997).

The infectious dose of *Cryptosporidium* has been reported to be less than 10 oocysts (WHO, 2004b). In theory, the ingestion of one viable oocyst could cause infection. Water polluted by human or animal faeces and then used for irrigation or spraying is a potential

vehicle for contamination of crops. *Cryptosporidium* is characterised by a high tenacity and high resistance to disinfectants.

Two genotypes of *C. parvum* are responsible for outbreaks of waterborne diarrhoeal disease (Peng *et al.*, 1997; Sulaiman *et al.*, 1998). The human genotype (genotype 1; *C. hominis*) parasites have so far been found only in humans, whereas the bovine genotype (genotype 2; *C. parvum*) parasites have been found in farm animals and some humans (Fayer *et al.*, 2000a). Detection of genotype 1 is therefore indicative of human contamination of the water body, whereas detection of genotype 2 could be either from an animal or human source. Drinking-water borne outbreaks have been associated with both genotypes, and descriptive data have shown the possibility of both human and animal sources of contamination in source waters (Casemore, 1998; Dolejs *et al.*, 2000). The transmission of *C. parvum* (genotype 2) in humans is shown to be different in different areas, with zoonotic transmission important in certain places and anthroponotic transmission in others. The role of other mammals and birds in zoonotic transmission of *Cryptosporidium* is uncertain. It is known that humans can be infected by other species of *Cryptosporidium*, such as the previously presumed avian-specific species *C. meleagridis*, but the prevalence of the various species and genotypes of *Cryptosporidium* is unknown and the frequency of cross-contamination is also unknown (Monis *et al.*, 2001).

Table 2.3 provides compiled data on outbreak sources.

Cattle have been reported to be one of the main sources of *Cryptosporidium* in the environment due to the propensity for high stocking levels and due to the high manure production rates of over 50 kg per day per animal (Ferguson, 2005). Concentrations in cattle faeces have been reported ranging from 19 to 1 x 10^5 oocysts per gram of faeces (Sturdee *et al.*, 2003; Hutchison *et al.*, 2004). In sheep faeces, prevalence has been reported between 6.4% (Sturdee *et al.*, 2003) and 75% (Chalmers *et al.*, 2002) with concentrations between 10 and 2800 oocysts per gram (Sturdee *et al.*, 2003; Hutchison *et al.*, 2005a). Pigs (13.5%) (Hutchison *et al.*, 2005a), and horses (8.9%), with concentrations of 2067 oocysts per gram (Sturdee *et al.*, 2003), are also reservoirs of the pathogen. In terms of wildlife in the UK, deer, hedgehogs, rodents, voles, rabbits and badgers have all tested positive for *Cryptosporidium*, with barn animals (mice, voles and shrews) having the highest concentration of 4.7 x 10^4 oocysts per gram of faeces (Sturdee *et al.*, 2003).

Table 2.3 Putative sources of human cryptosporidiosis compiled from case reports and geographic surveys[a]. After Fayer and Ungar (1986). (A complete reference list for the compilation is given in that work)

Putative sources[a]	Number of infected persons		Surveys
	Case reports		
	Immunodeficient (n = 25)[b]	Immunocompetent (n = 33)[b]	
Pet cats or dogs[c]	7	8	38
Farm animals (cattle or horses)[c]	3	7	66
Laboratory animals (infected)	0	13	0
Water supply	0	3	47
Association with presumed infected persons	5	9	102
Attendance at day-care centres	0	0	89
Following international travel	11	12	64

[a] an individual was included in each category which was reported a potential source

[b] total number of patients for which a potential source was suggested

[c] actual infection was demonstrated in only a few instances

A three year study of *Cryptosporidium* concentrations in sewage from six sewage treatment plants in Scotland reported mean concentrations in raw sewage from 4 (±7) oocysts per litre to 668 (± 986) oocysts per litre (by ether clarification, ~50% recovery) (Robertson *et al.*, 2000b), with removal in primary and secondary treatment generally low and variable between plants. Mean concentrations in treated sewage ranged from 5 to 22 oocysts per litre, with maximum reported concentrations of 160 oocysts per litre. Studies in Australia have reported *Cryptosporidium* concentrations in sewage of 1.0×10^4 oocysts per litre (Ferguson, 2005).

The use of manure as a fertiliser is considered to be a potential route of transmission of *Cryptosporidium* (and *Giardia*) to water. Hoogenboezem *et al.* (2001), for example, report that wastewater from cattle, pig and poultry slaughterhouses does not make a significant contribution to the discharge of *Cryptosporidium* and *Giardia* in surface waters. However, a study of water quality in a Warwickshire livestock farm (Bodley-Tickell *et al.*, 2002) identified a high occurrence (79%) of *Cryptosporidium* oocysts in a neighbouring stream over 17 months, although the contribution by source was not differentiated. The highest oocyst levels were reported to coincide with calving and increased wild animal numbers following breeding, with no correlation of oocyst levels with rainfall or slurry spreading. In Australian catchments, *Cryptosporidium* concentrations in streams have been reported to be highest in dry weather where there are sewage treatment plant discharges, with livestock and septic systems contributing significant loads in wet weather (Ferguson, 2005; Roser *et al.*, 2005).

The widespread distribution of *Cryptosporidium* in water poses a risk of crops being contaminated by irrigation water, although there seem to be few documented incidents. Inadvertent faecal contamination is implicated in many instances of cryptosporidiosis from food. It is reasonable to surmise that infected foodhandlers unwittingly transmit *Cryptosporidium* infection by contaminating beverages, salad greens or other uncooked foods with oocysts.

Although agricultural sources (e.g. run-off from dairies, grazing lands) are clearly a concern, it has recently been suggested that the most frequent source of infections with *Cryptosporidium* is from other humans, rather than from cattle (Olson *et al.*, 2004). Studies in the USA and Canada have not proved that cattle are the source of any waterborne outbreak of cryptosporidiosis (Olson *et al.*, 2004). However, this needs further investigation in other geographical locations since there are many reports of cattle, sheep and other livestock and wildlife infected with *Cryptosporidium* and contamination in associated water bodies (Sturdee *et al.*, 2003). For example, in a waterborne outbreak in Cranbrook, British Columbia, Canada, where oocysts of the bovine genotype have been identified (Fayer *et al.*, 2000b).

2.3.4 Emerging Pathogens

The epidemiology of foodborne disease has changed due to the emergence of newly recognised pathogens and re-emergence of previously recognised pathogens, such as through increases in occurrence or being newly associated with food or new food vehicles. There are a number of factors involved in the emergence or re-emergence of pathogens associated with foodborne illness – new environments, new technologies, changes in human behaviour and vulnerability and scientific advances. These include:

- environmentally-related factors, such as climate change,

- food-related factors, such as changes in food production and distribution practices,

- consumer-related factors, such as increased international travel and changes in eating habits, and

- pathogen-related factors, such as genetic changes in microorganisms as a result of exposure to environmental stresses such as heat, cold or acid shock (Sheridan *et al.*, 1998).

Understanding why pathogens emerge or re-emerge is important to be able to gauge any risk from any emerging disease and requires constant re-evaluation. Hepatitis E is

described as an example of one emerging pathogens of potential interest to irrigation water.

Hepatitis E

The clinical spectrum of infection with hepatitis E (HEV) is similar to infection caused by other hepatitis viruses. Typical symptoms include fever, chills, anorexia and nausea, vomiting, joint pain, epigastric pain, dark urine, clay-coloured stools, and jaundice. In pregnant women, HEV has a mortality rate of 17 – 33 % (Seymour *et al.*, 2001). The virus is excreted from the liver via the bile duct into the intestine and faeces. Viraemia and shedding of HEV in the faeces reach a peak during the incubation period (six weeks on average), and excretion in faeces may continue for up to 14 days after the onset of jaundice. HEV is spread by the faecal-oral route; however, the quantity of virus in the faeces is small, which is consistent with the low rate of secondary spread by person-to-person contact (Zuckerman, 2003). Zoonotic transmission of the virus from pigs has also been described (Renou *et al.*, 2007).

The highest prevalence of infection occurs in regions with low standards of sanitation and non-chlorinated drinking water. Although currently very little is known about this virus, the potential exists for foodborne transmission. Smith (2001) reports that HEV isolated from swine in the USA or Taiwan are closely related to human HEV found in those areas. The close genetic relationship of the swine and human virus suggests that swine may be a reservoir of HEV. In areas where swine are raised, swine manure could be a source of HEV contamination of irrigation water.

2.4 Conclusion

The pathway between the source of a pathogen and its eventual appearance on fruit and salad vegetables is complex. Irrigation, using a contaminated water source, is potentially a significant vehicle for transferring pathogens to crops. Even at this level, risk assessment of the irrigation process presents a challenge, but the challenge becomes more difficult when factors specific to the individual characteristics of the pathogens are included. In order to limit the complexity of the risk assessment models published in Chapter 5, we have focused on the selected reference pathogens, a common practice in water microbiology, to create a boundary around the characteristics that contribute to pathogen survival and mobility in the environment. Several criteria were used to select pathogens representing three groups of micoorganisms: bacteria, viruses and protozoa. The sources of each pathogen are described in relation to their potential to contaminate irrigation water, and outbreaks of disease from water and food sources, where they exist, are discussed. It

can be concluded from this review that the reference pathogens have a significant, theoretical potential to be applied to crops in contaminated irrigation water. How these pathogens respond to the environment and how this translates into a risk to the consumer are the subject of later chapters.

Table 2.4 Epidemiology of selected priority pathogens

Pathogen	Symptoms	Infective dose and ID_{50}	Duration of illness	Excretion rate
Salmonella	Salmonellosis typically includes fever, diarrhoea and abdominal cramps. In persons with poor underlying health or weakened immune systems, it can invade the bloodstream and cause life-threatening infections.	Between <10 and <1000 organisms (Hunter *et al.*, 1998), with an ID_{50} of 23,600 (Westrell, 2004)	Recovery is usual in a couple of days but symptoms may last a couple of weeks, with excretion lasting 26 to 51 days (Westrell, 2004).	10^6 per gm faeces (Geldreich, 1996); 10^4 to 10^8 per gram (Westrell, 2004)
E. coli O157:H7	The illness caused by *E. coli* O157 is often severe and bloody diarrhoea and painful abdominal cramps, without much fever. In 3% to 5% of cases, a complication called Haemolytic uremic syndrome (HUS) can occur several weeks after the initial symptoms. This severe complication includes temporary anaemia, profuse bleeding, and kidney failure.	<100 organisms (Percival *et al.*, 2004). Consumption of less than 50 organisms and possibly as low as five (Armstrong *et al.*, 1996). Westrell (2004) used an ID_{50} of 1,120. Haas *et al.* (Haas *et al.*, 2000) developed a dose response model based on a study of rabbits, which suggested the ID_{50} was around 10^5.	People generally become ill from *E. coli* O157:H7 two to eight days (average of 3-4) after being exposed to the bacteria. The illness usually resolves in 5 to 10 days, with excretion lasting up to 12 days (Westrell, 2004).	$10^2 – 10^3$ per gram of faeces (Westrell, 2004)
Campylobacter	*C. jejuni* and *C. coli* are major causes of acute entercolitis. Clinical symptoms include cramps, abdominal pain, diarrhoea, chills and fever,	Studies have shown the infective dose is between 500 organisms (Park, 2002)and 1000 (WHO, 2004a), although most infections probably require at least 10^4 organisms (Hunter, 1998).	The incubation period for the diarrhoeal disease is usually 2-4 days. Symptoms are self limited and usually resolve in 3-7 days (Hunter, 1998)..	Varies. Can be $>10^5$ organisms per gram faeces in cattle (Stanley, 1996)
Norovirus	Norovirus infection usually presents as acute-onset vomiting, watery non-bloody diarrhoea with abdominal cramps, and nausea. Low-grade fever also occasionally occurs, and vomiting is more common in children. Dehydration is the most common complication, especially among the young and elderly, and may require medical attention.	10 viral particles may be sufficient to infect an individual (Sair *et al.*, 2002)	Symptoms usually last 24 to 60 hours. Shedding lasts 5 to 22 days (Rockx *et al.*, 2002)	8.4×10^5 (range $2.2 \times 10^4 – 2.9 \times 10^{10}$) viral cDNA copies per gram for genotype I and 3.0×10^8 (range $2.5 \times 10^4 – 7.7 \times 10^{10}$) per gram for genotype II (Chan *et al.*, 2006). The highest shedding occurs during the symptomatic phase when vomits or faeces can contain 10^8 and 10^9 virus particles per mL (Westrell *et al.*, 2006)
Cryptosporidium	Diarrhoea, abdominal pain, vomiting, malaise and fever are the characteristic signs of the disease, with infection potentially life-threatening in immuno-compromised individuals	ID_{50} 165 organisms (Westrell, 2004), <30 oocysts (DuPont *et al.*, 1995) , <10 oocysts (WHO, 2004b)	2 – 30 days (Westrell, 2004)	Between 10^7 and 10^8 oocysts per gram faeces (Westrell, 2004)

Chapter 3 Pathogen behaviour

The risk of infection from pathogens introduced onto crops from contaminated irrigation water is determined by a number of factors such as pathogen density and dispersion in water, the infective dose of the pathogen and the susceptibility of the exposed population. In turn, these factors are influenced by the possibility of faecal contamination of the source water and the efficacy of any water treatment processes used prior to irrigation. Survival and transport characteristics of the pathogens are also important in determining the risk to human health from crops irrigated with contaminated water. Figure 3.1 shows the possible sources of pollution that may affect waters that are used in irrigation and thus contaminate crops.

But what is the risk of infection and how many cases can be linked to irrigation? Chapter 2 reviewed the outbreaks of foodborne infectious intestinal disease associated with the consumption of salad items, fruit and vegetables or their products, and the epidemiology of the pathogens, including the potential sources. In this chapter we describe the potential pathways between the pathogen source and the water used for irrigation, and the fate and transport of pathogens as it applies to irrigation of fresh produce. These factors are important as:

- Knowledge of pathogen pathways increases understanding of when contamination of irrigation water is most likely, and how the risks can be reduced; and

- Understanding pathogen fate and transport behaviour provides information on the attachment to and persistence on fresh produce.

Finally, this chapter summarises the factors affecting pathogens associated with fruit and vegetables and provides a synopsis of survival and transport properties for the reference pathogens described in Chapter 2.
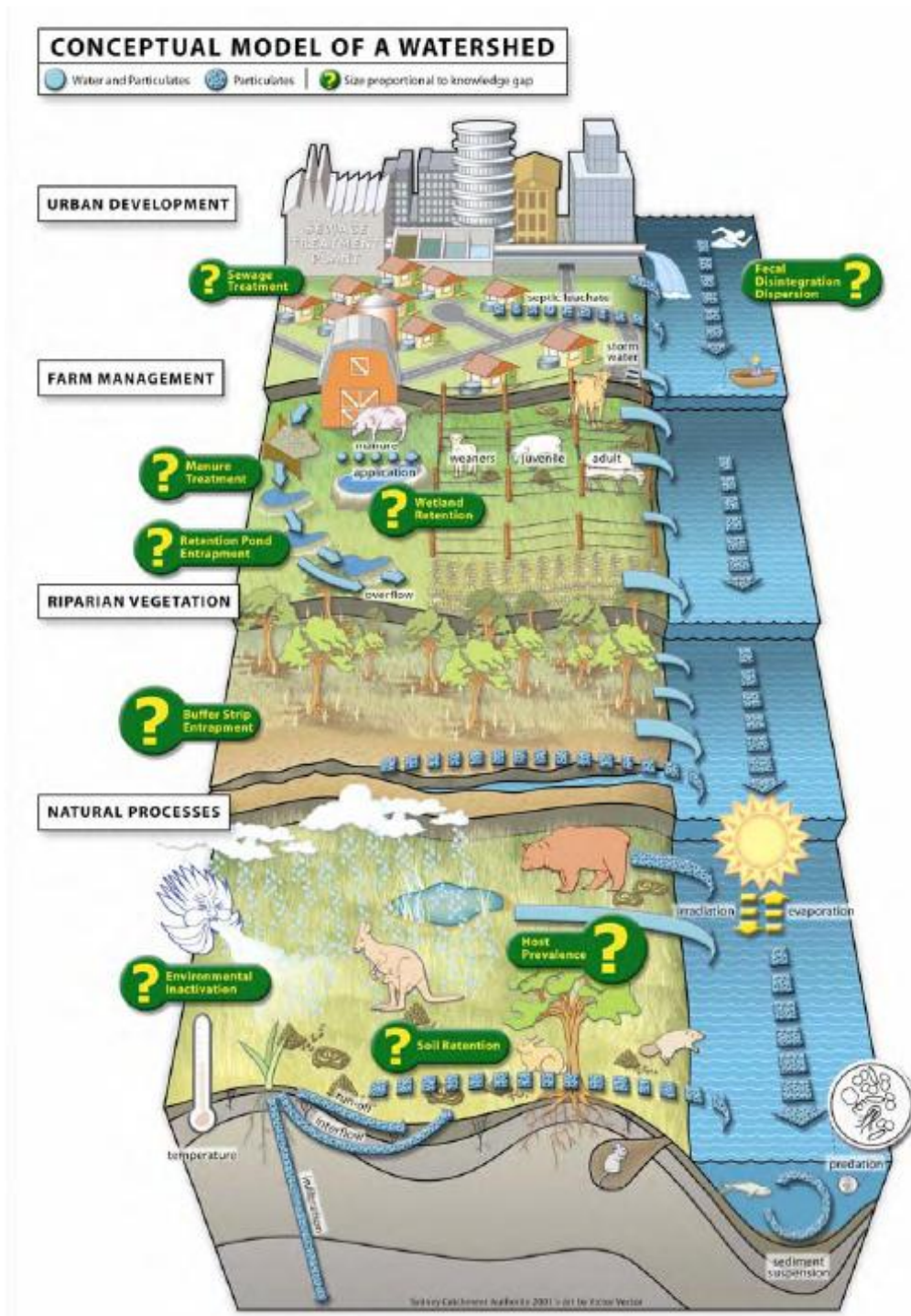
Figure 3.1 Conceptual model of pathogen sources, transport and fate in a watershed (Ferguson *et al.*, 2003a)

3.1   Introduction

The pathogens of interest for this report infect the gastrointestinal tract of humans and/or animals resulting in excretion in the faeces. Once excreted from the host, pathogens are exposed to environmental conditions that may not be favourable for growth and survival, and their numbers decline. However, some organisms can tolerate these conditions and remain viable for considerable lengths of time; for example, enteric bacteria have been

shown to survive for at least 60 days (Fenlon *et al.*, 2000). Organic-rich sediments and soils, such as agricultural soils, support microbial activity (Millis, 1988; Ferguson, 1994). It is possible that introduced pathogenic microorganisms may survive for extended periods of time in these conditions (Davies *et al.*, 1995), thereby increasing the risk of pathogens contaminating food crops.

Internalisation or infiltration of the pathogens can increase survival on the crop, and protect pathogens during processing (Ibarra-Sanchez *et al.*, 2004). Cut product, i.e. produce where the intact protective surfaces of the plant have been breached or removed can result in the pathogen having been removed before it reaches the consumer, but only if the process is done hygienically. If not, cutting the produce can allow the pathogens access to nutrients available on and from the inside of the plant, which may support their multiplication (with the exception of viruses) during storage. Furthermore, there is the possibility that pathogens could be transported to uncontaminated produce during the process of cutting.

Sprouted seeds (e.g. alfalfa, radish, soy, cress, mustard, beans), i.e. those where the germination stage breaks the barrier of the seed coat, may allow the pathogen to access the nutrients from the growing plant (Jablasone *et al.*, 2005). In some cases the seed coat is mechanically scratched to allow ingress of water to improve germination. If hygiene and temperature are not strictly controlled during germination, storage and transport of the produce there is the potential for pathogens to multiply. Unpasteurised fruit juice carries the same potential risks as sprouted seeds, in that there is the possibility for pathogen growth.

Unlike conventionally grown RTE vegetables, the requirement for organic produce is to provide a product where only restricted chemical treatments have been employed either during growth or processing. Therefore, organic vegetables are likely to retain much of their indigenous microflora even after minimal processing.

Some microorganisms are able to adapt to stress in the environment – *E. coli* and *Salmonella*, for example, are known to adapt to reduced pH and, therefore, exhibit increased tolerance to stress environments (Foster *et al.*, 1990; Deng *et al.*, 1999) and may therefore be a greater potential threat to consumers of crops.

Accepting that irrigation water can be a source of pathogens on crops, there are a number of factors which should be considered as they may affect the fate of the pathogens in irrigation water. These include: the water application method; water quality – particulates; vegetable or fruit growth; timing of irrigation and harvest and the effect of cooking or

processing the vegetables. The relative significance of the different sources of pathogens in irrigation water is determined by a combination of factors: (1) the load of pathogens from the source, (2) the persistence of the pathogen, (3) their transport behaviour from the source to the specific site and finally, (4) their resistance against treatment processes.

The following provides information on the main factors affecting the survival and transport, or mobility, of pathogens in the water environment. Information specific to the pathogens of interest follows.

3.2 Overview of pathogen fate and mobility in the environment

Microorganisms are introduced into the environment in liquids (e.g. sewage), solids (e.g. manure) or in aerosols (e.g. irrigation), and can be dispersed by water, wind or farm management practices. The fate and transport of pathogens in the environment is a function of a range of factors which are summarised in Table 3.1. However, it should be noted that the properties of one pathogen will differ from that of another pathogen with regard to both fate and transport. In general, bacteria have the shortest survival times (although bacterial spores will survive considerably longer) and protozoa the longest. This has been demonstrated by Stine (2005) who reported the relative survival times of micro-organism on vegetables as being *E. coli* < *E. coli* O157 < Feline calicivirus (FCV) < Salmonella < hepatitis A virus < *C. perfringens* spores. With respect to the potential for transport of microorganisms, protozoa, due to their large size, often will be retained in the soil by filtration. Similarly, bacteria are frequently removed during passage through soil by a combination of filtration and adsorption onto the soil particles. Viruses are more readily transported in groundwater than other microorganisms due to their small size, although the surface charge of viruses affects how rapidly they are transported.

Temperature

Temperature is considered one of the most important factors influencing the inactivation and persistence of microorganisms in the environment. Laboratory studies have demonstrated a negative correlation between temperature and the survival of coliform bacteria and enteric viruses, although the magnitude of the effect varies between different strains (Table 3.2). Skraber *et al.* (2002) reported a significant negative correlation between thermotolerant coliforms and temperature, with similar behaviour reported for *E. coli* O157 (Guan *et al.*, 2003). However, some authors have reported the inactivation of *E. coli* to be independent of temperature, with survival ranging from days to months (Nasser *et al.*, 1999; Gordon *et al.*, 2003)*.*

Table 3.1 Factors that affect pathogen fate and transport in the environment (after WHO, 2006)

Factor	Comment
Temperature	Most important factor in pathogen die-off. High temperatures lead to rapid die-off and low temperatures lead to prolonged survival. Freezing temperatures can also cause pathogen die-off or allow pathogens to survive indefinitely.
Sunlight/UV	Direct sunlight leads to rapid inactivation through desiccation and exposure to ultraviolet radiation.
pH	Soil pH may act to affect adsorption of viruses and bacteria onto the soil, with adsorption increasing as pH decreases in the case of viruses (Hurst *et al.* 1980) Survival times will thus be affected.
Biofilms	Increased predation may decrease survival. May provide protection against disinfection and desiccation, increasing survival.
Moisture content	Increased moisture content increases survival.
Soil type	Clay soils and soils with high organic content favour survival of pathogens. Increased clay content increases the attachment and filtering of pathogens.
Foliage/plant type	Certain plants have sticky surfaces (e.g. courgettes) or can absorb pathogens from the environment (e.g. lettuce, sprouts) which can lead to prolonged survival of some pathogens; root crops such as onions are more prone to contamination and facilitate pathogen survival.
Competition with native flora and fauna	Antagonistic effects from bacteria or algae may enhance die-off; bacteria may be preyed upon by protozoa.
Water flow rate	Increasing flow rate increases the transport of pathogens by increasing the shear forces between pathogens and surfaces.
Attachment to particles	Attachment to particles can affect inactivation depending on the chemistry of the particle (Stagg *et al.*, 1977). Increasing particle size will limit transport in porous media and increase settling in surface water. Attachment to colloidal particles can increase transport in porous media (Jin *et al.*, 2000).
Organic matter	Competes for attachment sites, increasing virus transport.
Ionic strength	Decreasing ionic strength increases transport, hence transport is greatest with rainwater then surface water then groundwater.
Irrigation type	Spray irrigation will increase inactivation by sunlight Drip irrigation will result in increased transport due to repeated irrigation at the same site.

Enteric viruses are renowned for their ability to survive for prolonged periods in aquatic environments. Water temperature has been shown to be the dominant factor in determining survival of viruses. Usually, increased temperature results in increased mortality (Feacham *et al.* 1981; Lo *et al.* 1976; Ward *et al.* 1986; Olson *et al.* 2004). The influence of temperature on the migration of bacteria and viruses is currently unknown.

Table 3.2 Effect of temperature on inactivation of microorganisms

Organism	Temperature			Reference
	10	20	30	
	Rate of inactivation (log.d^{-1})			
Salmonella				
E. coli O157	0.007-0.14	0.007-0.13	0.023-0.23	(Nasser *et al.*, 1999)
Campylobacter	0.5-7.3	4.3-8.6		(Blaser *et al.*, 1980; Lund, 1996; Buswell *et al.*, 1998; Talibart *et al.*, 2000)
Norovirus	Inactivated at 100°C			(Koopmans *et al.*, 2004)
Enterovirus	0.01-0.43	0.05-2.9	0.12-15	(Hurst *et al.*, 1980a; Yates *et al.*, 1985; Blanc *et al.*, 1996; Nasser *et al.*, 1999; Nasser *et al.*, 2002)
Cryptosporidium	0.01-0.02	0.030	0.033	(Medema *et al.*, 1997; Jenkins *et al.*, 2002)

Several studies have looked at the effect of temperature on the infectivity and/or viability of *Cryptosporidium* (Robertson *et al.*, 1992; Jenkins *et al.*, 1997; Walker *et al.*, 2001). The general relationship between temperature, freezing time and infectivity is that *C. parvum* can remain viable and infective after freezing (Fayer *et al.*, 1996).

Hurst *et al.* (1989) showed that temperature affected the survival of coxsackievirus B3, echovirus 7 and poliovirus 1 in samples of freshwater collected from five different sites. The average amount of viral inactivation was minimal at –20°C (0.4-0.8 $\log_{10}$ units over 12 weeks), but increased to 4-5 $\log_{10}$ units over 12 weeks at 1°C and 6.5-7.0 $\log_{10}$ units over 8 weeks at 22°C.

Pathogen inactivation in water at low temperatures is relevant in conditions where ice covers the surface of the water. The formation of ice cover contributes to stratification and riverine intrusions would still move quickly through the storage introducing fresh pathogens to the system and potentially resuspending previously settled pathogens from sediments. Consequently, freezing of the water body does not necessarily negate the pathogen risk. In fact, low water temperature may actually prolong the pathogen survival. Sattar *et al.* (1999) showed that the rate of inactivation of *Giardia* at –20 °C is faster than inactivation of *Cryptosporidium* at the same temperature with a 1 $\log_{10}$ reduction in viability in the first 12 hours and most *Giardia* cysts not viable after 24 hours. *E. coli* O157 has similar survival characteristics to other enteric bacteria such as *Salmonella*. It survives freezing at -20 °C and can grow down to a minimum of 6.5^{o}C (Anon, 1997).

Sunlight/UV

Direct sunlight leads to rapid inactivation through desiccation and exposure to ultraviolet radiation. The most active UV wavelengths against viruses and other microbes are in lower ranges of UV B (280-320 nm) and UV C (185-280 nm) because wavelengths in this

range are highly absorbed by nucleic acids (Sobsey *et al.*, 2003). The amount of natural UV radiation available from sunlight in Boston, USA, has been reported to be 120 mJ/cm^2 over three hours in summer (Webb *et al.*, 1988), with about 60 mJ/cm^2 of that produced over one hour around solar noon. In winter, the radiation reduces to approximately 5 mJ/cm^2 in one hour. UV-light is adsorbed by the ozone layer allowing only a small proportion to transmit to the earth's surface of which the bulk part is UV-A light (315-400 nm). As a consequence, the proportion of highly effective UV-C light is orders of magnitude smaller than the total UV light. Therefore, the UV-A radiation levels over three hours in summer are comparable with water treatment dosages which are normally in the range of 20-120 mJ/cm^2 (Craik *et al.*, 2001), but significantly longer exposure will be required for the same dosage with UV-C light .

A recent review of UV disinfection studies highlighted that all waterborne pathogens are susceptible to increased inactivation by UV, with viruses, in particular adenoviruses, being the most UV-resistant organisms (Hijnen *et al.*, 2006). Light has both direct and indirect effects on viruses. The direct activity is due to radiation at wavelengths below 370 nm (UV radiation) being absorbed by proteins and nucleic acids. This results in the breaking of chemical bonds and covalent bond formation changing the virion conformation (Attree-Pietri *et al.*, 1970).

The effect of sunlight on the pathogens of interest is summarised in Table 3.3. Based on the UV fluence requirements in this table, and the above estimate of 120 mJ/cm^2 from solar radiation in three hours, three hours of sunlight in summer would be sufficient to provide a 3 log$_{10}$ reduction of all but the most resistant of organism: adenoviruses (125 – 167 mJ/cm^2), *C. perfringens* (145 mJ/cm^2) and *Bacillus subtillis* (167 mJ/cm^2) (Hijnen *et al.*, 2006).

Limitations to the data:

There are a number of limitations to the application of this data to field conditions as most of the UV disinfection data in the literature has been obtained from bench-scale UV exposures of pure-culture microorganisms in particle-free water (Templeton *et al.*, 2005). Firstly, it was noted that environmental samples of organisms had a higher UV resistance than those seeded in the experiments (Hijnen *et al.*, 2006), which suggests that laboratory studies may overestimate the efficacy of UV radiation.

Secondly, in practice many microorganisms are attached to particles which may provide protection from UV disinfection. Coliform bacteria in wastewater have been shown to be protected from UV disinfection when coated with particles greater than 10 µm in diameter

(Emerick *et al.*, 2000). In most treatment facilities, particles of this size are likely to be removed by filtration. In contrast, viruses may be protected from UV disinfection by much smaller particles (particles <10 μm in diameter), which may readily pass through the filters in a water treatment facility. Attachment to particles may also protect coliform bacteria and viruses from chemical disinfectants (Ormeci *et al.*, 2002). As well as providing protection from UV, particles may also decrease survival, depending on the chemical composition of the particles (Templeton *et al.*, 2005).

Additionally, solar energy passing through water will be attenuated by reflection and absorption, resulting in less fluence with depth within a reservoir or stream. The proportion of transmitted sunlight is a function of depth, turbidity and the optical properties of the water such as the presence of colouring materials, mineral salts, and humates. For example, it has been reported that solar UV-B intensity drops exponentially in tertiary sewage lagoons, to 20% at a depth of 10 cm, 3% at 20 cm, 0.6% at 30 cm, and 0.1 % at 40 cm (Moeller *et al.*, 1980).

Furthermore, sunlight, and in particular UV, as well as decreasing the survival of microorganisms, can stimulate photo repair, which enables microorganisms to recover infectivity. This has been illustrated with bacteria (Zimmer *et al.*, 2002), although *Cryptosporidium* oocysts have been reported not to recover infectivity (Shin *et al.*, 2001).

Table 3.3 Summary of the effect of UV light on the pathogens of interest

Pathogen	Effect of UV light on survival	Reference	UV fluence ($mJ.cm^{-2}$) requirements for 3 log_{10} reduction (Hijnen *et al.*, 2006)
E. coli	Inactivated by UVB	(Davies-Colley *et al.*, 1997)	14
Cryptosporidium	Inactivated with wavelengths of 250-270 nm	(Linden *et al.*, 2001)	12
Campylobacter	Inactivated by natural sunlight in 30 mins	(Obiri-Danso *et al.*, 2001)	10
Viruses	Generally inactivated by wavelengths of 200-280 nm	(Sobsey *et al.*, 2003)	17 – 167

pH

In general, every species of organism has a narrow pH range that is optimum for growth. Depending on the normal environment of the organism, the pH requirements can range from highly acidic to highly alkaline: for many human pathogens the optimum pH is close to neutral. Despite having a preference for a narrow pH range, most species can tolerate a short exposure to a much broader range of pH. Outside these limits, the organisms are rapidly killed. Of the pathogens considered here, *Cryptosporidium* has been reported to

show little response to pH (Jenkins *et al.*, 1998), and some human viruses are relatively stable up to pH 11 (Rao *et al.*, 1988). However, the pH of surface water is generally close to neutral, with many groundwaters also within the range at which microorganisms are stable.

The pH of many vegetables is in the range for growth of pathogenic bacteria. With the exception of some types of melons (eg cantaloupe and watermelon) which are recognised as good substrates for growth of *Salmonella* and *E. coli* O157:H7 due to their pH which is in the range of 5.2 – 6.9 (Guo *et al.*, 2002), fruits with a pH less than 4.0 are not usually considered as able to support the growth of pathogenic bacteria (Guo *et al.*, 2002).

In addition to affecting survival, pH can affect the surface charge of microorganisms and hence their adsorption to soils and vegetables.

Biofilms

Biofilms are groups of microorganisms attached to each other and/or to a surface and embedded in a matrix of exopolymers. Biofilms have been observed on plant surfaces and may contain pathogens, protecting them from the antimicrobial activity of sanitizers and disinfectants, from desiccation and environmental stress. They may also provide the conditions for bacterial growth. The nature of attachment to solid surfaces and the attachment rate depends upon the bacterial species, cell density and surface properties, as well as environmental conditions. Biofilms contain extracellular products, and inorganic and organic debris that may affect pathogen survival through a variety of mechanisms. For example the uptake by protozoa will generally reduce survival although some microorganisms have evolved to become resistant to protozoan digestion, e.g. *Campylobacter jejuni* (Snelling *et al.*, 2006).

Moisture content

Soil moisture content can influence the survival of bacterial and viral pathogens (Pedley *et al.*, 2006). An increase in soil moisture content has been shown to extend survival, particularly when the moisture content is close to soil saturation (Hurst *et al.*, 1980b). High humidity can also increase pathogen survival (Mbithi *et al.*, 1991). However, there are exceptions to this general correlation between humidity/moisture and survival. Hepatitis A virus has been reported to behave in an inverse manner – with increased survival at low relative humidity (Mbithi *et al.*, 1991; Stine *et al.*, 2005). On crops, Stine *et al.* (2005) reported a range of behaviour from a study of pathogen survival on lettuce, bell pepper and cantaloupe at low and high humidity. Of the pathogens and indicators studied, none exhibited increased survival at high humidity for all produce types. Salmonella had

increased survival at high humidity on cantaloupe and lettuce, with *E. coli* only exhibiting this behaviour on cantaloupe. Of three viruses studied, survival was only proportional to humidity for PRD1 on bell peppers and feline calicivirus (FCV) on lettuce.

There is also evidence that temperature/humidity may increase attachment of bacteria to tomatoes (Iturriaga *et al.*, 2003).

Soil type

Fate and transport of pathogens in soil is of significance in the irrigation of RTE crops, particularly where groundwater is a source of irrigation water. There is a risk of internalisation of pathogens via the root systems, and pathogen reservoirs in soil and sediment which may result in contamination of the crop during harvest, or additional contamination of the irrigation water, respectively. In the subsurface, pathogen transport is influenced by attachment and filtration, as well as water flow, dispersion and dilution. Increased clay content increases the attachment and filtering of pathogens, but will favour survival of pathogens.

Microbial predation

Bacteria and other microbial predators (fungi, grazers etc.) play a role in virus inactivation, either by using the virion as a source of nutrition or through the production of metabolites that adversely affect the virus particle. Predation can be a significant factor in environments with high microbial iacitivty, such as soils and sewage, although enzymatic activity of natural waters has also been implicated in the inactivation of viruses (Sobsey *et al.*, 1973).

Flow rate

Flow rate will affect not just the speed at which microorganisms are transported (Jin *et al.*, 2002), but will also affect their attachment to particles, and settling.

In surface water, riverine inflow is considered to be a major source of pathogens. The behaviour of these inflows is therefore important. There are a number of factors which determine the hydrodynamic distribution of pathogens in lakes and reservoirs. Warm inflows will flow over the surface of a lake as a buoyant surface flow and cold, dense inflows will sink beneath the lake water where they will flow along the bathymetry towards the deepest point. In both situations, the inflow will entrain water from the lake, increasing its volume, changing its density and diluting the concentrations of pathogens and other properties (Brookes *et al.*).

Aggregation

The aggregation of pathogens to particulate material, or the integration of pathogens within a matrix of organic material, will influence the rate of pathogen settling. The surface charge of the particles is important in the interaction between the particles (Ongerth *et al.*, 1996). Drozd and Schwartzbrod (1996) suggest that aggregation of *Cryptosporidium* oocysts to particles and to each other is pH-dependent which is a result of the pH adjusting the hydrophobic and electrostatic nature of the oocyst surface. Studies have shown that there is little variation over a small range of pH values as found in drinking water reservoirs. The size of the particles with which an organism is associated is a major factor influencing the transport of these pathogens across a landscape, river or reservoir. If *Cryptosporidium,* for example is associated with large particles, there is a greater chance of interception, or settling, and so less of a risk than if they are associated with small particles (e.g. clay) or transported as single unattached oocysts (Brookes *et al.*).

Aggregation affects the size of pathogen-associated particles. Ongerth and Pecoraro (1996) indicate that *Cryptosporidium* oocysts are strongly negatively charged at neutral pH. Consequently, they may be aggregated and flocculated during conventional water treatment but may not adsorb well on natural clays in the environment. Dai and Boll (2003) suggested that oocysts do not attach to natural soil particles and would travel freely in the water. This theory has been supported by Considine *et al.* (2000; 2001) but they also concluded that protein-linked tethering between silica and oocysts can occur and may facilitate adhesion. Since this interaction relies on contact, there must be adequate turbulence in the system to increase the probability of collision between particles and oocysts.

There appears to be two conflicting arguments as to whether *Cryptosporidium* is associated with particles. As discussed above, the surface charge of oocysts suggest that they would not absorb readily to particles, but the very high settling velocities recorded by Hawkins *et al.* (2000) and Medema *et al.* (1998) suggests that, at least in certain situations, oocysts must be associated with larger particles. One alternative is that the oocysts may be physically mixed within an organic matrix of faecal material and/or soil particles during entrainment in surface water run-off (Brookes *et al.*). There have been few studies published on the dispersion, survival and viability of pathogens excreted in faecal matrices (Bradford *et al.*, 2002; Jenkins *et al.*, 2002). It is possible for example that the mastication of plant material by cattle and the subsequent scouring of the stomach wall, which dislodges oocysts, will have a significant impact on the interaction between *Cryptosporidium* and particles (Brookes *et al.*, 2004).

Feng *et al.* (2003) showed that suspended particles present in reservoir water contributed to enhanced recovery of *C. parvum* oocysts and that particle size and concentration could affect oocyst recovery. The optimal particle size was found to be in the range of 5-40ųm, and the optimal concentration of suspended particles was 1.42 g for 10 litres of tap water.

Viruses appear to readily adsorb to sediment. Gantzer *et al.* (2001) showed significant adsorption to soil of somatic coliphages, F-specific RNA phages and faecal coliforms from wastewater (61%, 78% and 86% respectively).

Sediments

Pathogens can remain viable in sediments for variable lengths of time, and therefore it is important to determine the significance of their resuspension and subsequent redistribution in irrigation water. Sediment resuspension occurs when turbulent velocity fluctuations reach a critical level (Brookes *et al.*, 2004). Concentration of *Giardia* oocysts, for example has been shown to be positively correlated to water flow and turbidity levels (Atherholt *et al.*, 1998).

Contradictory results on the effect of organic matter on virus behaviour have been reported in the literature. Adsorption status has been shown to affect survival of viruses. Gerba and Schaiberger (1975) showed that in general a virus that is adsorbed is more likely to survive than one that is free. Gerba (1984) showed that the presence of organic matter can reduce virus attachment and thus facilitate virus transport by providing additional negative charges, covering positively charged sites, or competing with viruses for attachment sites. On the other hand, Bales *et al.* (1995) and Kinoshita *et al.* (1993) showed that organic matter inhibits virus transport by promoting hydrophobic interactions between viruses and grain surfaces. Viral capsids are made up of one or more structural proteins and consequently have electrically charged surfaces due to the ionic functional groups (primarily carboxyl, amino, sulfhydryl, etc.) of the acidic and basic amino acids comprising the virion proteins. The iso-electric point of a virus (or any particle) refers to the point at which there is no net surface charge on the particle (Gerba, 1984). This means that the ionic functional groups of positive and negative charge or pockets of them are charge-balanced across the surface as a whole. The iso-electric points vary greatly even between strains of a particular virus type, indicating that the degree to which they will adsorb to different materials (such as soil particles and other surfaces) will also vary (Gerba, 1984). Additionally, a virus may have more than one iso-electric point. Most viruses have iso-electric points in the acid pH region.

3.3 Contamination of irrigation water supplies

The quality of water used for crop irrigation is a key factor in determining the risk of crops becoming contaminated with pathogens. The primary sources of water for irrigation in the UK are reported to be surface water (54%) and groundwater (41%), with the remainder coming from public mains water, rainwater and other sources (Weatherhead, 2007). For salad crops, the proportion of area irrigated with surface water is 71% (Tyrrel *et al.*, 2006). This section focuses on the microbial contamination of surface and groundwater supplies. For public mains waters and reuse water, the level of contamination will depend on the level of treatment prior to use. For harvested rainwater, microbiological contamination may occur during collection, which is not discussed, and storage, which is addressed below.

3.3.1 Surface water

Surface water contamination from animal faeces can occur via direct deposition, entrainment of pathogens in surface run-off during a rainfall event from either direct deposition on the land or by application of manure. Contamination from human faeces is assumed to be due to discharge of treated sewage from large centralised sewage treatment plants, small package sewage treatment plants, and septic tanks, as well as discharge of untreated sewage from sewer overflows and accidental sewage releases.

It is well known that correlations exist between microbial contamination of waterways and rainfall (Crowther *et al.*, 2001) due to the combination of wash off of animal faeces, increased transport from septic tanks and sewer overflows. Results from a study undertaken in Australia (Table 3.4) indicated consistently higher microbial concentrations during rainfall events, compared to baseline flow (Roser *et al.*, 2005). Land use had a significant impact on baseline and event water quality. *Cryptosporidium* densities in stream flows in protected catchments were 1,000-fold lower than in septic-impacted catchments. Intensive agriculture or urban development representing more than 5% of the catchment area resulted in a doubling in pathogen concentrations and risk. There were also differences between the pathogens and indicators present in different catchment types: Somatic coliphages were not present in protected water and were abundant in cattle-impacted catchments. *Cl. perfringens* were high (>100 colony forming units (cfu).100mL^{-1}) where human sewage impacts were suspected. *Cryptosporidium* was most abundant in the urbanised catchment (Roser *et al.*, 2005).

Table 3.4 Geometric (dry) and flow weighted (wet) means of selected pathogens and indicators during dry periods and rainfall events in six catchments (Roser *et al.*, 2005)

Catchment type		E. coli .100mL^{-1}		Cryptosporidium .10L^{-1}		Campylobacter .100mL^{-1}	
		Dry	Wet	Dry	Wet	Dry	Wet
Fully protected	A	26	400	< 0.3	< 0.3	0.03	0.07
	B	30	1190	< 1	< 0.3	0.03	< 2.3
Partially impacted	A	31	6250	< 1	4.5		
	B	130	6690	1.1	39	0.43	3
Urbanised		450	10400	16	290	0.36	15
Intensive agriculture		210	17700	1.9	31	3.5	18

3.3.2 Water quality in reservoirs

The storage of water provides the opportunity for pathogen die-off and predation, the rate and extent of this being influenced by factors such as the duration of storage and environmental conditions (eg water temperature, UV and pH). However, water stored in open reservoirs is also exposed to potential contamination by wildlife which may serve to offset pathogen declines. As reservoirs are important habitats for aquatic birds, these birds represent one of the main potential sources of recontamination. Other sources may include direct faecal deposition (where farm animals or wildlife have access to the reservoir) and run-off (where the reservoir is not bunded on each side), however these sources are considered to be low risk with adequate design.

3.3.3 Groundwater

One mechanism for groundwater contamination is by rapid transport pathways accidentally introduced by human intervention and connecting the contamination source to the groundwater abstraction point. Such pathways could include, for example, inadequate sanitary protection of springs, wells and boreholes, or the presence of a forgotten conduit connecting the source of contamination to the groundwater abstraction point. The implementation of management actions to reduce faecal contamination close to the abstraction point, or the rehabilitation or improvement of the well or spring is usually sufficient to control access of pathogens to the water source.

Rapid transport pathways cannot, however, explain all groundwater source contamination events (groundwater contamination with pathogenic microorganisms can occur by direct discharge of human or animal faecal matter or by contaminated recharge from surface water, or infiltration). It is now widely accepted that the transport of microbial pathogens within groundwater systems is a significant mechanism for waterborne disease transmission. In the UK, detection of viruses has been reported in groundwater at depths

of up to 91 m in confined sandstone and 60m in unconfined sandstone (Powell *et al.*, 2003).

As discussed, the presence of pathogens in water is due to a number of factors, controlling input, survival and transport, depending on the type of water and on aquifer characteristics in the case of groundwater. The duration of a contamination event in groundwater is a function of hydrodynamic properties. Therefore, a spring collecting high quantities of direct infiltration water, will show high levels of contamination lasting several months after the cattle or other potential source of contamination have left the catchment area. In extreme cases, the persistence of contamination is so great that the presence of the source of contamination is no longer significant at all. There is therefore the possibility that certain pathogens may persist for considerable periods in a natural environment, probably adsorbed on soil particles or on silts so as to increase their chances of survival (Schaffter *et al.*, 2002).

3.4 Fate of pathogens in water supplies and storage

Pathogens are readily transported in surface water and will generally only sediment out when they are associated with larger particles. In groundwater, the larger pathogens such as bacteria and protozoa will be filtered out in most aquifers whereas virus transport may be extensive depending on the attachment properties of the aquifer material. As discussed above, fissures in aquifers can provide rapid transport pathways, and enable the larger pathogens to be more readily transported. Chalk aquifers, which provide water in much of southern England, can be highly fissured allowing the rapid flow of water and any associated contaminants (Price *et al.,* 1992).

The fate of pathogens in surface water supplies and storage is primarily a function of temperature and sunlight. While there is considerable information published on survival of pathogens in surface and groundwater supplies, there is limited information published on survival in stored irrigation water. Flint (1987) examined the long-term survival of *E. coli* in river water. In sterilised river water *E. coli* was found to survive for up to 260 days, at temperatures ranging from 4 to 25 °C, with no loss of viability. However, the inactivation rates are considerably higher with exposure to sunlight (Sinton *et al.*, 2002; Noble *et al.*, 2004), with Sinton *et al.* (2002) reporting decreasing survival in waste stabilising pond effluent at 14 °C from 135 hours for a 1 $\log_{10}$ reduction (0.41 ln .d^{-1}) in dark conditions to 20 h (2.7 ln .d^{-1}) in winter sunlight and 9 h (6.0 ln .d^{-1}) in summer sunlight.

Studies conducted by Kutz and Gerba (1988) indicated that enteroviruses could survive in freshwater sources for prolonged periods of time, with inactivation ranging from 0.325 $\log_{10}$

.d^{-1} (0.75 ln .d^{-1}) for polluted river sources and 0.374 log$_{10}$ d^{-1} (0.86 ln .d^{-1}) for impounded water; to 0.25 log$_{10}$ d^{-1} (0.58 ln .d^{-1}) for unpolluted river sources 0.174 log$_{10}$ .d^{-1} (0.40 ln .d^{-1}) for groundwater. Allwood *et al.* (2003) reported 1 log$_{10}$ reductions in FCV, a surrogate for norovirus, in dechlorinated tap water between 2.0 days at 37 °C and 7.3 days at 4 °C. MS2 bacteriophage had considerably longer survival, particularly at lower temperatures: 2.7 days at 37 °C and 25.7 days at 4 °C.

Campylobacters have been shown to survive in water for many weeks, and even months, at temperatures below 15 °C (Höller, 1988; Buswell *et al.*, 1998). Dorner (2006) summarised published inactivation rates in water and manure, with ranges in water of 0.25 to 8.6 ln .d^{-1} (9 days to 6 hours for 1 log$_{10}$ reduction) reported for *Campylobacter* from 15 to 30 °C, 0.31 to 2.7 ln .d^{-1} (7.4 to 0.9 days) for *E. coli* O157 from 15 to 30 °C and 0.074 to 0.32 ln .d^{-1} (31 to 7 days) for *Cryptosporidium* from 20 to 30 °C.

The survival of *Giardia* in water has been reported to be correlated with temperature, such that the log$_{10}$ inactivation rate is equal to 0.01 times the temperature (°C) (Medema *et al.*, 2001).

As reported by ADAS (2003), there are no readily available data regarding the quality of reservoir water used for crop irrigation as growers rarely test reservoir waters prior to use. Furthermore, the residence time in storage is highly variable due to difference in abstraction licences and crop requirements.

3.5 Fate of pathogens during irrigation

Irrigation methods are discussed in section 2. The predominant irrigation method in England is by hose-reel and raingun (67%; Weatherhead *et al.,* 2002; 2006), but the percentage varies with region and crop type. The fate of pathogens during irrigation is a function of the irrigation method and the crop type, as that will determine the pathogens retained on the crop and internalised within the crop. The pathogens retained on the crop will in turn be a factor of the amount of water retained on the crop and the attachment of the pathogens to the crop.

The irrigation method will determine the exposure of the crop to pathogens in irrigation water. Direct application via overhead methods such as raingun, boom and sprinkler deliver water onto the leaves and stems, as well as, via infiltration to the roots. Hydroponic and trickle irrigation deliver water to the root zone only.

The irrigation method can also impact the quality of the irrigation water. Due to the moist environment and likely constant supply of nutrients, irrigation equipment may be ideal

environments for biofilm growth (refer to part 1, 3.2). The growth of biofilms within irrigation lines can accumulate and protect pathogens, releasing them as the biofilm gets sloughed off. In hose-reel systems, biofilms may form during periods of no flow, protecting pathogens or enabling growth. In trickle irrigation, the lower flows increase the probability of biofilms forming in the pipework. The quality of the irrigation water is a factor in biofilm development.

3.5.1 Pathogens retained on the crop

The retention of pathogens from irrigation water on a crop depends on the amount of water retained on the crop and the attachment of the pathogens to the crop. The amount of water retained will depend on the structure of the plant. In the context of overhead irrigation methods, horizontal surfaces such as leaves can hold more water than vertical surfaces. Water can also collect in natural depressions within the plant structure such as at the base of the leaf or leaf blade, or in the leaf sheath. For example, water will be retained between leaves in a lettuce as well as collecting at the bottom.

The retention of water on plants after irrigation has been studied as a surrogate for pathogen retention on crops, where all the pathogens in the water retained are assumed to attach to the plant (Shuval *et al.*, 1997; Petterson *et al.*, 2001a; Hamilton *et al.*, 2006). The World Health Organisation (2006) in developing their Guidelines for the safe use of wastewater, excreta and greywater have assumed that 10 – 15 mL wastewater remains on a lettuce and 1 – 5 mL on an onion. Similarly, Asano *et al.* (1992) used an estimate of 10 mL reclaimed municipal wastewater per day consumed on food crops. Shuval *et al.* (1997) submersed vegetables in water and found 10.8mL per 100 g retained on lettuce and 0.36mL per 100 g on cucumber (Shuval *et al.*, 1997). Hamilton *et al.* (2006) undertook spray irrigation experiments, reporting average water retention of 1.9 mL per 100 g for broccoli, 3.5 mL per 100 g for savoy king cabbage and 9.9 mL per 100 g for winter head cabbage.

Petterson *et al.* (2001b) quantified the recovery of *Bacillus fragilis* HSP40 phage from lettuce and carrot crops, which had been irrigated with spiked (10^6 – 10^7 pfu/ml) primary sewage or dechlorinated tap water. The results highlighted the increased retention over multiple events and the ready attachment of viruses to root systems with more than a ten fold increase in phage for lifelong irrigation of lettuce and carrot compared to one irrigation event. Furthermore, Petterson (2002) derived attachment rates of 2.4% from viruses applied in irrigation water to the crop, and modelled virus attachment for carrots using adsorption isotherm.

Using a lettuce model, Takeuchi *et al.* (2000) demonstrated that *L. monocytogenes* and *E. coli* O157:H7 showed preferential attachment to cut edges of iceberg lettuce compared to intact leaf tissues. In contrast, *S. typhimurium* attached equally as well to both types of surfaces. Recently, it was reported that particular *L. monocytogenes* strains adhered to and colonised alfalfa sprouts significantly better than other strains by a factor that varied by nearly 5 $\log_{10}$ cfu per sprout (Gorski *et al.*, 2003). The presence of flagella has been shown to be important in the initial stages of attachment of *Listeria* to both abiotic as well as plant surfaces in other studies (Vatanyoopaisarn *et al.*, 2000; Gorski *et al.*, 2003). The production of flagella is temperature dependent. Therefore, prior growth temperature and other conditions encountered by bacteria before entering the food production chain may determine whether or not the cells will attach and remain on a food surface.

3.5.2 Internalisation of pathogens within the crop

Whereas pathogens on the surface of the crop may be removed at the processing stage by washing and disinfection practices, internalised pathogens are less likely to be affected by these management practices.

Internalisation of human pathogens has been observed in various vegetables (Itoh *et al.*, 1998; Solomon *et al.*, 2002b; Wachtel *et al.*, 2002; Warriner *et al.*, 2003; Jablasone *et al.*, 2005). Solomon *et al.* (2002b) and Wachtel *et al.* (2002) showed through laboratory experiments that *E. coli* O157:H7 applied to lettuce in irrigation water is capable of entering the roots of mature lettuce plants and can be transported upward to locations within the edible portions of the plant. Direct contact between the leaves and a contamination source is not required for the organism to become integrated into edible lettuce tissue. Although Solomon *et al.* (2002b) and Wachtel *et al.* (2002) recognise that under natural conditions, lower levels of contamination are likely, this could still present a potential human health risk, since the infective dose of *E. coli* O157:H7 and other pathogens is low.

Franz *et al.* (2007) used a surface sterilisation method to look specifically at the internalisation of *E. coli* O157:H7 and *S. Typhimurium* on lettuce to quantify the level of total contamination and internal contamination. Although the study showed that both can become present at high levels (2.4 to 4.0 log cfu/g from 7 log cfu/g in manure) at internal or subsurface locations where they are protected from sterilisation, Franz *et al.* (2005) indicated that contamination is not so prevalent in the 'field' situation where pathogen densities are lower.

Internalisation of pathogens has been shown to occur irrespective of irrigation method, although the irrigation method affects the rate of internalisation with greater uptake reported for spray irrigation (>90% plants contaminated) compared to flood irrigation (19%) (Solomon *et al.*, 2002a) and greater internalisation with a soil system than with a hydroponic system (Franz *et al.*, 2007). Internalisation from exposure to contaminated soil has also been detected for high concentrations in soil (10^4 to 10^8 per gram) (Solomon *et al.*, 2002b) which are associated with manure application rather than as a result of contaminated irrigation water.

Little research has been reported about survival of internalised bacteria, or the internalisation of enteric viruses or protozoa. The low pH of tomatoes would limit the survival of bacteria, however, viruses are generally quite resistant to low pH.

Infiltration is a similar mechansism that can protect pathogens on the crop before harvest, and at the processing stage. Differences in surface morphology, internal tissue composition, and metabolic activities of leaves, stems, florets, fruits, roots and tubers provide a variety of ecological niches for microorganisms (Guo *et al.*, 2002). Infiltration of pathogens into crevices and intercellular spaces of fruits and vegetables has been shown by several researchers. For example, infiltration of tomatoes with *Salmonella* (Wei *et al.*, 1995), and of lettuce (Seo *et al.*, 1999), apples (Buchanan *et al.*, 1999) and oranges (Walderhaug *et al.*, 1999) with *E. coli* O157:H7 has been described. Addition of detergents to water also promotes infiltration of crops, by reducing the surface tension of the water and the air-water interface with damaged cutin or pores leading to the tissues (Guo *et al.*, 2002).

3.6 Fate of pathogens on crops

For pathogens that have been retained on a crop during irrigation, the key factors that will determine their survival between irrigation and harvest will include the temperature, exposure to sunlight, desiccation and pH. The duration of the harvest interval, the minimum time between last irrigation and harvest, will be crop dependent. The survival of pathogens on crops is typically shorter than in water and in soil due to less protection from temperature changes, desiccation and sunlight (Table 3.5).

Table 3.5 Survival of various organisms in selected environmental media at 20 – 30 °C (WHO, 2006)

Organism	Survival time (days)		
	Fresh water and sewage	Crops	Soil
Viruses			
Enteroviruses	<120, usually <50	<60, usually <15	<100, usually <20
Bacteria			
Thermotolerant coliforms	<60, usually <30	<30, usually <15	<70, usually <20
Salmonella spp.	<60, usually <30	<30, usually <15	<70, usually <20
Shigella spp.	<30, usually <10	<10, usually <5	
V. cholerae		<5, usually <2	<20, usually <10
Protozoa			
E. histolytica cysts	<30, usually <15	<10, usually <2	<20, usually <10
Cryptosporidium oocysts	<180, usually <70	<3, usually <2	<150, usually <75
Helminths			
Ascaris eggs	Years	<60, usually <30	Years
Tapeworm eggs	Many months	<60, usually <10	Many months

The risk will vary depending on the crop due to the ability of the plant structure to provide a protected environment (e.g. moist and dark conditions increases survival), as well as the time of year and duration of the growing periods. Stine *et al.* (2005) reported survival of a range of organisms in pre-harvest conditions to be greatest on cantaloupe, followed by bell peppers with survival lowest on individual lettuce leaves.

The study undertaken by Stine *et al.* (2005) is one of few studies reporting on the pre-harvest survival of pathogens. The application of pathogens to the outside of the lettuce leaf only is expected to result in an overestimation of the inactivation rate for irrigated lettuces, however, previous studies (Table 3.6) have reported inactivation rates for poliovirus on lettuce which are comparable with the results of other studies from the field and at sale reported here, with values ranging from 1.8 ln.d^{-1} (T_{90} 1.25) to 0.12 ln.d^{-1} (T_{90} 20).

The reported inactivation rates of *E. coli* and *E. coli* O157 on crops (Table 3.7) showed high variability between vegetables, with significantly higher rates than in water, particularly for lettuce. However, Cooley *et al* (2006) reported that the presence of different bacteria can significantly alter survival with *Wausteria paucula* enhancing the survival of *E. coli* O157:H7 six-fold on lettuce foliage and *Enterobacter asburiae* decreasing survival 20- to 30-fold. Beuchat (1999) detected *E. coli* O157:H7 on manure-contaminated lettuce stored at 4°C for up to 15 days.

Table 3.6. Inactivation of viruses on various crops (WHO, 2006)

Crops	T_{90} (days)	Data source	References
Artichoke, broccoli, celery and lettuce	1.45	Seeded poliovirus inactivation over 4 days in an environmental chamber	(Engineering Science, 1987; Asano *et al.*, 1992)
Celery (environmental chamber)	1.82[a]	Poliovirus seeded onto plants and time for 99% removal were recorded in both an environmental chamber and in the field	(Sheikh *et al.*, 1999)
Iceberg lettuce (environmental chamber)	3.3[a]		
Romaine lettuce (field conditions)	1.25[a]		
Butter lettuce (field conditions)	1.7[a]		
Winter triumph lettuce	0.4 (fast phase) 20 (slow phase)	Plants spray-irrigated at maturity with wastewater seeded with B. fragilis bacteriophage B40-8; experiment undertaken in uncontrolled greenhouse conditions.	(Petterson *et al.*, 2001a)

T_{99} – time required for a 99% (2-log) reduction
[a]Estimated value of inactivation coefficient assuming log-linear relationship and time for 2 log virus removal.

The remainder of survival studies on fresh produce reviewed have been undertaken to assess the survival with regards to shelf life. Therefore, the studies are undertaken on cut produce, which has been prepared for use or sale.

Survival studies of norovirus on fresh produce are lacking due to difficulties in working with the virus but Seymour and Appleton (2001) reviewed studies looking at other viruses and concluded that viability of viruses on fruit and vegetable generally exceeds the product shelf life. Dawson *et al.* (2003) studied the inactivation of MS2 bacteriophage, poliovirus, FCV (a surrogate for norovirus) and rotavirus SA-11 on a range of fruit and vegetables. MS2 bacteriophage was the most stable of the viruses studied. Each of the viruses had increased die-off at 22 °C, compared to 4 °C, with FCV the least temperature sensitive and Poliovirus the most temperature sensitive. Inactivation was greatest on the soft fruit (strawberries and raspberries), and lowest on tomatoes.

This study did not include the effects of sunlight and desiccation that may decrease virus survival on produce in the field. Experiments undertaken in field studies (Stine *et al.*, 2005) reported higher inactivation rates for FCV on lettuce and peppers than studies undertaken in a refrigerator (Dawson, 2003).

Table 3.7 Inactivation (ln) rates of microorganisms on crops at dry and wet humidity at 18 – 30.6 °C (Stine _et al.,_ 2005)

Vegetable	Cantaloupe		Lettuce		Bell pepper	
Humidity	Dry	Wet	Dry	Wet	Dry	Wet
PRD1	0.069 ± 0.02	1.27 ± 0.21	0.21 ± 0.046	0.58 ± 0.18	0.32 ± 0.069	0.18 ± 0.05
Hepatitis A	0.023 ± 0.07	0.14 ± 0.092	0.28 ± 0.069	0.67 ± 0.12	0.25 ± 0.092	0.41 ± 0.05
FCV	0.65 ± 0.12	2.56 ± 0.76	2.60 ± 0.41	2.44 ± 0.65	1.45 ± 0.44	1.84 ± 0.37
E. coli O157	0.62 ± 0.12	0.16 ± 0.12	10.4 ± 0.88	11.3 ± 0.28	0.74 ± 0.37	0.76 ± 0.55
E. coli	0.85 ± 0.32	0.46 ± 0.14	2.51 ± 1.1	11.5 ± 4.9	1.82 ± 0.51	11.7 ± 2.6
Shigella	0.51 ± 0.07	0.51 ± 0.23	0.99 ± 0.81	5.7 ± 3.6	2.67 ± 3.3	3.4 ± 2.9
Salmonella	0.55 ±0.09	0.30 ± 0.069	0.81 ± 0.35	0.14 ± 0.069	0.46 ± 0.23	1.8 ± 1.2
Clostridium	0.092 ± 0.05	0.30 ± 0.14	0.32 ± 0.046	0.23 ± 0.092	0.32 ± 0.069	0.18 ± 0.02

Acidic foods (defined by the US FDA's Retail Food Sanitation Code as those with a pH of less than 4.6) are generally considered to be at low risk for transmission of pathogenic bacteria, but _E. coli_ O157:H7, under certain circumstances, can survive a pH as low as 2.0 and can persist for up to several weeks when inoculated into apple cider or mayonnaise (Armstrong _et al._, 1996) and to not have significantly different inactivation on cut versus whole strawberries (Yu _et al._).

Karenlampi (2004) reported the inactivation rate of nine strains of _Campylobacter_ on fresh cut iceberg lettuce at 21 °C was 3.08 ± 0.62 ln.d^{-1} and at 7 °C was 1.36 ± 0.21 ln.d^{-1}. For other prepared produce the rates at 21 °C were: cantaloupe 1.52 ± 0.17; cucumber 1.55 ± 0.52; carrot 2.61 ± 0.62; strawberries 8.74 ± 2.63.

No data was found relating to the survival of _Cryptosporidium_ on crops. However, data was available for survival on grass following waste spreading (Hutchison _et al._, 2005b). _Cryptosporidium_ inactivation rates extrapolated from graphs (Hutchison _et al._, 2005b) were comparable with those for _Clostridium_ on crops from Stine _et al._ (Stine _et al._, 2005). Hutchison _et al._ (2005b) illustrated two phases of decay in _Cryptosporidium_ with an initial rapid decay (0.15 ln.d^{-1}) over 16 days of 99.7% of the population, followed by a slower decay rate (0.005 ln.d^{-1}). _E. coli_ O157 inactivation rates (Table 3.8) are comparable with inactivation on vegetables (Stine _et al._, 2005) but not with lettuce. _Campylobacter_ inactivation rates were lower than those reported on prepared produce.

Table 3.8 Survival of microorganisms on grass following waste spreading (ln) (Hutchinson _et al.,_ 2005)

Micro-organism	Minimum	Average	Maximum
Campylobacter	0.75	1.03	1.42
E. coli O157	1.35	1.51	1.76
Cryptosporidium	0.053	-	0.33

Certain crops may be more susceptible to contamination than others. Table 3.9 shows viral inactivation rates (determined experimentally) on a variety of crops.

Table 3.9 Ln inactivation coefficient for four viruses on fresh produce, from data in (Dawson, 2003).

	MS2 Bacteriophage		Poliovirus		Feline calicivirus		Rotavirus SA-11	
Temperature	4	22	4	22	4	22	4	22
Carrot	0.039	0.193	0.219	0.414	0.173	0.898	0.074	0.974
Lettuce	0.044	0.322	0.039	0.691	0.230	0.668	0.081	0.484
Pepper	0.078	0.145	0.039	0.414	0.253	0.645	0.078	0.408
Strawberry	0.044	0.322	0.039	0.691	0.230	0.668	0.081	0.484
Tomato	0.062	0.101	0.044	1.773	0.189	0.645	0.253	0.725

The possibility of biofilms forming on irrigation equipment has been discussed earlier. In addition, Fett (2000) examined the cotyledons, hypocotyles, and roots of alfalfa, broccoli, cloves and sunflower sprouts and found biofilms on plant parts. He concluded that naturally occurring biofilms on sprouts may provide protection for pathogens such as *Salmonella* and *E. coli* O157:H7. The formation of biofilms on leaf surfaces of spinach, lettuce, Chinese cabbage, celery, leek, basil, parsley and endive has also been shown by (Morris *et al.*, 1997).

3.7 Conclusions

A wide variety of bacteria, viruses and parasites have been linked to outbreaks of illness associated with fresh produce. These microorganisms have specific characteristics, such as size or charge, which determine their movement and survival in the aquatic environment and their susceptibility to various water and wastewater treatment processes. However, these microorganisms do share some common features. Contamination of raw fruit and vegetables with the pathogens of interest can occur directly or indirectly via animals, soil, water and human handling. Conditions for survival and/or growth of pathogens on fresh produce are influenced by the type of micro-organism, the produce, and environmental conditions in the field. Of interest to this report are the survival and transport mechanisms of pathogens in irrigation water. Table 3.10 summarises the key information on transport and fate for the priority pathogens. Key conclusions are:

- The pathogens of interest are from enteric environments. The presence of cattle and other livestock or sewage discharges within the catchment are therefore particularly significant factors for their occurrence in irrigation water originating from surface water and groundwater.

- Conditions for survival of pathogens in irrigation water are influenced by the type of micro-organism, and key environmental factors such as temperature, pH, sunlight, humidity, biofilms and microbial predation.

- On crop surfaces the most important factors that affect pathogen survival are the type of micro-organism and leaf surface, relative humidity, moisture content (water activity), temperature, composition of the suspending medium, light exposure and microbial predation. Cut leaf surface may result in greater retention of pathogens.

- Internalisation of pathogen within a crop will generally only represent a small proportion of those that the crop is exposed to, hence, the relative importance of internalisation will depend on the inactivation or removal of pathogens on the surface such as through washing. The method of irrigation is also important in determining the rate of internalisation of pathogens within the crop. Spray irrigation appears to result in the highest rate of internalisation.

Knowledge of pathogen characteristics can help in the design of effective barriers or control strategies and will be discussed in terms of risk management (Chapter 5).

Table 3.10 Fate and transport of priority pathogens

Pathogen	Sources	Examples of Reported outbreaks	Survival T$_{90}$	Isoelectric point	Size	Modes of transmission
Salmonella	Humans, livestock,	*Salmonellas* the main source of outbreaks from fresh produce in UK at 41% (Long *et al.*, 2002) and US at 48% (Sivapalasingam *et al.*, 2004), including outbreaks attributed to salad, melon, fruit juice, tomatoes and lettuce	In groundwater, 14 days (range 2 – 33) (John *et al.*, 2005)	5.0-8.4 (Kabir, 1977)	0.6 µm by 0.7 µm by 2.5 µm (Pedley *et al.*, 2006)	Contaminated food, water, or contact with infected animals
E. coli O157:H7	*E. coli* O157:H7 has been found in the intestines of healthy cattle, deer, goats, and sheep.	Apple cider, lettuce, sprouts, carrot, pineapple (Sivapalasingam *et al.*, 2004) and spinach (2006)	Surface water: 7 – 19 days (Wang *et al.*, 1998)	5.0 (Dickie *et al.*, 1989)	0.5 µm by 1.0 µm by 2.0 µm (Pedley *et al.*, 2006)	Contaminated foods, primarily meat and milk, Direct contact with animals and person-to-person spread. Waterborne transmission reported.
Campylobacter	The largest reservoir is in animals, probably poultry, cattle and sheep.	Between 1995 and 2005 5 outbreaks of intestinal disease associated with salad were attributed to *Campylobacter* in England and Wales	Surface water: 25 min in artifical sunlight (Obiri-Danso *et al.* 2001). Mesophilic anaerobic digestion of beef slurries: 438.6 days (1993)	5.9 (Tompkins *et al.*, 1988)	0.2 - 0.5 µm by 0.5 - 5 µm (Smibert, 1986)	Contaminated meat or through water contaminated with the excreta of infected animals.
Norovirus	Exclusively human faeces and vomit	Washed salad, frozen raspberries, coleslaw, green salads, fresh cut fruits, potato salads (Seymour *et al.*, 2001)	Dechlorinated water: 5.2 days for FCV and 18.7 days for MS2 at 25 °C (Allwood *et al.*, 2003).	5.5 – 6.0 (Goodridge *et al.*, 2004)	30-35 nm (Seymour *et al.*, 2001)	Primarily faecal-oral. Aerosolization of vomitus and environmental and fomite contamination may also act as a source of infection.
Cryptosporidium	Humans, livestock, companion animals and wildlife	Apple cider and green onion (Sivapalasingam *et al.*, 2004)	Surface water: 40 – 100 d (Medema *et al.*, 1997)	2.5 (Drozd *et al.*, 1996)	4 – 6 µm	Main route of infection is by person-to-person contact. Transmission through contaminated water is well documented.

Chapter 4 Impacts of wastewater discharges on water quality of source waters used for irrigation

The types of water sources used for irrigation include surface water, groundwater, public mains water, rainwater and other sources (Weatherhead, 2007). Direct reuse of water for crop irrigation from wastewater treatment works is not normally practiced in the UK. Therefore the relevance of the discussion in this chapter is in the discharge of wastewater to surface water which is the primary source of irrigation water.

In the UK, around 96% of the population is connected to sewers leading to a wastewater treatment works (WwTW), the majority of which treat the waste from 2000 people. Most of the remainder are served by small private treatment works, cesspits or septic tanks. These small WwTWs and cesspits/septic tanks are located predominantly in rural areas and are relatively likely to impact sources of irrigation water. On average each person produces 150 litres of wastewater a day. The daily combined flow to the 9000 WwTWs in the UK is in the region of 11 billion litres, conveyed through about 347,000 km of sewers (Defra, 2002). Sewers, particularly those built before 1970 also receive run off from roofs, paved areas and roads ('combined systems'). During times of heavy rainfall this can form the majority of the flow within the sewerage system.

The treatment and disposal of sewage is governed by the European Council Directive 91/271/EEC concerning urban waste water treatment. The urban waste water treatment (UWWTD) directive applies to all works treating flows above 2000 population equivalent (pe). (CEC, 1991). The Directive specifies treatment requirements and limit values for BOD, COD and phosphorus (for discharges to sensitive waters). It sets secondary treatment as the normal standard, but requires tertiary treatment for works discharging to 'sensitive areas', generally those receiving waters that would be subject to eutrophication in the absence of additional treatment, usually reduction in levels of nutrients. Receiving waters potentially at risk of eutrophication include enclosed water bodies and sluggish lowland rivers. There are no microbiological standards specified by the Directive, which is enforced by the EA in England & Wales and SEPA in Scotland. A relatively small number of WwTWs are provided with UV disinfection because they discharge to estuaries and coastal areas subject to European Directives concerning bathing water and/or shellfish waters to which microbiological standards do apply.

Treated wastewater is discharged to inland water, estuaries and the sea. The majority (90%) of the daily 11 billion litres is discharged to inland waters (the scope of this study).

Data for the UK from 2000 show that of the 1995 agglomerations[1], only 194 discharge to coastal waters (Defra, 2002).

4.1 Wastewater treatment

Wastewater treatment works are designed to accept and pass forward to full treatment a finite volume of sewage. As a general design objective, a treatment works will be designed to treat in the region of three times the dry weather flow (DWF). In addition, there will be storage at the works capable of receiving six times DWF during heavy rainfall. In the UK, the design criterion for the volume of storage provided at WwTWs is 68 l/head of population served. This will be sufficient to retain several hours storm water at peak flow. As the flow to the works reduces, the retained storm water will be progressively passed forward to receive full treatment. Sewage treatment consists of a series of unit processes applied sequentially – preliminary, primary, secondary and tertiary treatment.

Secondary (biological) treatment is the minimum level of treatment specified by the UWWTD, which must achieve 70% and 75% removal of BOD and COD, or limit values of 25 mg/l (upper tier 50 mg/l) and 125 mg/l (upper tier 250 mg/l), respectively.

4.1.1 Microbial Content of Wastewater

Untreated wastewater (sewage) contains microorganisms of human (and possibly animal) faecal origin. Typical levels of indicator bacteria and pathogens in untreated domestic wastewater are shown in Table 4.1.

Average figures are misleading. Sewage strength varies according to the time of day (diurnal) and the amount of rainfall and/or infiltration. Changes due to diurnal variation are, to some extent, predictable and attenuated through the treatment process and within the receiving water. By contrast the effect of rainfall is less predictable and is likely to be significant in terms of the delivery of microorganisms to receiving waters. Monitoring data for a works receiving domestic sewage show that the numbers of indicators can vary by more than two orders of magnitude (Figure 4.1).

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[1] An agglomeration is a community of homes, shops and hospitals and certain industries which are sufficiently concentrated for the waste water to be collected for treatment at a sewage works. With very few exceptions, an agglomeration is the community served by a single sewerage collection network and served by a single works, its catchment.

Table 4.1 Types and numbers of microorganisms found in untreated domestic wastewater (Tchobanoglous *et al.,* 1991)

Organism	Concentration Number/mL
Total coliforms	$10^5 - 10^6$
Faecal coliforms	$10^4 - 10^5$
Faecal streptococci	$10^3 - 10^4$
Salmonellae	$10^0 - 10^2$
Enteric viruses	$10^1 - 10^2$
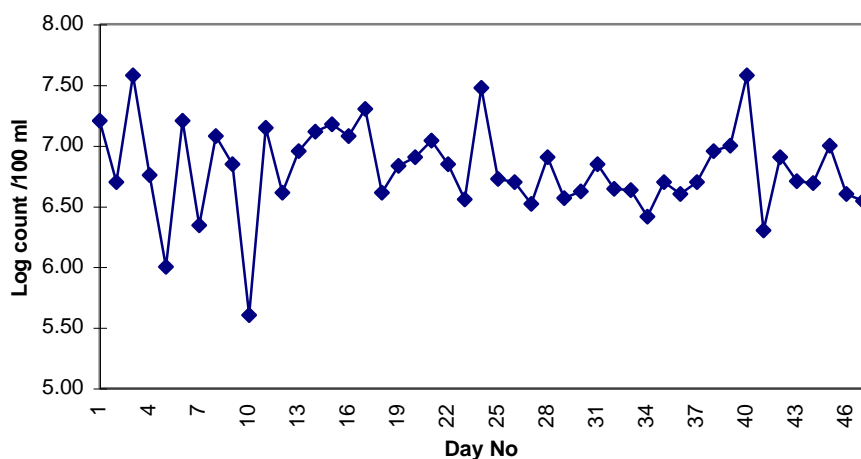
Figure 4.1 Counts of faecal coliforms in untreated domestic wastewater sampled at treatment plant inlet (Unpublished data)

4.2 Effects of treatment on microbial quality

The primary purpose of treatment is to reduce the amount of carbonaceous material and ammonia to a level consistent with the assimilative capacity of the receiving water. Coincidentally this reduces the numbers of indicators and pathogens, the degree of which is dependent on the nature of the treatment process. Reduction is the combined result of separation of solid material (most microorganisms are associated with solids), predation, competition from naturally occurring organisms, inactivation due to changes in pH etc. The effect of various treatment processes on the removal or destruction of bacteria and viruses is shown in Table 4.2 and Table 4.3.

Table 4.2 Removal or destruction of bacteria by different treatment processes (Tchobanoglous *et al.*, 1991)

Process	% Removal
Coarse screens (0.1 - 0.2 mm)	0 - 5
Fine screens (0.01 - 0.1 mm)	10 - 20
Grit chambers	10 - 25
Simple sedimentation	25 - 75
Chemically-aided sedimentation	40 - 80
Trickling filters	90 - 95
Activated sludge	90 - 98

Table 4.3 Removal or destruction of bacteria and viruses by different treatment processes (Feachem *et al.*, 1983)

Process	% Removal		
	Faecal coliforms	Salmonella	Enteric Viruses
Primary sedimentation	50 - 90	50 - 90	0 - 30
Trickling filter	90 - 95	90 - 95	90 - 95
Activated sludge	90 - 99	90 - 99	90 - 99
Oxidation ditch	90 - 99	90 - 99	90 - 99
Waste stabilisation pond†	4 - 7 Log_{10} ?	99.99 - 100	99.99 - 100
Lagoon	2 - 6 Log_{10} ?	99 - 100	99 - 100

† 3 cells, 25 days minimum total retention.

Monitoring of effluent shows that levels of indicator bacteria vary with time, showing a similar pattern to that observed in untreated wastewater (Figure 4.2).
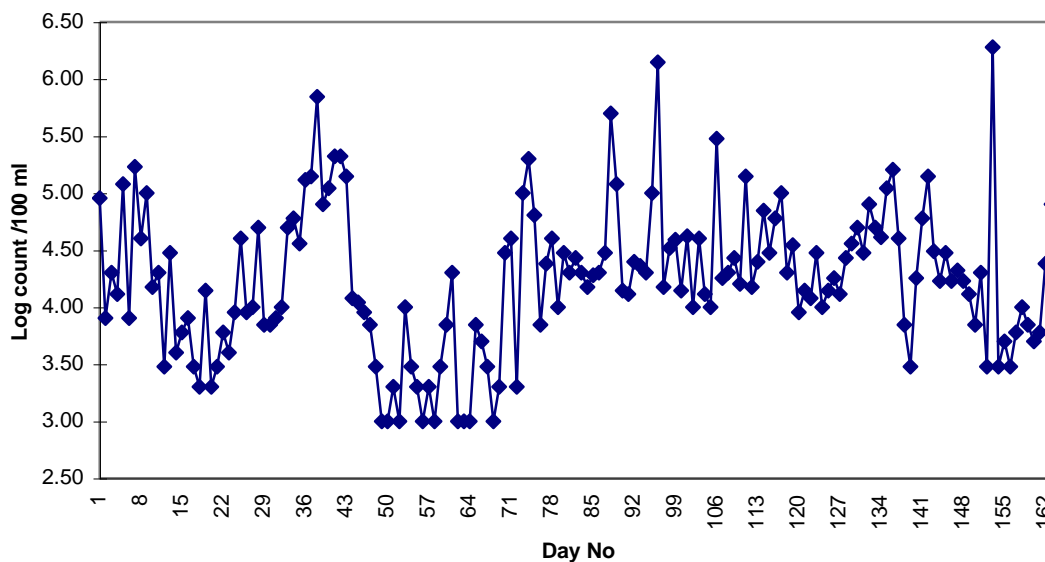
Figure 4.2 Counts of faecal coliforms in treated wastewater sampled at treatment plant outlet (Unpublished data)

Tertiary treatment may be applied with the explicit intention of disinfection by means of UV irradiation, chemical disinfection (chlorine, ozone) or microfiltration (MF). Concerns regarding the formation of harmful by-products during chemical disinfection has led to greater emphasis on the use of UV and increasingly MF, either as a tertiary stage or in combination with a biological process in a membrane bioreactor (MBR). The effectiveness of these technologies in reducing microbial levels further can be seen in Figure 4.3 and Table 4.4 respectively.
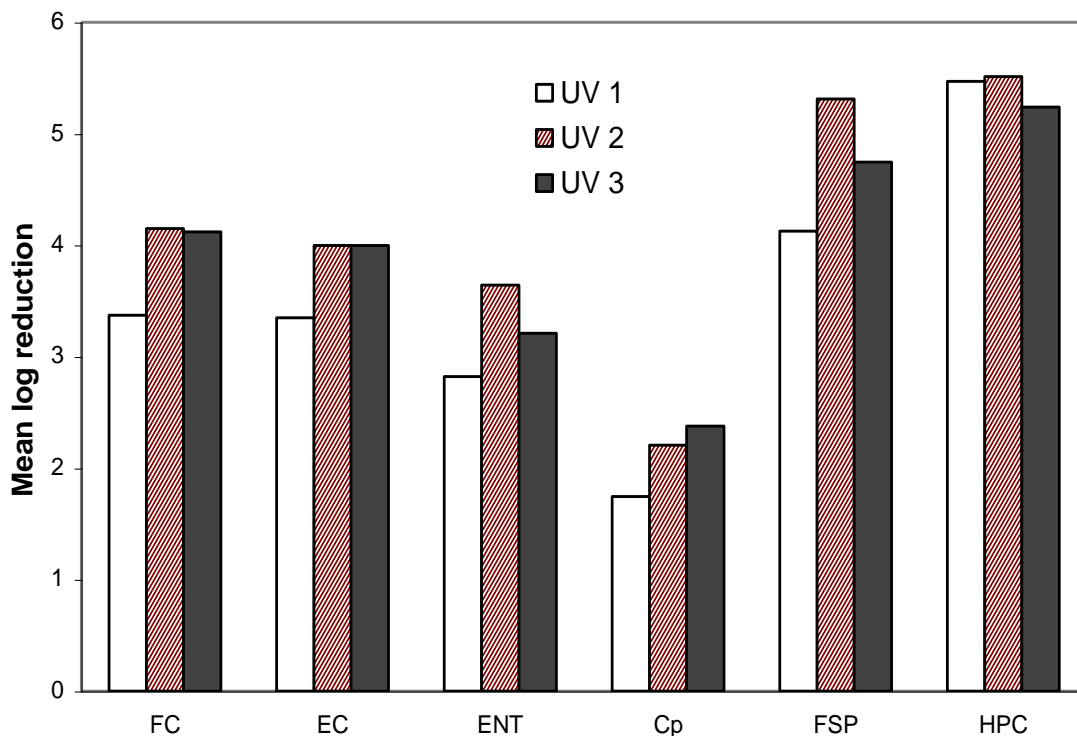
Figure 4.3 Inactivation of faecal indicators, bacteriophages and heterotrophic bacteria in an operational wastewater UV disinfection plant. (FC, faecal coliforms; EC, *E. coli*; ENT, enterococci; Cp, *Clostridium perfringens*; FSP, F[+] specific phage; HPC, heterotrophic plate count) (Moreland *et al.*, 1998)

Table 4.4 Removal of bacteria and viruses using microfiltration (MF) or ultrafiltration (UF) (Jacangelo *et al.*, 1995)

Membrane type	Log removal		
	E. coli	Ps. aeruginosa	MS2 phage
MF (a)	>7.8	>8.2	<1.0
MF (b)	>7.8	>8.2	<1.0
MF (c)	>7.8	>8.2	<1.0
UF (a)	>9.0	>8.2	1-2
UF (b)	5.6	>8.2	4.0
UF (c)	7.8	>8.2	>6.0

More recent data on the effect of several wastewater treatment processes on numbers of faecal indicator organisms is reported by UKWIR (2003). Seventeen WwTWs in England and Wales were monitored for a period of six months. At each site samples of preliminary screened and secondary treated effluent were collected and analysed for total coliforms, faecal coliforms, Enterococci and F+ RNA bacteriophage. The results are summarised in Table 4.5 and Table 4.6.

Table 4.5 Removal of bacteria and bacteriophage by different wastewater treatment processes (UKWIR)

Secondary treatment process	Median Log_{10} reduction rates			
	Total coliforms	Faecal coliforms	Enterococci	F+ RNA bacteriophages
Activated sludge	1.87	2.09	1.97	2.04
Biological aerated flooded filters	1.02	1.79	1.86	ND
Chemically assisted settlement	1.61	1.09	1.16	1.01
Oxidation ditch	1.99	1.96	1.81	1.6

ND, No Data

Table 4.6 Numbers of faecal indicator organisms in treated wastewater (UKWIR, 2003)

Treatment	Organism	Number per 100ml		
		Min	Max	Median
Activated sludge	Total coliforms	1.67×10^3	9.8×10^6	1.8×10^5
	Faecal coliforms	9×10^2	3×10^6	3.1×10^4
	Enterococci	1×10^2	6.8×10^5	5.8×10^3
	F+ bacteriophage	<1	3.6×10^2	1.7
Chemically assisted settlement	Total coliforms	8×10^3	2×10^7	2.7×10^5
	Faecal coliforms	2×10^3	3.1×10^7	3×10^5
	Enterococci	8×10^2	4.7×10^6	7.5×10^4
	F+ bacteriophage	<1	8.3×10^2	28.5
Biological aerated flooded filters	Total coliforms	6×10^4	2.3×10^7	3×10^6
	Faecal coliforms	1.1×10^4	5.6×10^6	2.7×10^5
	Enterococci	2.9×10^3	6.3×10^5	3.7×10^4
	F+ bacteriophage	ND	ND	ND
Oxidation ditch	Total coliforms	1.2×10^4	3×10^6	1.4×10^5
	Faecal coliforms	3×10^3	3.1×10^7	3×10^5
	Enterococci	5×10^2	8.4×10^5	5.1×10^4
	F+ bacteriophage	<1	8.1×10^2	3

ND, No Data

4.3 Other wastewater discharges to receiving waters

Not all wastewater receives full treatment before being discharged to the aquatic environment. Flows exceeding the capacity of the treatment works (once storm storage is exhausted) will bypass the treatment process having been subject to preliminary treatment (screening). Numbers of faecal indicator organisms in storm water depend on a number of factors including, antecedent weather conditions, catchment characteristics, and duration and intensity of the rainfall event (Ellis, 2004). In general terms the microbial content of storm water is similar to that of treated wastewater.

Combined sewer systems (i.e. those that collect rainwater) are the norm in the UK. They are designed with overflows (combined sewer overflows – CSOs) located at strategic points along the route of sewers. At times of increased flows due to rainfall, excess flows are discharged through CSOs, usually to surface water. Without CSOs, surcharging will occur resulting in flooding of premises and the wastewater treatment works. Sewage pumping stations are fitted with overflows that will operate if flows exceed the pumping capacity or in the event of pump failure.

4.4 Impacts on water quality

Wastewater discharges to inland waters are an important contributor to faecal indicator organisms and pathogens in sources that may be used for irrigation. During the drier summer period when irrigation is at its height, in certain catchments river flows may consist predominately of treated wastewater. The magnitude of changes in microbial quality arising from wastewater discharges will depend on a range of factors, many of them site specific. These include:

- The degree of dilution at the point of discharge.

- Environmental conditions e.g. amount and intensity of sunlight, water temperature, pH, concentration of dissolved oxygen, river flow, suspended solids.

From the point of discharge, numbers of faecally-derived microorganisms will decrease as a result of the combined physical effects of dilution and the environmental stressors discussed previously. Clearly the relative locations of wastewater discharges and abstraction points for irrigation is a crucial factor affecting the degree to which the quality of irrigation water is affected.

Studies on the River Ribble catchment in NW England (Kay *et al.*, 2005; Wither *et al.*, 2005) and elsewhere (Crowther *et al.*, 2002) have demonstrated the relative contributions of wastewater discharges (from WwTWs, storm overflows, CSOs) and diffuse pollution.

The relative importance of the differing sources of faecal indicator organisms is catchment specific. However what these studies have demonstrated is the major impact of rainfall in combination with land use.

The drainage area of the River Ribble is the sole UK sentinel study area intended to pilot management approaches for implementation of the European Water Framework Directive (WFD) (CEC, 2000). A detailed description of the catchment is provided in Fewtrell *et al.* (1998). Briefly, the catchment covers 1583 km^2, comprising five main sub-catchments draining into the rivers Ribble, Douglas, Darwen, Lostock and the Yarrow. Of these, the R. Ribble sub-catchment is the largest (1130 km^2). Within the drainage area there are 53 major WwTWs and 574 consented discharges for intermittent discharges of wastewater located at treatment works, pumping stations and CSOs. Information on land use was obtained from remotely sensed land cover data. Within the catchment there are extensive conurbations. Agricultural land use is primarily improved pasture or rough grazing.

During July-September 2002, an intensive survey of river flows, rainfall, and microbial analysis of river water and sources of wastewater was carried out. Water quality sampling was carried out at 41 sites (WwTW, CSO, rivers). Water quality monitoring revealed significantly increased numbers of faecal indicator organisms during high river flow compared with base (dry weather) flow. Spatial analysis of the faecal indicator organism numbers revealed that land use was the most important factor in determining microbial water quality. In rural sub-catchments, the amount of improved pasture was the determining factor. The rural and agricultural nature of the upper reaches of the River Ribble contributed only 10% of the input of faecal indicator organisms yet accounted for nearly three quarters of the flow volume. This is in stark contrast to built-up land where the major input was from the wastewater infrastructure.

Similar studies in the UK and elsewhere have revealed a similar pattern of increasing numbers of faecal indicator organisms and pathogens in response to rainfall. Factors that contribute to this effect are increased surface run-off and extension of stream networks that expands the area being drained. There may also be resuspension of organisms from stream sediments. Another major effect of rainfall is to increase flow in combined sewerage systems causing CSOs to discharge directly to watercourses. Environmental conditions during and immediately following rainfall events will favour microbial survival (increased turbidity, reduced sunlight) and persistence (reduced sedimentation, enhanced transport) (Kay *et al.*, 2005).

Areas of the UK in which irrigation is routinely practised are characterised by a predominance of arable land use. Here, the input of faecal indicator bacteria and pathogens as result of run off from agricultural land will be less than for the more livestock intensive farming areas in which the reported studies have been conducted. Discharges from wastewater treatment works and associated infrastructure assume a greater importance in these arable catchments. This is clearly demonstrated by Kay et al. (2005) who used the same methodology in a predominantly arable (cereal cropping) area of south east England.

4.4.1 Sanitary survey

Sanitary surveys provide a method for understanding the sources of pollution within a catchment. Surface and subsurface water quality models can provide a method of predicting the changes in the quality of irrigation waters with regards pollution sources and climatic changes. A review of models was undertaken to assess and compare models that can predict microbiological water quality. The results are provided in Appendix 1.2. As part of the current project a risk assessment model has been developed to investigate the factors affecting pathogen loads in irrigation waters. This is presented in Chapter 5.

4.5 Conclusions

As surface water is the predominant source of irrigation water for salad crops, it is important to understand the potential sources of pathogens. UK studies have reported that land use is the most important factor in determining microbial water quality, with the amount of improved pasture the determining factor in rural sub-catchments. These sub-catchments were reported to contribute nearly three quarters of the flow volume but only 10% of the faecal indicator organisms loads. Rainfall also had a significant impact on water quality.

During the drier summer period when irrigation is at its height, in certain catchments river flows may consist predominately of treated wastewater. The treatment and disposal of sewage is governed by the European Urban Waste Water Treatment Directive. This sets secondary treatment as the normal standard, but requires tertiary treatment for works discharging to 'sensitive areas'. It does not include microbiological standards.

In the UK, around 96% of the population is connected to sewers leading to a wastewater treatment works. Sewers may also receive storm water, and during heavy rainfall this can form the majority of the flow and result in bypass flows being discharged to receiving waters without treatment. The composition of wastewater will be determined by this

rainwater as well as water usage, although pathogen loads will also be determined by the number of infections in the community.

Wastewater treatment aims to reduce concentrations of carbonaceous material and ammonia, to minimise the impacts on receiving waters. Reductions in the loads of indicator organisms and pathogens is incidental and varies depending on the treatment process. Research in the UK has reported comparable reductions of faecal coliforms, *Enterococci* and bacteriophage in activated sludge, chemically assisted settlement and oxidation ditches, although reductions in faecal coliforms were generally highest.

In conclusion, it is important for an irrigator to understand the water source from which they are abstracting, including the relative location of wastewater discharges and impact on weather conditions. Sanitary surveys are one method for achieving this. At a catchment level, the relative sources of faecal indicator organisms can be modelled on the basis of land use characteristics.

Chapter 5 Quantitative Microbial Risk Assessment: Irrigation of Fresh Produce in the UK

Risk analysis comprises of risk assessment, risk management and risk communication. Risk assessment enables a ranking of exposure events, which can be used as a management tool and can be qualitative or quantitative. Risk assessment is advocated for use in several international guidelines including the WHO Guidelines for the safe use of wastewater, excreta and greywater (WHO, 2006) and the WHO Guidelines for Drinking Water Quality (WHO, 2004b), and are employed in the UK in the drinking water safety plans. Qualitative risk assessment is currently undertaken to a certain extent by growers based on monitoring results, use of storage, harvest interval, type of irrigation, etc. This can be rapidly undertaken on a farm-by-farm basis to prioritise management actions. Quantitative risk assessment enables the assessment of, within the limitations of the available data, the probability and the consequences of an event (e.g. irrigation method) in terms of the human health outcome (i.e. the risk of becoming ill from the consumption of irrigated RTE vegetables). As quantitative risk assessment requires considerable amounts of data, it is generally used as a more general tool to influence risk management decisions than on an individual grower basis.

The aim of this risk assessment is to undertake a quantitative microbial risk assessment (QMRA) of the practices used in the irrigation of RTE crops in the UK, within the limitations of the available data, provide a quantitative risk ranking of different management and risk mitigation methods that can be applied on a local or national basis. These rankings could inform the risk management and risk communication processes undertaken by the FSA.

The objectives of the QMRA were to identify:

- how the loads on harvested RTE produce are affected by irrigation water quality;

- how the loads on harvested produce are affected by management options, such as harvest interval and storage interval; and

- the impacts of potential future changes in agricultural water use.

5.1 Methodology

The framework for QMRA includes the following: problem definition, hazard identification (section 5.1.1), exposure assessment (section 5.1.2) and risk characterisation (section 5.1.3). From above, the problem definition is to assess the practices used in the irrigation

of RTE crops in the UK. The risk assessment draws upon literature as well as the content of previous chapters with regards to pathogen source and behaviour and water quality.

5.1.1 Hazard identification

In hazard identification the microbial agents are identified as well as the spectrum of human illness and diseases associated with each specific pathogen. This also includes pathogenicity and virulence of the microorganism, aspects of acquired immunity and multiple exposures (for example exposure on different days) of the host.

The hazards were identified in the previous chapters as: *Campylobacter*, *E. coli* O157, norovirus (as an indicator of viruses), *Giardia* and *Cryptosporidium*. The properties of these pathogens have been described in Tables 2.4 and 3.10. *Salmonella* is the second most common reported cause of UK foodborne outbreaks, and the most common reported cause of outbreaks associated with fresh produce. However, probably due to the difficulty in undertaking quantitative analyses, we were not able to find sufficient data on concentrations in water to allow its inclusion in a risk assessment. Microbial indicators used in industry analyses of water quality and crop contamination were included in the risk assessment for comparison with pathogens, including *E. coli*, total coliforms and faecal streptococci.

5.1.2 Exposure assessment

The exposure assessment aims to determine the frequency, duration and magnitude of pathogen exposure by one or more pathways. The assessment is dependent on adequate methods for recovery, detection, quantification, sensitivity, specificity, virulence and viability of the microorganisms in question and is often dependent on studies and models of transport and fate in the environment.

The scope of the risk assessment was focussed on what was percieved to be the greatest risk pathway. This was considered to be, based on expert opinion, irrigation via overhead methods using surface water. Overhead irrigation methods were considered the highest risk in the majority of cases due to the direct application of the irrigation water to the edible portion of the produce (see section 3.5). There is also the possibility of pathogen transmission to crops as a result of soil splashes during irrigation.

Over half (54 %) of irrigation water in the UK is reported to be from surface water (Weatherhead, 2007). As discussed in section 3.3, surface waters will generally have a higher level of contamination than groundwater due to inputs from sewage discharges and run-off. Mains water was assumed to meet drinking water standards. Groundwater was

assumed to have significantly lower pathogen concentrations than surface water. Additionally, for surface water, correlations exist between indicator and pathogen concentrations, albeit limited ones. However, in groundwater, the additional filtration of larger pathogens and longer survival times due to lack of sunlight among other factors severely restrict attempts to correlate indicator and pathogen concentration. No information is available on the pathogen concentrations in UK groundwater.

The method of irrigation was not included as in the scope of the QMRA due to a lack of quantitative data on the impacts of different methods. Additionally, soil contamination was considered outside the scope of the project.

The scope of the exposure assessment is illustrated in Figure 5.1. The source water quality in the QMRA model was modelled based on the recorded concentrations of faecal indicator organisms in waterways in the UK, with concentrations of pathogens predicted based on correlations from literature. Water quality after storage was based on the predcited duration of storage and the inactivation rates for the different pathogens under condtions expected during storage. After spray irrigation, all organisms in water retained on the crops were assumed to be retained on the crop, so retention of microbes was based on water retention distributions for each crop type. Lastly, the microbial load on crops at harvest was based on the time of last irrigation before harvest and the survival properties of each of the microbes on crops. Further details of the parameters used are given below, with the model equations provided in section 5.1.3.
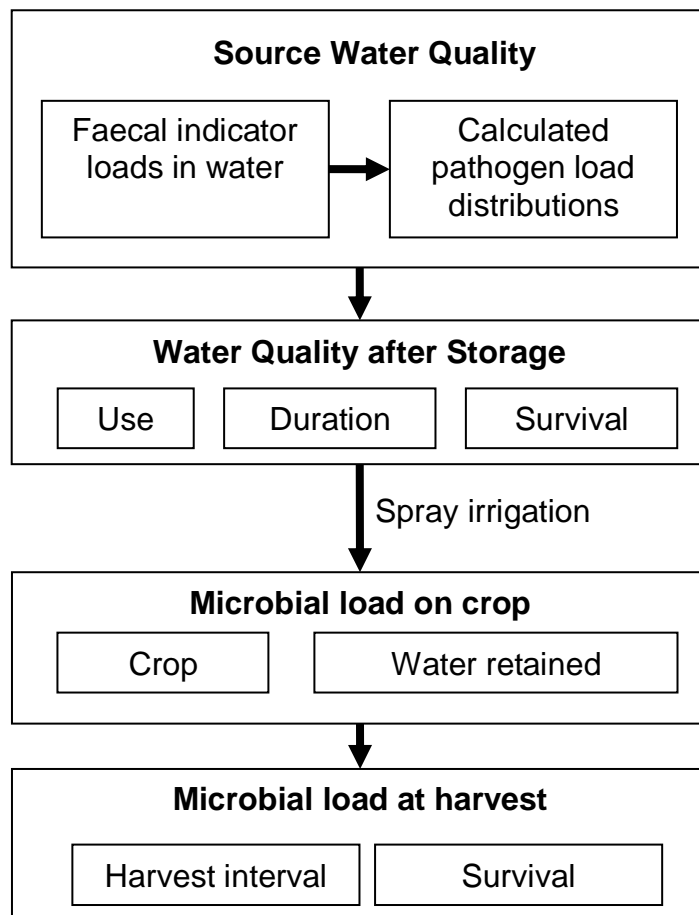
Figure 5.1 Conceptual model of risk assessment

Source water quality

Surface water quality data was collated from water companies in England and the EA. The greatest uncertainty in assessing the risk to consumers is in the prediction of the microbiological quality of irrigation water.

Table 5.1, Table 5.2 and Table 5.3 provide the key statistics for concentrations in surface water of faecal indicators.

There was a disparity between the geographic distribution of data that was available on irrigation practices and water quality. Information from the Defra survey of irrigators (Weatherhead *et al.*, 2006) is primarily for the EA Anglian (11 CAMS units), Midlands (7), Southern (4) and North East (4) regions. Data on surface water quality was readily available for the South West region, in which little irrigation is reported to take place, however, only groundwater data was available for the Southern or Anglian regions.

Table 5.1 Concentrations of Total Coliforms (per 100 mL) in surface waters in England and Wales (Data from water companies and the EA)

EA Region	Sites	Min	Max	Median	Geometric mean	Log_{10} Standard deviation
Midland	4	307	382,750	5,988	7,380	0.62
Wales	10	599	105,900	5,967	5,921	0.62
North East	5	2,129	336,800	12,855	14,285	0.49
South West	28	1,564	69,275	7,907	8,607	0.46
Thames	7	2,453	55,871	12,254	12,169	0.38
North West	8	1,329	402,125	18,646	13,851	0.53
All	62	1,443	158,416	9,745	9,631	0.50

Table 5.2 Concentrations of Thermotolerant Coliforms (per 100 mL) in surface waters in England and Wales (Data from water companies and the EA)

EA Region	Sites	Min	Max	Median	Geometric mean	Log_{10} Standard deviation
Midland	4	116	115,770	1,744	1,930	0.64
Wales	10	229	48,460	1,617	1,766	0.62
North East	5	178	48,860	4,851	3,739	0.51
South West	33	383	43,298	2,122	2,462	0.50
Thames	7	249	24,071	2,026	1,956	0.43
North West	8	328	98,375	5,123	4,805	0.57
All	67	308	53,378	2,576	2,648	0.53

Table 5.3 Concentrations of Faecal Strep (per 100 mL) in surface waters in England and Wales (Data from water companies and the EA)

EA Region	Sites	Min	Max	Median	Geometric mean	Log_{10} Standard deviation
Midland	4	11	20,531	224	228	0.71
Wales	9	23	13,082	362	351	0.61
North East	5	484	37,895	2,539	3,102	0.70
South West	30	86	19546	422	578	0.62
Thames	6	15	5,060	231	259	0.57
North West	8	80	19,910	723	705	0.67
All	62	96	18,796	592	712	0.63

In order to estimate the concentrations of pathogens in water from the faecal indicator data available, correlations of concentrations and presence/absence between specific pathogens and indicators were adopted (Table 5.4). Thermotolerant coliform concentrations were assumed to be equivalent to *E. coli* concentrations. This is a conservative assumption, as *E. coli* are the predominant bacteria that comprise thermotolerant coliforms in most waters. Three main data sources were used:

Hein *et al.* (2006) summarised studies of indicator and pathogen concentrations in various waters from which correlations were able to be derived. The studies included untreated wastewater and river water from the Meuse and Rhine rivers. Thermotolerant coliforms or *E. coli* were reported as the indicator for each data set. Pathogens reported included *Campylobacter*, *Cryptosporidium*, *Giardia* and Enterovirus. The same project also provided information on *E. coli* O157 concentrations in surface water (Deschesne *et al.*, 2006).

Horman *et al.* (2004) reported on the concentrations of *E. coli*, *Campylobacter*, *Cryptosporidium*, *Giardia* and norovirus in surface water in Finland, and the relationships between the *E. coli* and pathogen concentrations. Of these parameters, only norovirus and *Giardia* had an appropriate linear relationship that could be used for extrapolation.

Westrell *et al.* (2006) reported a Gamma distribution for norovirus concentrations in the Meuse river based on two years of study, including seasonal variation. The Gamma distribution is a continuous statistical distribution for values which are always positive and which are skewed. In this case, the values are skewed to cover the high proportion of low level detections.

The concentrations of *E. coli* in surface waters reported in these studies were generally lower than those reported in Tables 5.1 to 5.3. The average for rivers and lakes in Finland was 150 ± 434 MPN.100mL^{-1} (Horman *et al.*, 2004), with 70% of samples between 1 and 100 MPN.100mL^{-1} and only 4% over 1000 MPN.100mL^{-1}. River water from the Meuse and Rhine rivers were reported to have *E. coli* concentrations of 780 ± 650 cfu.100mL^{-1} at one site (range: 290 to 2,800 cfu.100mL^{-1}), however thermotolerant coliform concentrations at another site were comparable with the data for England and Wales with an average concentration of 6,300 ± 10,000 cfu.100mL^{-1} at another (range: 160 to 47,000 cfu.100mL^{-1}) (Hein *et al.*, 2006).

Table 5.4 Presence and concentrations of pathogens and indicators in water

Item	Distribution	References
Faecal indicators	Log Normal distribution based on geometric mean and Log$_{10}$ standard deviation	see Table 5.1 to 8.3
Campylobacter	Presence: Binomial(1, 0.56) Concentration: (log$_{10}$) Normal(0.652, 0.343) + Normal(0.390, 0.050).Log$_{10}$ *E. coli* (count/litre)	58/104 positive (Hein *et al.*, 2006) (Hein *et al.*, 2006)
E. coli O157	Presence: Binomial(1, 0.38) Concentration: 0.08 x *E. coli*	18/47 positive river/lake samples (Deschesne *et al.*, 2006) 8% of *E. coli* reported to be VTEC *E. coli*
Norovirus	Presence: Binomial(1,p) Where p is a function of the *E. coli* concentration Concentration: Gamma(0.1,333)	(Horman *et al.*, 2004) (Westrell *et al.*, 2006)
Giardia	Presence: Binomial(1,p) Where p is a function of the *E. coli* concentration Log$_{10}$ Concentration: Normal(-0.885, 0.402) + Normal(0.376, 0.071).Log$_{10}$ *E. coli* (count/litre)	(Horman *et al.*, 2004) (Hein *et al.*, 2006)
Cryptosporidium	Presence: no suitable data Log$_{10}$ Concentration: Normal(-1.354, 0.335) + Normal(0.307, 0.059).Log$_{10}$ *E. coli* (count/litre)	(Hein *et al.*, 2006)

Water quality changes during storage

The quality of irrigation water during storage will be altered by inactivation and reintroduction of pathogens. Winter storage reservoirs are reported to be present on approximately 42% of farms in England and Wales (Weatherhead, 2007). While storage design will vary between farms, for the purposes of this risk assessment they were assumed to be relatively shallow (less than 5 m), open reservoirs. Reservoir filling is assumed to vary from winter only filling, to continuous top up; however, reintroduction of pathogens may occur at anytime in an open reservoir such as from direct faecal deposition. No data was available on the duration for which the irrigation water is held in storage prior to application, the storage interval. Hence, a distribution was derived to fit the assumptions above. This distribution was based on limited evidence that storages could be filled in winter and stored until the growing season, however, from an NFU survey, 72% of respondents who had storages did not fill their storages prior to the growing season. Table 5.5 summarises the distributions adopted to describe the duration of storage.

Table 5.5 Summary of statistical distirubutions used to represent storage of irrigation water

Parameter	Distribution	References
Storage present (%)	Binomial (1, 0.42)	Average for UK, (Weatherhead, 2007)
Storage used (%)	Binomial (1, 0.30)	Average for UK, (Weatherhead, 2007)
Storage interval (days)	Lognormal (10, 5)	Derived

The survival of indicators and pathogens in storage reservoirs is a function of the duration of time the water is stored, and the temperature and exposure to sunlight during that retention time. It was beyond the scope of the model to predict the temperature of reservoirs or the exposure to sunlight. However, sunlight was considered likely to be an important factor due to the generally shallow depths of the reservoir and the use of management practices such as extracting from near the surface. To account for the variation in inactivation, distributions of inactivation rates were adopted (Table 5.6) that spanned the range of temperatures, and where available, sun exposure conditions.

Table 5.6 Statistical distributions of pathogen and indicator survival in water storage (k_{water})

Item	Distribution	References
Campylobacter	Uniform(0.25, 8.63)	(Dorner *et al.*, 2006) at 15 – 30 °C
E. coli O157	Uniform(0.31, 2.74)	(Dorner *et al.*, 2006)
Norovirus	Uniform(0.09, 0.44)	(Allwood *et al.*, 2003) FCV and MS2 survival at 4 and 25 °C dechlorinated tap water
Giardia	Uniform (0.23, 0.69)	Log_{10} rate 0.01 times temperature (°C) (10-30 °C) (Medema *et al.*, 2001)
Cryptosporidium	Uniform (0.074, 0.32)	20 – 30 °C (Dorner *et al.*, 2006)
Indicator bacteria	Uniform(0.168, 3.3)	Faecal coliforms (Sinton *et al.*, 2002)

Microbial load on crop

Of the RTE fruit and vegetables irrigated in the UK, the focus of the QMRA was lettuce due to this being the only one that had sufficient data available. However, the QMRA did include investigation in the relative impact of crop differences where data was available for baby leaf crops, broccoli, and cucumber. It is important to note that in the UK there is limited overhead irrigation of cucumbers, and irrigation of broccoli is primarily at establishment, so the QMRA results for these crops will not necessarily reflect the situation in the UK.

Over 99% of salad crops have been reported to be irrigated by overhead methods (Tyrrel *et al.*, 2006). On short rotation crops, such as lettuce, a significant proportion of irrigation water use can occur in the last two weeks prior to harvest.

The microbial load on the crop in this model did not consider internalisation. As discussed in Chapter 3, internalisation is of most concern for spray irrigated crops in soil systems; however, the proportion internalised is likely to be three to five $\log_{10}$ lower than that applied to the surface (Franz *et al.,* 2007).

The retention of organisms on crops was modelled based on the assumption that all organisms in the water retained on the plant are assumed to attach to the plant. That volume of water was defined by a statistical distribution (Table 5.7). In addition to data for lettuce, distributions were available for broccoli and cucumbers which had considerably less water retained. Despite the difference in structure, the water retention on baby leaf crops was assumed to be equal to that on lettuce crops as a conservative analogue.

Table 5.7 Summary of statistical distributions for the volume of water retained on a crop (mL/g)

Item	Distribution	References
Baby leaf	No data: assumed equal to lettuce	
Broccoli	Loglogistic (0.00109, 0.0158, 4.246)	(Hamilton *et al.*, 2006)
Cucumber	Normal (0.0036, 0.0012)	(Hamilton *et al.*, 2006)
Lettuce	Normal (0.108, 0.019)	(Hamilton *et al.*, 2006)

Microbial load at harvest

The load at harvest is defined by the duration of time that the organisms are on the crop prior to harvest, and the inactivation within this time. The time between the last irrigation and harvest is defined as the harvest interval, and will vary depending on the weather. Distributions for harvest intervals were defined based on the minimum harvest intervals reported in literature (Table 5.8), and therefore made the general assumption that irrigation was required up until harvest. Data from Tyrell *et al.* (2006) highlighted the variability in the minimum harvest interval, and was fitted to a user defined cumulative distribution. In order

to reflect this variability in the harvest interval for broccoli, which was reported to have a minimum harvest interval of one week, a triangular distribution (a continuous distribution defined by the minimum, mode and maximum) was adopted. Where there was a range in the minimum harvest interval, a uniform distribution was adopted defined by the range.

Table 5.8 Summary of statistical distributions for harvest intervals for selected crops

Item	Distribution	References
Baby leaf	Cumulative from 0 to 15 days	(Tyrrel *et al.*, 2006)
Broccoli	RiskTriang(7, 10, 21)	
Cucumber	No data: assumed equal to broccoli	
Lettuce	Cumulative from 0 to 15 days	(Tyrrel *et al.*, 2006)

The survival of pathogens during the harvest interval is primarily dependent on crop type, moisture levels, temperature and sunlight. Furthermore, survival may be affected by the plant structure (e.g. moist and dark inside a lettuce increases survival), as well as the time of year and duration of the growing periods. Hence, six indicator crop species were selected to compare the risks associated with different forms of irrigation.

Temperature and sunlight are primary factors in the inactivation of pathogens in the environment as discussed in Chapter 3, hence there was considered to be a greater opportunity for die-off in plants grown outside and harvested in late summer.

Due to the range of conditions experienced, the inactivation rates of pathogens and indicators on vegetables were modelled with broad distributions to cover the range of inactivation rates reported (Table 5.9). The survival on baby leaf salad was assumed to be comparable to lettuce as lettuce inactivation studies were undertaken on a single leaf. Limited data was available on inactivation rates, with high variability between conditions. Norovirus was assumed to be represented by FCV. FCV is the least robust of the viruses studied by either Stine *et al.* (2005) or Dawson *et al.* (2003), however it was more robust the bacterial pathogens and indicators report in Stine *et al.* (2005).

Inactivation rates for *Cryptosporidium* were only available for manure spreading on grass (Hutchison *et al.*, 2005b), with the reported inactivation exhibiting non linear behaviour: a decrease in the inactivation rate for the last 15% of the population to 0.05 ln.d^{-1}.

Table 5.9 Assumed statistical distributions for the value of the inactivation coefficient for pathogens and indicators on fresh produce

Item	Produce	Distribution	Assumptions and References
Campylobacter	Lettuce	Uniform(0.75, Normal(3.1, 0.62))	Grass and lettuce (Karenlampi *et al.*, 2004; Hutchison *et al.*, 2005b)
	Cucumber	Uniform(Normal(0.94, 0.37), Normal(3.6,1.2))	(Karenlampi *et al.*, 2004)
E. coli O157	Lettuce	Uniform(Normal(10.4,0.87), Normal(11.28,0.28))	(Stine *et al.*, 2005)
	Cucumber	Uniform(Normal(0.74,0.37), Normal(0.76,0.55))	Bell pepper (Stine *et al.*, 2005)
	Cantaloupe	Uniform(Normal(0.16,0.12), Normal(0.62,0.12))	(Stine *et al.*, 2005)
Norovirus	Lettuce	Uniform (0.62, Normal(2.6,0.41))	Feline Calicivirus (Dawson, 2003; Stine *et al.*, 2005)
	Broccoli	0.69 [single value only]	(Engineering Science, 1987; Asano *et al.*, 1992)
	Cucumber	Uniform (0.35, Normal(1.84,0.37))	Bell pepper (Dawson, 2003; Stine *et al.*, 2005)
Giardia		No data	Assumed equal to *Campylobacter*
Cryptosporidium	Lettuce	Uniform(0.053, 0.33)	Grass (Hutchison *et al.*, 2005b)
Indicator bacteria	Lettuce	Uniform(Normal(2.51,1.06), Normal(11.51,4.9))	(Stine *et al.*, 2005)
	Cucumber	Uniform(Normal(1.8, 0.51), Normal(11.7, 2.6))	Bell pepper (Stine *et al.*, 2005)

5.1.3 Risk Characterisation

A quantitative risk assessment model was developed in MS Excel with @Risk (Palisades Inc), based on the conceptual model in Figure 5.1. Faecal indicator concentrations were modelled as Normal distributions based on the water quality data gathered from the water companies and the EA (Table 5.1 to Table 5.3)

C_w = **Normal** ($\log_{10} \mu_c$, σ_c)   **Equation 1**

where C_w is the concentration of the indicator organism in river water, and μ_c and σ_c are the geometric mean and $\log_{10}$ standard deviation, respectively, of the measured data.

The pathogen concentrations in water were then predicted based on these indicator concentrations and the derived correlations for presence/absence and concentrations outlined in Table 5.4.

The duration of storage, $t_{storage}$, was modelled as a function of the probability of a storage reservoir being present (p_{st}) and the probability of the storage reservoirs being used (p_{st_use}), as well as an estimate of duration based on a lognormal statistical distribution defined by the average (μ_c) and standard deviation (σ_c):

$$t_{storage} = \text{Binomial}(1, p_{st}) \cdot \text{Binomial}(1, p_{st\_use}) \cdot \text{Lognormal}(\mu_s, \sigma_s) \quad \textbf{Equation 2}$$

The water quality at application, Q_{app}, is therefore defined by the inactivation coefficient for the microorganism in water, k_{water} (Table 5.6):

$$Q_{app} = C_w \cdot \text{Exp}[-t_{storage} \cdot k_{water}] \qquad\qquad \textbf{Equation 3}$$

The amount of pathogens retained on the plant was conservatively assumed to be equal to the number of pathogens in V, the volume of water retained on the plant (Table 5.9). The load on the plant at harvest, $L_{harvest}$, following a single irrigation event was modelled as a function of the time between the last irrigation and harvest ($t_{harvest}$), and the inactivation coefficient for the microorganisms on the crop (k_{crop}).

$$L_{harvest} = Q_{app} \cdot V / 1000 \cdot \text{Exp}[-t_{harvest} \cdot k_{crop}] \qquad\qquad \textbf{Equation 4}$$

A sensitivity assessment was undertaken on the model to identify the parameters, based on the data used and definition described above, which most strongly predicted the resulting load at harvest.

Risk scenarios

The health risk scenarios were developed from the integration of the investigations above of the water quality and irrigation practices, coupled with consideration of the time and method of harvesting, potential for contamination or disinfection in the transport, packaging and handling, and in the potential end product use, including preparation and amount consumed.

Health risk scenarios assist in identifying control points for minimising risk, and providing recommendations for management practices.

Storage reservoirs can improve the microbiological quality of water, particularly where they are no additional pathogen inputs. Insufficient data is available on the duration or type of storage to adequately represent the current situation. However, the benefit of storage over no storage was able to be modelled, including predicting the benefits of increased duration of storage assuming no additional contamination.

There are a number of potential changes to water availability, water quality and water use based on changes in policy, climate and consumer demands. Some of the key changes, and their likely impact on the risk of pathogen contamination of fresh produce, include:

Increased temperatures: in agricultural terms this will extend the growing period. In terms of pathogens, increased temperatures reduce the time required for die-off of pathogens, although changes in timing within the growing period may result in no net overall change during the growing period.

Decreased rainfall: less rainfall is expected to result in less dilution for sewage effluent in rivers, increasing the concentrations of human pathogens. This may also increase the frequency of irrigation and the amount of water used.

Changes to rainfall patterns: a change from summer to winter rainfall will increase the demand for summer irrigation, but is also likely to increase the use of stored water.

Hence, the following scenarios were assessed:

- How risk varies between vegetables with variation in water retention and variation in harvest intervals;

- The relationship between concentrations at harvest and the initial *E. coli* concentrations, storage intervals, and harvest intervals;

- The relationship between indicators and pathogens and changes with storage and harvest intervals

- The impact of recontamination of source water with bird or animal inputs on changes in the relationship between indicators and pathogens

- The impact of potential future changes in water availability and use through increased concentrations of pathogens in river water and multiple irrigation events, close to harvest.

It is recognised that flooding of crop land will contaminate soils and may contaminate any crops growing at that time. However, innundation with floodwaters was not addressed by this risk assessment. The impact of flooding on river water quality was reflected in the variability of river water quality, and was not addressed as a single event.

5.2 Results and Discussion

A summary of the risk assessment results is provided here with full details of the results provided in Appendix 1.3. The results are reported in terms of the 95th percentile of the distribution, as well as in terms of detection, where the detection limit is assumed to be 1 organism per 100 grams of produce for all organisms and types of produce. The 95th percentile was reported, rather than the maximum, as it was considered to provide a more representative view of the average high end results.

There was some variation in the results of the sensitivity assessment between the different microorganisms, due to the differences in the model (e.g. concentration based on faecal coliforms vs concentration from distribution) and differences in the data ranges. The combined results of the sensitivity analysis (Table 5.10) for *E. coli*, *E. coli* O157, *Giardia*,

Cryptosporidium, *Campylobacter* and norovirus identified that the harvest interval was the most sensitive parameter, with a strong negative correlation with the $\log_{10}$ load of microorganism at harvest. This reflects the higher inactivation rates during this period. The sensitivity analysis identified that use of the storage reservoir was more significant than the length of the storage, which reflects the lower inactivation in water and the short retention times used in the model.

Table 5.10 Sensitivity analysis results for $\log_{10}$ load of microorganism at harvest by regression, combined data for *E. coli*, *E. coli* O157, *Giardia*, *Cryptosporidium*, *Campylobacter* and norovirus

Rank	Parameter	Significant for N micro-organisms	Average Regression Coefficient (N=6)
1	Harvest interval	6	-0.405
2	Inactivation coefficient on vegetables	5	-0.150
3	Use of storage reservoir (%)	6	-0.146
4	$\log_{10}$ concentration in source water	4	0.119
5	Presence of storage reservoir (%)	5	-0.105
6	$\log_{10}$ concentration of faecal coliforms in source water	3	0.053
7	Inactivation coefficient in water	4	-0.044
8	Storage interval	5	-0.042
9	Concentration in source water	1	0.030
10	Volume of irrigation water retained	1	0.018

The modelled range of concentrations of organisms in water, and on crops, reflected the magnitude of the inactivation rates. *E. coli* had a high inacitvation rate, as well as high input loads, and had the largest range between high and low loads of greater than 20 orders of magnitude. In contrast *Cryptosporidium*, which had low inactivation rates, had low variability in the load of oocysts in irrigation water, with only five orders of magnitude difference between the maximum and minimum. Due to these ranges, *E. coli* concentrations in irrigation water were generally modelled to be the highest of the organisms for the upper 20% of cases, but were lower where longer storage intervals had been modelled.

The results of the modelling indicated that the load of pathogens and indicators at harvest were generally below levels that would be detectable by standard methods (<1 per 100g). At the 95th percentile of loads on lettuce, *E. coli* were the highest, followed by *Campylobacter*, norovirus, *Cryptosporidium*, *E. coli* O157 and *Giardia*. There was less than one order of magnitude difference between the 95th percentiles for norovirus and *Giardia*, from 0.008 to 0.07 per 100 grams of fresh produce, respectively. The proportion of samples with microorganisms modelled to be above detection (≥1 per 100g) was 17% for *E. coli*, 8.9% *Campylobacter*, 2.2% *E. coli* O157, 1.1% for *Giardia* and 0.4% for norovirus, with no *Cryptosporidium* concentrations at the level of detection. These results are also

provided in Table 5.11 in a form designed to be comparable with data reported in literature (see section 5.2.2 below).

Table 5.11 Modelled loads of microorganisms on lettuce from spray irrigation

Microorganisms	<1 per gram	1 – 10 per gram	10-100	>100
E. coli	95%	3.9%	0.8%	0.04%
Campylobacter	100%	0	0	0
Norovirus	100%	0	0	0
Cryptosporidium	100%	0	0	0

The different properties of four different vegetables were investigated: baby leaf salads, broccoli, cucumber and lettuce. Baby leaf salads, which were modelled with the shortest harvest interval, had the highest loads (Figure 5.2), with approximately double the number above the level of detection for *E. coli* and *Campylobacter*. Cucumber, which had the lowest rate of water retention, had the lowest risk of the produce modelled. Furthermore, Figure 5.2 highlights the impact of the inactivation rate on horticultural crops, with the difference in the relative *E. coli* loads and those of other organisms changing from prevalent *E. coli* dominant in lettuce and baby leaf salad (with harvest intervals of 5.4 ± 4.2 and 2.9 ± 3.0 days respectively) to the more persistent *Cryptosporidium* dominant in broccoli and cucumber (with harvest intervals of 12.7 ± 3.0 and 12.7 ± 3.0 days respectively).
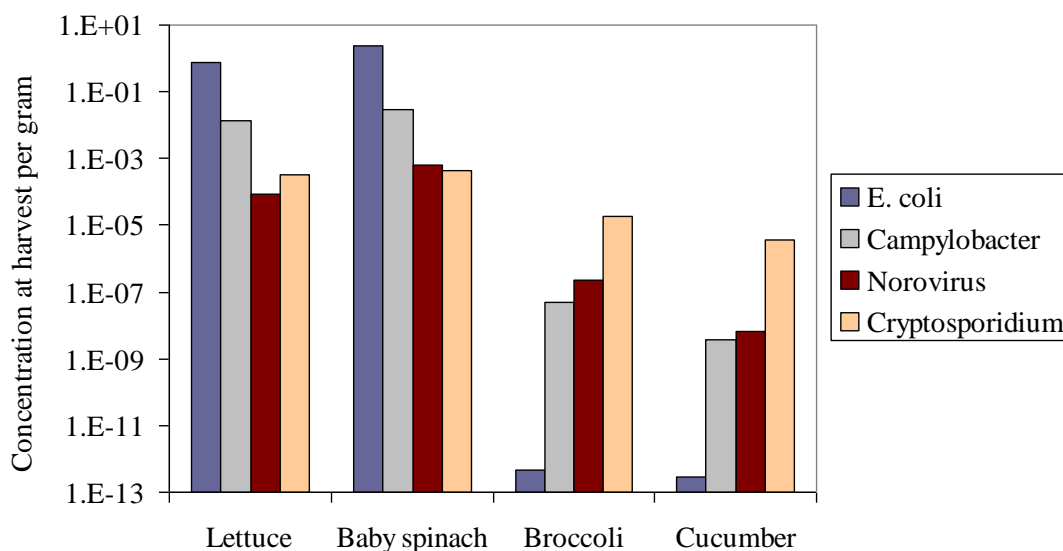
Figure 5.2 Comparison of 95th percentile of loads of key pathogens and indicators on different crops from spray irrigation

The modelled concentrations of indicators in surface water (Figure 5.3) were comparable to water quality data for livestock dominated catchment in Scotland and the River Stour, Essex (Groves *et al.*, 2002). Data from the EA's harmonised monitoring programme from

1989 to 1999, as reported in Groves *et al.* (2002), showed maximum counts of faecal coliforms greater than 10^5 per 100 mL across the majority of monitoring sites in the EA's Southern, Anglian, Southwest, Thames and Midlands regions, with median counts of 1,001 to 10,000 per 100 mL at approximately half of the monitoring sites.

The relationship between the indicator and pathogen concentrations (Figure 5.4) from the model indicates an increase of 0.39 $\log_{10}$ *Campylobacter* per $\log_{10}$ increase in *E. coli* concentration, and an increase of 0.34 $\log_{10}$ *Cryptosporidium*. No relationships between *E. coli* and viruses were modelled; the relationship between Norovirus and *E. coli* in surface waters was reported by Horman *et al.* (2004). The relationship between the concentrations of microorganisms in irrigation water and the load at harvest, illustrated in Figure 5.5, reflect the inactivation rates for each organism. The similarities between the pathogens on the log scale graph highlight the influence of irrigation water quality on produce contamination. From this graph, an initial concentration of 10^2 per L corresponds roughly with the one organism per 100 g detection limit assumed here.
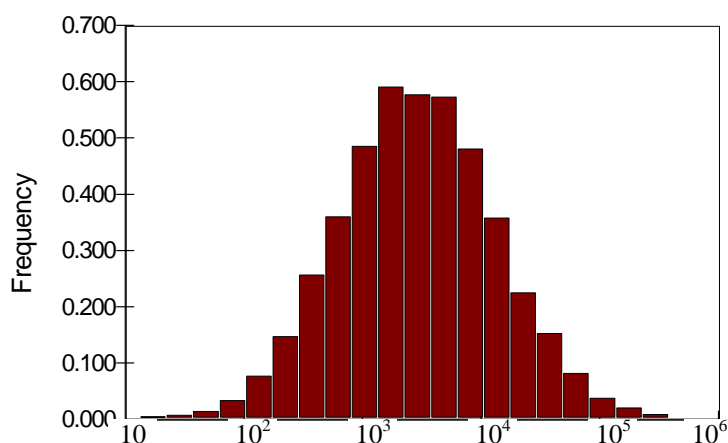
Figure 5.3 Concentration of *E. coli* in surface water (per 100mLs)
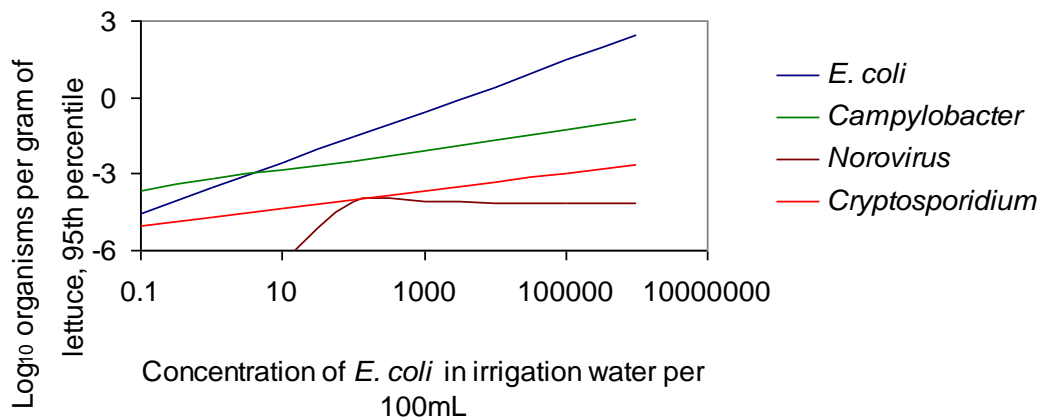
Figure 5.4 Comparison of $\log_{10}$ loads of the 95th percentile of organisms on lettuce at harvest for different initial indicator concentrations in water

Storage provides an opportunity for the natural decay of pathogens before irrigation of the crop. Figure 5.6 illustrates the modelled decrease in the pathogen load with the increasing duration of storage. Without recontamination, 28 days storage afforded 1.5 $\log_{10}$ removal of *Cryptosporidium* and 3.0 $\log_{10}$ removal of norovirus, as well as greater than 7 $\log_{10}$ removal of *E. coli* and *Campylobacter*. The 95th percentile for *E. coli* was 0.45 $\log_{10}$ removal per day in storage, for *Campylobacter* 0.51, norovirus 0.11 and *Cryptosporidium* 0.05.
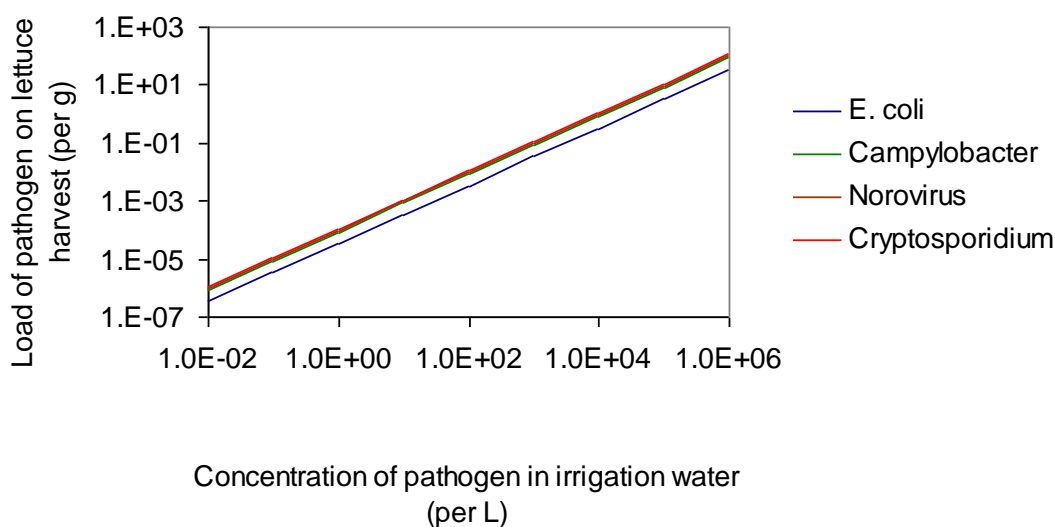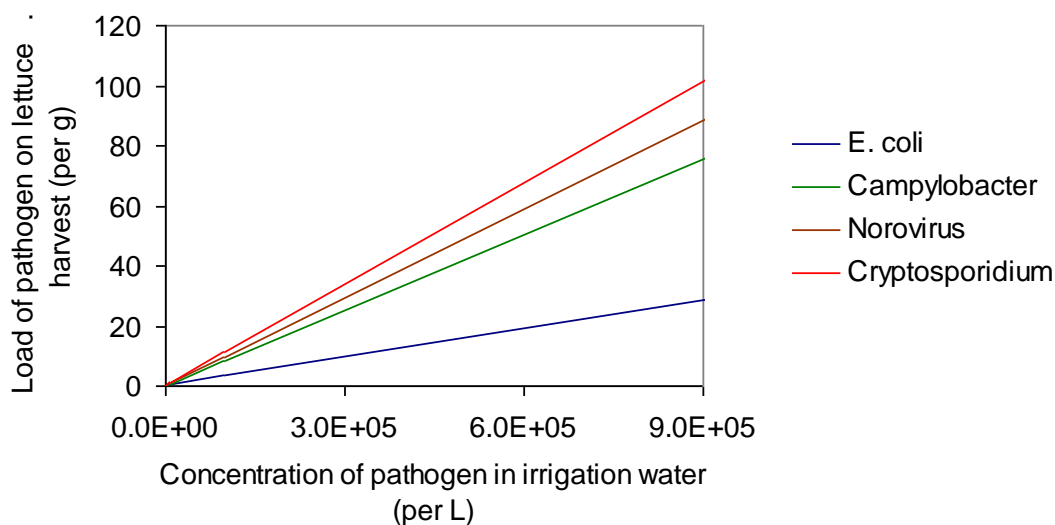
Figure 5.5 Relationship between concentrations of microorganisms in irrigation water (per L) and the resulting 95th percentile of the loads at harvest on lettuce shown on linear (top) and $\log_{10}$ (bottom) scales
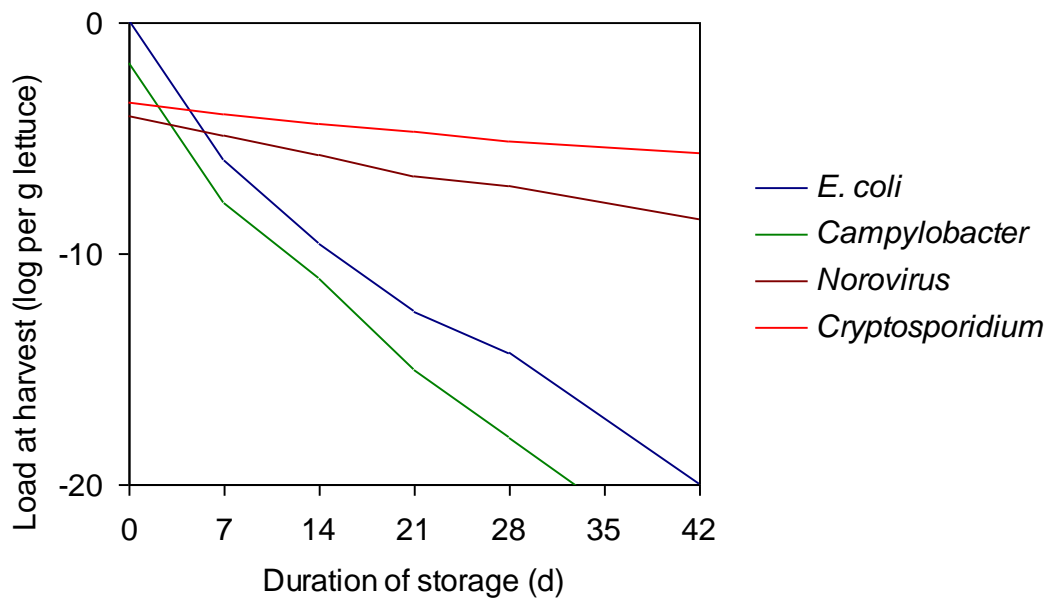
Figure 5.6 Comparison of log$_{10}$ loads of the 95th percentile of organisms on lettuce at harvest with storage of water in a reservoir before irrigation

Similarly, the harvest interval (Figure 5.7) provides an opportunity for the natural decay of pathogens. At the 95th percentile, the harvest interval provides 1.1 log$_{10}$ reduction of *E. coli* per day, 0.4 log$_{10}$ reduction of *Campylobacter*, 0.5 log$_{10}$ reduction of norovirus and 0.06 log$_{10}$ reduction of *Cryptosporidium*.

Indicator organisms such as *E. coli* are used to indicate potential faecal contamination of water supplies and fresh produce. However, while indicators are more prevalent and more numerous in faecal matter, the differing inactivation rates as well as different transport properties will change this relationship. As illustrated in Figure 5.6 and Figure 5.7, the duration of storage and the harvest interval will change the ratio of *E. coli* to pathogens. Table 5.12 provides a summary of the ratios of the pathogens to *E. coli*, such that a ratio of less than one indicates greater numbers of *E. coli*, and a ratio greater than one indicates greater numbers of pathogens. In surface water used for irrigation, there were significantly higher concentrations of *E. coli* than pathogens as defined by the model inputs. On average, in the model, there was one *Campylobacter* per 100 *E. coli*, one norovirus per 1 000 *E. coli*, and one *Cryptosporidium* per 10 000 *E. coli*.
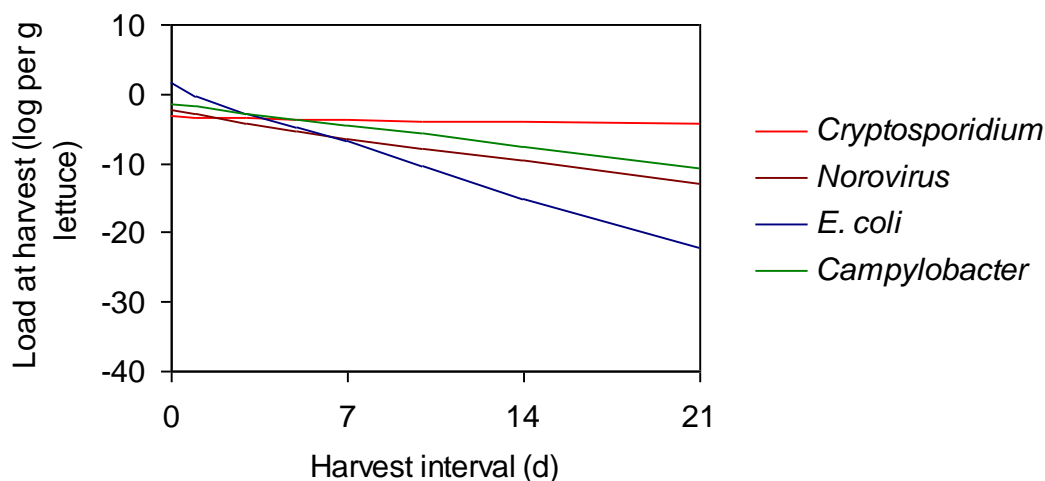
Figure 5.7 Comparison of log$_{10}$ loads of the 95th percentile of organisms on lettuce at harvest with harvest interval

Indicator organisms such as *E. coli* are used to indicate potential faecal contamination of water supplies and fresh produce. However, while indicators are more prevalent and more numerous in faecal matter, the differing inactivation rates as well as different transport properties will change this relationship. As illustrated in Figure 5.6 and Figure 5.7 above, the duration of storage and the harvest interval will change the ratio of *E. coli* to pathogens. Table 5.12 provides a summary of the ratios of the pathogens to *E. coli*, such that a ratio of less than one indicates greater numbers of *E. coli*, and a ratio greater than one indicates greater numbers of pathogens. In surface water used for irrigation, there were significantly higher concentrations of *E. coli* than pathogens as defined by the model inputs. On average, in the model, there was one *Campylobacter* per 100 *E. coli*, one norovirus per 1 000 *E. coli*, and one *Cryptosporidium* per 10 000 *E. coli*.

At harvest, the loads of pathogens on lettuce were higher than the loads of *E. coli* in 12% of cases for norovirus, 38% for *Campylobacter* and 28% for *Cryptosporidium*. In these cases, testing for indicators at harvest would not adequately reflect the potential human health risks.

In this risk assessment, only a single irrigation event has been simulated, as it was assumed that the last irrigation event conveyed the highest risk to consumers. Chapter 3 discusses the possibility that repeated irrigation events may result in increased contamination. Simulating seven irrigation events over 22 to 86 days resulted in large increases in the number of organisms on the crop, although much of this increase was still below the level of detection (Table 5.13 and Table 5.14), and below the levels reported on crops.

Table 5.12 Relationships between the concentration of *E. coli* and select pathogens

Pathogen	Scenario	Average ± standard deviation	Range	Proportion of ratios		
				Equal to 0	Between 0 and 1	Greater than 1
Norovirus	In water	0.001 ± 0.01	$0 - 0.7$	61	39	0
	Harvest	10^{35}	$0 - 10^{37}$	62	16	12
Campylobacter	In water	0.01 ± 0.04	$0 - 0.8$	44	56	0
	Harvest	10^{35}	$0 - 10^{37}$	45	17	38
Cryptosporidium	In water	0.0001 ± 0.002	$10^{-7} - 0.003$	0	100	0
	Harvest	10^{35}	$10^{-7} - 10^{37}$	0	72	28

Table 5.13 Level of detection (% more than 1 per 100 g) on lettuce after a single and multiple events

Number of events	*E. coli*	*Campylobacter*	Norovirus	*Cryptosporidium*
1	17	8.9	0.4	0
7	90.9	43.4	4.0	0

Table 5.14 Modelled loads of microorganisms on lettuce after seven irrigations

Microorganisms	<1 per gram	1 – 10 per gram	10-100	>100
E. coli	28.7	56.3	14.5	0.5
Campylobacter	99.98	0.01	0	0
Norovirus	100	0	0	0
Cryptosporidium	100	0	0	0

5.2.1 Limitations of the data and the model

The QMRA model was limited to within the scope of the project and by the availability of suitable data. A significant data gap was the lack of information on the storage interval, which was therefore modelled based on conservative assumptions about reservoir usage. Similarly, limitations of data available on the retention of irrigation water on different crops, harvest intervals and inactivation of some organisms resulted in assumptions being made to extrapolate available data to all conditions.

Salmonella was identified in Chapter 2 as the most common reported cause of outbreaks associated with fresh produce. However, there was insufficient data available to include it in the risk assessment. Data on *Salmonella* inactivation on crops (Table 5.7) suggests that it is a robust organism, with a lower inactivation rate than those that have been included in the QMRA, except for *Cryptosporidium*. The inactivation rate of *Salmonella* in surface water has been reported to be similar to, but greater than, that of *E. coli* (Sinton *et al.*, 2007). Hence, where *Salmonella* is present, it is expected to be persistent, and this may be a contributory factor to its status as the most common reported cause of outbreaks.

The water quality data available was restricted to indicator bacteria concentrations in surface waters, as well as restricted to areas which did not necessarily correspond with the areas where irrigation with surface water is prevalent. The available data on the Anglian region, where the majority of irrigation is undertaken, indicated lower faecal indicator concentrations than the data gathered for this study.

While a good fit was achieved of the modelled pathogen concentrations with the data used to develop the relationships between pathogens and indicators (Appendix 1.3), the data used to develop the relationships was quite limited. The available data for correlation between concentrations of indicators and pathogens in surface water, namely *Giardia*, *Cryptosporidium* and *Campylobacter*, consisted of two databases: one with concentrations in sewage and one with concentrations in surface water. The variability in surface water meant it was not possible to extrapolate between indicator and pathogen concentration from this data set alone. Furthermore, the thermotolerant coliform concentrations reported in this study (Table 5.2) had a median value of 10^4 per 100mL, which was in between the median values for the sewage dataset (10^7 per 100mL), and river water dataset (10^3 per 100mL for *E. coli* and 10^4 for thermotolerant coliforms). Therefore the combined dataset was considered the most appropriate for covering the range of values in the model, and fitting the combined data resulted in a lower standard error than that for the river water dataset only. However, the modelled distribution provided a better fit for the river water dataset than the combined dataset in most cases due to the similarities of the thermotolerant coliform concentrations.

Cryptosporidium was one pathogen for which water quality data was available. *Cryptosporidium* was reported for one site in the south west of England where it had a mean of <0.001 oocysts per L and a maximum of 0.12 oocysts per L which is ten fold lower than the average modelled concentration of 1.8 oocysts per L. Furthermore, the south west is also likely to have higher concentrations of *Cryptosporidium* than irrigation areas due to higher numbers of sheep and cattle which are a primary reservoir of *Cryptosporidium*. The *Cryptosporidium* distribution in the model had a low standard deviation, resulting in the prediction of constant low levels of *Cryptosporidium* in water and on produce, however, these concentrations were routinely below detection and the infectious dose.

The data used to predict norovirus concentrations was based on an annual distribution of concentrations. While norovirus is present year-round in the community, the peak in infections has been in winter which the data reflected with the majority of detections, and

indeed high levels, occuring over approximately four months in winter. Hence, the annual-average predictions for norovirus may underestimate the peak risk associated with the seasonality of norovirus infections in the community, if irrigation water is used, or stored for later use, during the winter.

This QMRA model was developed to provide estimates of risk from irrigation management practices. The model looks at the average overall result. This does not allow for scatter which can affect the public health risk, for example the variation within the distribution of pathogens on a crop may be on average well below the level likely to cause infection but in reality an uneven distribution may result in a number of infectious doses. The impact of scatter on risk has been previously investigated by Petterson *et al.* (2001b).

5.2.2 Detection on produce

There is limited data on the detection of microorganisms on produce, especially for the UK. *E. coli* loads on fresh produce in Europe (O'Brien *et al.*, 2000) have been reported to be 90% less than 10 per gram, 7 % between 10 and 100 per gram and 3% over 100 per gram. These *E. coli* loads reported on fresh produce in Europe were higher than the loads predicted by the QMRA. Other results from literature are generally higher than the findings of the QMRA, which may be due to poorer irrigation water or other sources of pathogens pre- and post-harvest.

From Brazil (Froder *et al.*, 2007), a study of minimally processed salads reported 73% (n=181) with faecal coliform concentrations greater than 10^2 cfu per gram, with salmonella on 3%. The loads of *E. coli* predicted on broccoli were considerably lower than faecal coliforms reported from a survey of broccoli in Canada (Dallaire *et al.*, 2006) of ≥ 20 MPN per 100 g in 17% (n=126) of samples.

General coliform counts in the USA were high compared to the *E. coli* loads from the QMRA. Mukherjee *et al.* (2004; 2006) reported average coliform counts on a range of fresh produce of 2.9 $\log_{10}$ MPN per g (n=605) and 1.5 to 2.4 log MPN per g (n=2,029) on a range of fresh produce that included mainly lettuces, leafy greens, cabbages, broccoli, peppers, tomatoes, zucchini, summer squash, cucumber, and berries. None of the produce samples were reported to be contaminated with Salmonella or *E. coli* O157:H7. *E. coli* contamination was detected in 8% of the samples (n=2,029), with leafy greens, lettuces, and cabbages had significantly higher *E. coli* prevalence than did all the other produce types. Similarly, the initial study found *E. coli* prevalence to be highest in organic lettuce.

While *Cryptosporidium* results from the QMRA suggested that it is a low risk organism, present at levels well below detection, oocysts have been detected on fresh produce in Norway. Robertson and Gjerde (2000a) reported 19 *Cryptosporidium*-positive samples from 475 samples of fresh produce, of which 5 (26%) were in lettuce. The concentrations of *Cryptosporidium* detected were generally low with a mean of 3 oocysts per 100 g produce. In Costa Rica, *Cryptosporidium* was detected on lettuce, parsley, coriander and blackberries, but not on strawberries (Calvo *et al.*, 2004).

Experiments on the retention of *E. coli* O157:H7 on lettuce following spray irrigation resulted in no detections from an initial concentration of 10^2 cfu per mL, but high loads after irrigation with 10^4 cfu per mL (Solomon *et al.*, 2003). The QMRA model predicted, at initial concentrations of 10^2 cfu per mL, *E. coli* O157 loads at harvest of 1.5% above 1 cfu per gram up to a maximum of 11 per gram.

The reporting of higher loads on fresh produce than predicted in the QMRA model may be due to a number of factors. Firstly, the QMRA only addresses contamination from irrigation. Contamination from other sources may contribute to the higher loads detected including direct deposition of faeces, e.g birds, windborne contamination or contamination during or after harvest due from processing water or people. Secondly, the model is limited by the available data, and there are insufficient data in these studies of produce contamination to identify the potential sources.

One survey that reported lower loads on produce was a survey of 3200 of uncooked RTE organic vegetables from UK retail outlets, 70% of which was imported (Sagoo *et al.*, 2001). These samples had been processed for retail and were primarily prepacked (81%). *E. coli* was detected on only 1.5% of samples, with greater than 100 per gram on 0.2% of samples.

5.3 Conclusions

The QMRA developed here provides a tool to quantitatively predict the benefits of various irrigation and crop management activities that can be implemented by growers. The sensitivity assessment of the model identified the harvest interval as the most sensitive parameter, with a strong negative relationship to the pathogen load at harvest, i.e. the greater the interval between the last irrigation with contaminated water and harvest the lower the risk of contamination of the crop at harvest. The results highlighted that despite considerably higher loads of faecal indicators than pathogens in water, the pathogen loads at harvest can be greater than the faecal indicator loads due to the greater inactivation rates of indicators.

The results in terms of irrigation management are summarised in Table 5.15. Concentrations of *E. coli* in source water were defined as low, medium or high risk based on the resulting loads on lettuce at harvest. Norovirus concentrations are not included as there was no correlation for norovirus and *E. coli* in surface waters. The infectious dose considered the serving size and the infective dose reported in Table 5.10. The low, medium and high risk storage intervals were calculated, assuming no recontamination, based on a 7 $\log_{10}$, 3 $\log_{10}$ and ≤ 1 $\log_{10}$ reduction in the concentration in water for each pathogen. Similarly for harvest, the risk categories were based on the $\log_{10}$ reduction in harvest load. These results aim to inform the risk management and risk communication processes undertaken by the FSA.

Despite the robustness of *Cryptosporidium*, the results of the QMRA and from literature indicate that *Cryptosporidium* is generally a low health risk on fresh produce in the UK. The relative risks from *Campylobacter* and norovirus depend on the duration of storage and the harvest interval.

There are a number of limitations to these QMRA model results due to the lack of available data, in particular the lack of data on pathogen concentrations in irrigation water and on storage intervals. Data was available on faecal indicator concentrations, but the sampling locations did not correspond well with the main areas of irrigation. Published European studies were used to extrapolate pathogen concentrations based on faecal indicator concentrations. There was also limited data on the retention of water or pathogens on crops during irrigation. It is recommended that research is undertaken to address these limitations, which would increase the robustness of this model.

Table 5.15 Summary of outcomes from the QMRA model and research for management of irrigation practices (quantitative results based on QMRA for lettuce)

Category	Low Risk	Medium Risk	High Risk
Source water type	Mains water, Groundwater (consolidated aquifer)	Groundwater (fractured or unconsolidated aquifer	Surface water, Sewage
E. coli in source water	10^2 per 100ml	10^4 per 100ml	10^6 per 100ml
Campylobacter	1 per 288 g at harvest	1 per 47 g at harvest	1 per 8 g at harvest
Cryptosporidium	1 per 363 g at harvest	1 per 75 g at harvest	1 per 15 g at harvest
Irrigation method	Sub-irrigation, trickle irrigation minimises the contamination where the edible portion is above ground, and has low internalisation rate	Overhead irrigation with smaller drop size reduces secondary contamination from soil splash	Overhead irrigation with larger droplet size increases risk of soil splashed onto the crop. Internalisation reported to be greater in spray than flood irrigation
Storage type	Reservoirs protected from external influences		Reservoirs open to contamination from run-off and birds
Storage interval (days)	*Time required for 7 log_{10} reduction*	*Time required for 3 log_{10} reduction*	*Time required for ≤ 1 log_{10} reduction*
E. coli	15	7	2
Campylobacter	14	6	2
Norovirus	66	28	9
Cryptosporidium	134	57	19
Harvest interval (days)	*Time required for 7 log_{10} reduction*	*Time required for 3 log_{10} reduction*	*Time required for ≤ 1 log_{10} reduction*
E. coli	6	3	1
Campylobacter	16	7	2
Norovirus	14	6	2
Cryptosporidium	127	54	18
Crop, from QMRA	Broccoli (longer harvest interval), cucumber (lower water retention)		Baby spinach has the highest risk, with other leafy greens (higher water retention, short harvest interval)
Pathogen	*E. coli* O157 due to high inactivation *Cryptosporidium*		Norovirus, Campylobacter

Chapter 6 Conclusions

This study aimed to assess the microbiological risks to public health from the use of irrigation water in UK agriculture and the potential risks to food safety. The scope was limited to direct effects of irrigation, and does not include issues of secondary contamination by splash back of soil, or contamination during harvest and processing. The conclusions are summarised below:

6.1 Risks from consumption of ready-to-eat fresh produce due to poor irrigation water quality

- Between 1992 and 2006, 2274 foodborne general outbreaks of infectious intestinal disease were reported in England and Wales, of which 82 outbreaks (4%) were associated with the consumption of prepared salads (Little and Gillespie, 2008). There are likely to be many more cases than those reported because symptoms are often mild and self limiting. Ready-to-eat (RTE) crops pose a particular concern because they are not cooked before eating. These cases include potential contamination through irrigation water, harvest, processing, and the consumer.

- Key pathogens identified for this report are salmonella, *E. coli* O157:H7, norovirus, rotavirus, *Listeria*, *Campylobacter*, *Clostridium perfringens*, *Cryptosporidium* and *Giardia*. These are commonly found in faecal matter which can contaminate foods through polluted irrigation water which is applied directly to crops for irrigation. They tend to have a low infectious dose and in some cases can cause severe symptoms, including death. Their characteristics determine their fate and transport in the environment.

- The primary factors affecting pathogen fate and transport in irrigation water are: temperature, sunlight, pH, biofilms and microbial predation. On crop surfaces survival of pathogens is influenced by the plant surface, relative humidity, moisture content, temperature, composition of the suspending medium, light exposure and microbial predation. Pathogens generally die-off more rapidly on crops than in soil or water. Viruses are more resistant to environmental stress than bacteria.

- The extent of irrigation in the UK varies significantly from year to year, largely dependent on rainfall, but broad trends indicate that the area of land used for irrigation of vegetables has risen between 1982 and 2005 from 14810 ha to 32202ha. The volume of water applied to vegetables has risen during the same time period. Irrigation is concentrated in the EA's Anglian region of England.

- There are a number of methods of irrigation used in the UK. Overhead irrigation is considered to pose the greatest risk in terms of microbiological contamination to RTE crops due to the direct application to aerial parts of the plants. Trickle irrigation is considered to be low risk while sub-irrigation is considered to pose the lowest risk. Overhead irrigation using booms and rainguns are currently the most common method used in the UK.

- Surface water is the main source of irrigation water in the UK, although groundwater is used in some areas. Surface water in particular is vulnerable to contamination from raw sewage, treated sewage effluent and livestock manures from surface run off.

- There is limited data available on the quality of water used for irrigation, particularly in terms of actual pathogen numbers. The data that was available for the purposes of this report was concentrations of indicator bacteria from sampling programmes established for monitoring surface water resources that are used for drinking water abstraction. This resulted in discrepancies between the areas where surface water quality data was available and the main irrigation areas, for example surface water quality data was not available for the Anglian region. Additionally, there was a discrepancy between the quality of water reported by water companies and that of growers' and this needs to be resolved in order to enable risks to be evaluated.

- It was reported that 42% of irrigators in England have winter storage reservoirs. There is limited data available on the duration of storage. Survival of pathogens in storage reservoirs is a function of the duration of exposure to environmental conditions such as temperature and sunlight. Storage may improve the quality of the water due to pathogen inactivation and predation, but it is also prone to recontamination from wildlife.

- The availability of water for irrigation is expected to decline in the future due to potential restrictions on abstractions and anticipated reduced recharge. This may lead to changes in crops grown in the UK, production areas and irrigation techniques. Emerging and re-emerging pathogens may become issues for the future.

- A quantitative microbial risk assessment model was developed for this report. The model investigated the risks of contamination of six crops from contaminated irrigation water including baby leaf salad, broccoli, cucumber and lettuce. This showed that baby leaf salad were most vulnerable to contamination. Broccoli and cucumber are the least vulnerable.

- The sensitivity assessment for the QMRA model identified that the harvest interval was the most important factor in determining the contamination of the crops at harvest. The harvest interval varies depending on the crop and the weather conditions. The shorter the harvest interval the greater the risk. The other most sensitive parameters in the QMRA model were, in order of sensitivity, the proportion of time that storage reservoir, where present, was used; the inactivation rate on vegetables; the presence (%) of a storage reservoir; and the $\log_{10}$ concentration of the micro-organism in the irrigation water.

- The results of the QMRA for loads of pathogens and indicator organisms on crops were generally lower than reported in literature. This may indicate that irrigation is not the sole source of contamination on the crops in these studies, or may be attributed to the limitations in the available data or the model may require further validation..

- *Cryptosporidium* was not considered a significant risk based on results of the risk assessment and literature available on outbreaks. Risks from other pathogens were dependent on water storage and harvest intervals.

- There is no single national guidance document in the UK for growers. In general growers are reliant on industry-led guidance. At present, the use of water quality testing is limited. Monitoring is typically undertaken once a year, with no guidance on where or when to sample.

- There is no food safety or water legislation in the UK which is directly applicable to irrigation practices. Irrigators are subject to legislation governing the safety of the final product.

6.2 Recommendations

- While no foodborne outbreaks in the UK have been linked to irrigation practices, there are many examples from international literature. Furthermore the limitations of reporting of outbreaks have been discussed in Chapter 2. The international outbreaks, as well as the literature and risk assessment model, highlight that irrigation water quality does have an important role in the microbial contamination of RTE crops at harvest. High risk situations depend on a number of factors which may be identified by risk assessment techniques. Some of these have been identified in this report and guidance should be provided to growers as to best deal with them.

- Although guidance to growers is evident from a number of sources there is no single set of comprehensive good practice guidelines in the UK, and the provision of this

may be useful. There is a need for more detailed and practical guidance, which could include the provision of decision support tools to assist growers in the process of qualitative risk assessment.

- Monitoring and risk assessments of irrigation waters can aid growers in identifying high risk situations. However, monitoring methods are required that provide real-time results, with adequate quality control procedures in place. Advice should be developed to assist growers with sanitary surveys, monitoring and interpretation of results. On large catchments, it may be appropriate for sanitary surveys to be undertaken on a regional scale by the appropriate authority. This may include the use of land-use based methods for predicting water quality which are described in Chapter 4.

- Furthermore, guidance is required on abstraction and monitoring. Sanitary survey combined with water quality monitoring should be used inform growers of the best times to abstract. Monitoring programs should be developed on a catchment basis, and encompass wet and dry flows focusing on periods when irrigation is used.

6.3 Recommendations for further research

- Verification of quantitative risk assessment findings through on-farm sampling programmes of water and produce, and further experimental research on the parameters used in the risk assessment such as water retention on crops, pathogen survival on crops, pathogen attachment to crops, etc. This research could then be used to improve quantitative risk assessments undertaken at government level, and advise growers in their own qualitative risk assessments.

- Modelling of water quality in catchments where surface waters are heavily used for irrigation such as the EA's Anglian region of England. Risk assessment models can provide valuable management information to growers regarding timing/duration/methods of irrigation. Present models should be refined to produce an accessible system for growers to refer to.

- Development of a more detailed risk assessment model to take account of predicted climate change events.

- Review of storage systems and the impact on water quality used for irrigation.

Chapter 7 References

Ackers, M. L., B. E. Mahon, E. Leahy, B. Goode, T. Damrow, P. S. Hayes, W. F. Bibb, D. H. Rice, T. J. Barrett, L. Hutwagner, P. M. Griffin and L. Slutsker (1998). "An outbreak of *Escherichia coli* O157:H7 infections associated with leaf lettuce consumption." J. Infect. Dis. **177**: 1588-1593.

Adak, G. K., S. M. Meakins, H. Yip, B. A. Lopman and S. J. O'Brien (2005). "Disease risks from foods, England and Wales, 1996-2000." Emerg Infect Dis **11**(3): 365-72.

ADAS (2003). "Irrigation Best Practice. Water Management of Soil and Substrate-Grown Crops. A Guide for Top and Soft Fruit Growers." Department for Environment, Food and Rural Affairs, London.

ADAS (2003). "Water Management for Field Vegetable Crops. A Guide for Vegetable Growers." Department for Environment, Food and Rural Affairs. London.

ADAS (2005). "Irrigation Best Practice. Water Management for Potatoes. A Guide for Growers." Department for Environment, Food and Rural Affairs. London.

Advisory Committee on the Microbiological Safety of Food (2004). Advisory Committee on the Microbiological Safety of Food: Second report on Campylobacter. Food Standards Agency. http://www.food.gov.uk/multimedia/pdfs/acmsfcampyloreport.pdf

Alary, M. and D. Nadeau (1990). "An outbreak of *Campylobacter enteritis* associated with a community water supply." Canadian Journal of Public Health **81**(4): 268-271.

Allwood, P. B., Y. S. Malik, C. W. Hedberg and S. M. Goyal (2003). "Survival of F-Specific RNA Coliphage, Feline Calicivirus, and Escherichia coli in Water: a Comparative Study." Applied & Environmental Microbiology **69**(9): 5707-5710.

Anon (1990). "The Food Safety Act." The Stationary Office Limited. London.

Anon (1997). Harmonisation of safety criteria for minimally processed foods. Inventory Report FAIR Concerted Action FAIR CT96-1020.

Anon (1999). "Outbreak of *Escherichia coli* O157:H7 and *Campylobacter* among attendees of the Washington county fair—New York, 1999." Morb. Mortal. Wkly. Rep. **48**: 803-804.

Anon (2003). "Water Act, 2003." http://www.opsi.gov.uk/ACTS/acts2003/20030037.htm.

Anon (2006). "Ongoing multistate outbreak of Escherichia coli serotype O157:H7 infections associated with consumption of fresh spinach--United States, September 2006." MMWR Morb Mortal Wkly Rep **55**(38): 1045-6.

Anon (2007). "Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens."
http://www.unitedfresh.org/assets/files/LLG.GAP.Metrics.2007.04.20.pdf.

Armstrong, G. L., J. Hollingsworth and J. G. Morris, Jr. (1996). "Emerging foodborne pathogens: *Escherichia coli* O157:H7 as a model of entry of a new pathogen into the food supply of the developed world." Epidemiol Rev **18**(1): 29-51.

Arvantidou, M., G. A. Statopoulos and T. C. Constantinidid (1996). "The occurrence of Salmonella, Campylobacter and Yersinia spp. in river and lake waters." Microbiol. Res. **50**: 153-158.

Asano, T., L. Y. C. Leong, M. G. Rigby and R. H. Sakaji (1992). "Evaluation of the California wastewater reclamation criteria using enteric virus monitoring data." Water Science and Technology **26**(7-8): 1513-1524.

Assured Produce (2006). "Generic Crop Protocol Standards 2007."
http://www.assuredproduce.co.uk/resources/000/245/443/APGenericProtocolstandards2007final27_11_06.pdf.

Assured Produce (2006). "Generic Protocol Guidance Notes 2007."
http://www.assuredproduce.co.uk/resources/000/245/444/AP_Generic_Protocol_Guidance_Notes_2007.pdf.

Assured Produce (2007). "Assured Produce Newsletter. Spring 2007."
http://www.assuredproduce.co.uk/resources/000/237/477/ap_news_spring2007.pdf.

Atherholt, T. B., M. W. LeChevallier, W. D. Norton and J. S. Rosen (1998). "Effect of rainfall on *Giardia* and *Cryptosporidium*." Journal of American Water Works Association **90**(9): 66-80.

Attree-Pietri, C. and J. P. Breittmayer (1970). "Etude comparee de germes-test de contamination fecale et de bacteriophages en eau de mer: action du rayonnement solaire." J Fr Hydrol. **10**: 103.

Aureli, P., G. C. Fiorucci, D. Caroli, G. Marchiaro, O. Novara, L. Leone and S. Salmaso (2000). "An outbreak of febrile gastroenteritis associated with corn contaminated by Listeria monocytogenes." N Engl J Med **342**(17): 1236-41.

Bhaduri, S. and Cottrell, B. (2004). "Survival of cold-stressed *Campylobacter jejuni* on ground chicken and chicken skin during frozen storage". Applied and Environmental Microbiology **70**: 7103–7109.

Balbus, J. M. and M. A. Embrey (2002). "Risk factors for waterborne enteric infections." Current Opinion in Gastroenterology **18**(1): 46-50.

Bales, R. C., S. M. Li, K. M. Maguire, M. T. Yahya, C. P. Gerba and R. W. Harvey (1995). "Virus and bacteria transport in a sandy aquifer, Cape Cod, MA." Ground Water **33**(4): 653-661.

Beuchat, L. R. (1999). "Survival of enterohemorrhagic Escherichia coli O157:H7 in bovine feces applied to lettuce and the effectiveness of chlorinated water as a disinfectant." J. Food Prot. **62**: 845–849.

Beuchat, L. R., B. V. Nail, B. B. Adler and M. R. Clavero (1998). "Efficacy of spray application of chlorinated water in killing pathogenic bacteria on raw apples, tomatoes, and lettuce." J Food Prot **61**(10): 1305-11.

Beuchat, L. R. and J. H. Ryu (1997). "Produce handling and processing practices." Emerg Infect Dis **3**(4): 459-65.

Bidwells (undated). Water Framework Directive and Cross Compliance. Efficient use of water in the farming and food industry, East of England Development Agency.

Bitton, G. (1980). Adsorption of viruses to surfaces: technological and ecological implications. Adsorption of microorganisms to surfaces. G. M. Bitton, K. C. Brisbane, John Wiley & Sons.

Blanc, R. and A. Nasser (1996). "Effect of effluent quality and temperature on the persistence of viruses in soil." Water Science and Technology **33**(10-11): 237-242.

Blaser, M. J., F. M. LaForce, N. A. Wilson and W. L. Wang (1980). "Reservoirs for human campylobacteriosis." J Infect Dis **141**(5): 665-9.

Bodley-Tickell, A. T., S. E. Kitchen and A. P. Sturdee (2002). "Occurrence of *Cryptosporidium* in agricultural surface waters during an annual farming cycle in lowland UK." Water Research **36**(7): 1880-1886.

Bradford, S. A. and J. Schijven (2002). "Release of *Cryptosporidium* and *Giardia* from dairy calf manure:impact of solution salinity." Environment Science and Technology **36**(18): 3916-3923.

Brookes, J. D., J. Antenucci, M. Hipsey, M. D. Burch, N. J. Ashbolt and C. M. Ferguson (2004). "Fate and transport of pathogens in lakes and reservoirs." Environment International **30**.

Buchanan, R. L., S. G. Edelson, R. L. Miller and G. M. Sapers (1999). "Contamination of intact apples after immersion in an aqueous environment containing *Escherichia coli* O157:H7." J. Food Prot. **62**(444-445).

Buswell, C. M., Y. M. Herlihy, L. M. Lawrence, J. T. M. McGuiggan, P. D. Marsh, C. W. Keevil and S. A. Leach (1998). "Extended survival and persistence of *Campylobacter* spp. in water and aquatic biofilms and their detection by immunofluorescent-antibody and -rRNA staining." Applied and Environmental Microbiology **64**(2): 733-741.

Butaye, P., G. B. Michael, S. Schwarz, T. J. Barrett, A. Brisabois and D. G. White (2006). "The clonal spread of multidrug-resistant non-typhi Salmonella serotypes." Microbes and Infection **8**(7): 1891-1897.

California Department of Food and Agriculture (2007). "Scott Horsfall named CEO of California Leafy Greens Marketing Agreement." http://www.cdfa.ca.gov/pressreleases/PressRelease.asp?PRnum=07-045.

Callaway, T. R., T. S. Edrington, A. D. Brabban, J. E. Keen, R. C. Anderson, M. L. Rossman, M. J. Engler, K. J. Genovese, B. L. Gwartney, J. O. Reagan, T. L. Poole, R. B. Harvey, E. M. Kutter and D. J. Nisbet (2006). "Fecal prevalence of Escherichia coli O157, Salmonella, Listeria, and Bacteriophage Infecting E. coli O157:H7 in feedlot cattle in the Southern Plains region of the United States." Foodborne Pathog Dis **3**(3): 234-44.

Calvo, M., M. Carazo, M. L. Arias, C. Chaves, R. Monge and M. Chinchilla (2004). "[Prevalence of Cyclospora sp., Cryptosporidium sp, microsporidia and fecal coliform determination in fresh fruit and vegetables consumed in Costa Rica]." Arch Latinoam Nutr **54**(4): 428-32.

Campden and Chorleywood Food Research Association (2000). "HACCP in agriculture and horticulture (second edition)." http://www.campden.co.uk/publ/pubfiles/g10_2ed.htm.

Casemore, D. P. (1998). "*Cryptosporidium* and the safety of our water supplies." Communicable Disease & Public Health **1**(4): 218-219.

CEC (1976). "Council Directive of 8 December 1975 concerning the Quality of Bathing Water (76/160/EEC)." Official Journal of the European Communities **L 31, 5.2.1976**.

CEC (1979). "Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds." Official Journal of the European Communities **L 103, 25/04/1979**: 0001-0018.

CEC (1991). "Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC)." Official

Journal of the European Communities **http://ec.europa.eu/environment/water/water-nitrates/directiv.html**.

CEC (1991). "Directive concerning urban waste water treatment, 91/271/ EEC." Official Journal of the European Communities.

CEC (1992). "Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora." Official Journal of the European Communities **L 206, 22/07/1992**: 0007-0050.

CEC (1998). "COUNCIL DIRECTIVE 98/83/EC of 3 November 1998 on the quality of water intended for human consumption." Official Journal of the European Communities **L330/32**.

CEC (2000). "Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy." Official Journal of the European Communities **http://eur-lex.europa.eu/LexUriServ/site/en/oj/2000/l_327/l_32720001222en00010072.pdf**.

CEC (2002). "Regulation (EC) No 178/2002 of the European parliament and of the council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety authority and laying down procedures in matters of food safety." Official Journal of the European Communities. **http://eur-lex.europa.eu/pri/en/oj/dat/2002/l_031/l_03120020201en00010024.pdf**.

CEC (2004). "REGULATION (EC) No 852/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004 on the hygiene of foodstuffs." Official Journal of the European Union, **L139 of 30 April 2004.**

CEC (2006). "DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy." Official Journal of the European Communities **http://eur-lex.europa.eu/LexUriServ/site/en/oj/2000/l_327/l_32720001222en00010072.pdf**.

CFSAN (1998). "Guide to Minimise Microbial Food Safety Hazards for fresh Fruit and Vegetables." http://www.foodsafety.gov/%7Edms/prodguid.html.

CFSAN (2001). Analysis and Evaluation of Preventive Control Measures for the Control and Reduction/Elimination of Microbial Hazards on Fresh and Fresh-CVut Produce. http://www.cfsan.fda.gov/~comm/ift3-toc.html

Chalmers, R. M., H. Aird and F. J. Bolton (2000). "Waterborne *Escherichia coli* O157." Journal of Applied Microbiology **88**(Suppl S): 124S-132S.

Chalmers, R. M., K. Elwin, W. J. Reilly, H. Irvine, A. L. Thomas and P. R. Hunter (2002). "*Cryptosporidium* in farmed animals: the detection of a novel isolate in sheep." International Journal for Parasitology **32**(1): 21-26.

Chan, M. C., J. J. Sung, R. K. Lam, P. K. Chan, N. L. Lee, R. W. Lai and W. K. Leung (2006). "Fecal viral load and norovirus-associated gastroenteritis." Emerg Infect Dis **12**(8): 1278-80.

Chilled Food Association (2002). "Microbiological Guidance for Produce Suppliers to Chilled Food Manufacturers. Kettering." 43pp.

Chilled Food Association (2005). Water Quality Management Guidance. 2nd edition. Kettering, Chilled Food Association: 32 pp. www.chilledfood.org

Collins, R. and K. Rutherford (2004). "Modelling bacterial water quality in streams draining pastoral land." Water Res **38**(3): 700-12.

Considine, R. F. (2000). Force of interaction between *Cryptosporidium parvum* and silica: Complexity of surface deformation, roughness and brushlike behaviour. Melbourne, CSIRO Molecular Science.

Considine, R. F., C. J. Drummond and D. R. Dixon (2001). "Force of interaction between a biocolloid and an inorganic oxide: complexity of surface deformation, roughness and brushlike behaviour." Langmuir **17**: 6325-6335.

Cooley, M. B., D. Chao and R. E. Mandrell (2006). "Escherichia coli O157:H7 survival and growth on lettuce is altered by the presence of epiphytic bacteria." J Food Prot **69**(10): 2329-35.

Craik, S. A., D. Weldon, G. R. Finch, J. R. Bolton and M. Belosevic (2001). "Inactivation of *Cryptosporidium parvum* oocysts using medium- and low-pressure ultraviolet radiation." Water Research **35**(6): 1387-1398.

Crowther, J., D. Kay and M. D. Wyer (2001). "Relationships between microbial water quality and environmental conditions in coastal recreational waters: the Fylde coast, UK." Water Res **35**(17): 4029-38.

Crowther, J., D. Kay and M. D. Wyer (2002). "Faecal-indicator concentrations in waters draining lowland pastoral catchments in the UK: relationships with land use and farming practices." Water Res **36**(7): 1725-34.

Crowther, J., M. D. Wyer, M. Bradford, D. Kay and C. A. Francis (2003). "Modelling faecal indicator concentrations in large rural catchments using land use and topographic data." J Appl Microbiol **94**(6): 962-73.

Dai, X. and J. Boll (2003). "Evaluation of attachment of *Cryptosporidium parvum* and *Giardia lamblia* to soil particles." Journal of Environmental Quality **32**: 296-304.

Dallaire, R., D. I. LeBlanc, C. C. Tranchant, L. Vasseur, P. Delaquis and C. Beaulieu (2006). "Monitoring the microbial populations and temperatures of fresh broccoli from harvest to retail display." J Food Prot **69**(5): 1118-25.

Davies-Colley, R. J., A. M. Donnison and D. J. Speed (1997). "Sunlight wavelengths inactivating faecal indicator microorganisms in waste stabilisation ponds." Water Science and Technology **35**(11-12): 219-225.

Davies, C. M., J. A. H. Long, M. Donald and N. J. Ashbolt (1995). "Survival of fecal microorganisms in marine and freshwater sediments." Applied and Environmental Microbiology **61**(5): 1888-1896.

Dawson, D. J. (2003). The survival and decontamination of viruses on fresh produce. FSA Project B02014. Campden and Chorleywood Food Research Association. London, UK, Food Standards Agency.

Defra (2002). Directing the Flow. London, Defra.
http://www.defra.gov.uk/environment/water/strategy/directflow.htm

Defra (2002). Sewage Treatment in the UK: Implementation of the EC Urban Waste Water Treatment Directive.
http://www.defra.gov.uk/environment/water/quality/uwwtd/report02/default.htm, accessed 24 April 2007.

Defra (2005). "Single Payment Scheme. Cross Compliance Handbook for England. 2006 edition." Ref. PB 11305. London.

Defra (2006). "Single Payment Scheme. Cross Compliance Handbook for England. 2006 edition supplement." Ref. PB 11917. London.

Defra (2007). Water resources and abstraction. Restoring Sustainable Abstraction Programme. London, Defra.
http://www.defra.gov.uk/environment/water/resources/abstraction/index.htm

Deng, M. Q. and D. O. Cliver (1999). "*Cryptosporidium parvum* studies with dairy products." International Journal of Food Microbiology **46**(2): 113-121.

Department for Agriculture Fisheries and Forestry (2004). "Guidelines for On-Farm Food Safety for Fresh Produce."
http://www.horticulture.com.au/docs/publications/Guidelines_for_On_Farm_Food_Safety_for_Fresh_Produce_Second_Edition.pdf.

Department for Environment Food and Rural Affairs and Environment Agency (2006). Development and Testing of a Predictive Model to allow Sample Discounting. Final Report. ICREW (Improving Coastal and Recreational Waters).
http://www.icrew.info/public/psearch.php?type=documents&panel=document&document_id=459

Deschesne, M., E. Soyeux, J. F. Loret, T. Westrell, T. A. Stenstrom, V. Gornik, C. Koch, M. Exner, M. Stanger, P. Agutter, R. Lake, D. Roser, N. J. ashbolt, Y. Dullemont, W. Hijnen and G. J. Medema (2006). Pathogens in Source Water. Microrisk. Microbiological risk assessment: a scientific basis for managing drinking water safety from source to tap. European Commission.

DETR (1999). Taking water responsibly. London, Department of the Environment, Transport and the Regions.
http://www.defra.gov.uk/environment/water/resources/abstreview/index.htm

Dickie, N., J. Speirs, M. Akhtar, W. Johnson and R. Szabo (1989). "Purification of an *Escherichia coli* serogroup O157:H7 verotoxin and its detection in North American hemorrhagic colitis isolates." J Clin Microbiol. **27**(9): 1973-8.

Dolejs, P., O. Ditrich, T. Machula, N. Kalouskova and G. Puzova (2000). "Occurrence and separation of *Cryptosporidium* oocsts in drinking water treatment." Water Science and Technology **41**(7): 159-163.

Dorner, S. M., W. B. Anderson, R. M. Slawson, N. Kouwen and P. M. Huck (2006). "Hydrologic modeling of pathogen fate and transport." Environ Sci Technol **40**(15): 4746-53.

Dorner, S. M., P. M. Huck and R. M. Slawson (2004). "Estimating potential environmental loadings of Cryptosporidium spp. and Campylobacter spp. from livestock in the Grand River Watershed, Ontario, Canada." Environ Sci Technol **38**(12): 3370-80.

Drozd, C. and J. Schwartzbrod (1996). "Hydrophobic and electrostatic cell surface properties of *Cryptosporidium parvum*." Applied and Environmental Microbiology **62**(4): 1227-1232.

DuPont, H. L., C. L. Chappell, C. R. Sterling, P. C. Okhuysen, J. B. Rose and W. Jakubowski (1995). "The infectivity of *Cryptosporidium parvum* in healthy volunteers." <u>New England Journal of Medicine</u> **332**(13): 855-859.

Eberhart-Phillips, J., Walker, N., Garrett, N., Bell, D., Sinclair, D., Rainger, W. et al., (1997). "Campylobacteriosis in New Zealand: results of a case-control study." <u>J. Epidemiolo. Community Health</u> **51**(6): 686-691.

Ellis, JB (2004). "Bacterial Sources, Pathways and Management Strategies for Urban Run-off." Journal of Environmental Planning and Management. Vol. 47, no. 6, pp. 943-958.

Emerick, R. W., F. J. Loge, T. Ginn and J. L. Darby (2000). "Modeling the inactivation of particle-associated coliform bacteria." <u>Water Environ Res</u> **72**: 432-438.

Engineering Science (1987). <u>Monterey Wastewater Reclamation Study for Agriculture</u>. Berkeley,CA, Engineering Science.

Environment Agency (2001). <u>Managing Water Abstraction</u>. Environment Agency. http://www.environmentagency.net/commondata/acrobat/mwa_english.pdf

Environment Agency (2001). "Running water, whatever the weather." <u>Environment Action</u> **June 2001**.

Environment Agency (2007). <u>Identifying areas of water stress</u>. Bristol, Environment Agency.

Environment Agency (2007). "Waterwise on the Farm." http://www.environment-agency.gov.uk/commondata/acrobat/geho0307blvhepweb_432285.pdf.

Estes, M. K., J. M. Ball, R. A. Guerrero, A. R. Opekun, M. A. Gilger, S. S. Pacheco and D. Y. Graham (2000). "Norwalk virus vaccines: challenges and progress." <u>J Infect Dis</u> **181 Suppl 2**: S367-73.

EurepGAP. (2007). "IFA - Fruit and Vegetables Modules." http://www.eurepgap.org/fruit/Languages/English/documents.html.

EurepGAP. (2007). "IFA –All Farm Module (Crops) (FV)." http://www.eurepgap.org/fruit/Languages/English/documents.html.

EurepGAP. (2007). "IFA –Crops Base Module (FV)." http://www.eurepgap.org/fruit/Languages/English/documents.html.

Farber, J. M., S. L. Wang, Y. Cai and S. Zhang (1998). "Changes in populations of Listeria monocytogenes inoculated on packaged fresh-cut vegetables." <u>J Food Prot</u> **61**(2): 192-5.

Fayer, R., U. Morgan and S. J. Upton (2000). "Epidemiology of *Cryptosporidium*: transmission, detection and identification." International Journal for Parasitology **30**(12-13): 1305-1322.

Fayer, R. and T. Nerad (1996). "Effects of low temperatures on viability of *Cryptosporidium parvum* oocysts." Applied and Environmental Microbiology **62**(4): 1431-1433.

Fayer, R., J. M. Trout, T. K. Graczyk and E. J. Lewis (2000). "Prevalence of *Cryptosporidium, Giardia* and *Eimeria* infections in post-weaned and adult cattle on three Maryland farms." Veterinary Parasitology **93**(2): 103-112.

Fayer, R. and B. L. P. Ungar (1986). "*Cryptosporidium* spp. and cryptosporidiosis." Microbiological Reviews **50**(4): 458-483.

Feachem, R. G., D. J. Bradley, H. Garelick and D. D. Mara (1983). Sanitation and Disease: Health Aspects of Excreta and Wastewater Management. World Bank Studies in Water Supply and Sanitation 3. Chichester, England, John Wiley & Sons (for The World Bank).

Feng, Y. Y., S. L. Ong, J. Y. Hu, L. F. Song, X. L. Tan and N. W. Jern (2003). "Effect of particles on the recovery of *Cryptosporidium* oocysts from source water samples of various turbidities." Applied & Environmental Microbiology **69**(4): 1898-1903.

Fenlon, D. R., I. D. Ogden, A. Vinten and I. Svoboda (2000). "The fate of *Escherichia coli* and *E. coli* O157 in cattle slurry after application to land." Journal of Applied Microbiology **88**(Suppl S): 149S-156S.

Ferguson, C. (2005). Deterministic model of microbial sources, fate and transport: a quantitative tool for pathogen catchment budgeting. Sydney, Australia, University of New South Wales - Centre for Water and Waste Technology.

Ferguson, C. M. (1994). Faecal indicators and pathogens in water and sediment of the Georges River, Sydney. Sydney, University of Technology**:** 166.

Ferguson, C. M., N. Altavilla, N. J. Ashbolt and D. A. Deere (2003). "Prioritizing Watershed Pathogen Research." Journal of American Water Works Association **95**(2): 92-102.

Ferguson, C. M., N. J. Ashbolt and D. A. Deere (2004). "Prioritisation of catchment management in the Sydney catchment - construction of a pathogen budget." Water Science & Technology **4**(2): 35-38.

Ferguson, C. M., A. M. de Roda Husman, N. Altavilla, D. Deere and N. J. Ashbolt (2003). "Fate and transport of surface water pathogens in watersheds." Critical Reviews in Environmental Science and Technology **33**(3): 299-361.

Fett, W. F. (2000). "Naturally occurring biofilms on alfalfa and other types of sprouts." J Food Prot **63**(5): 625-32.

Fewtrell, L., D. Kay, M. D. Wyer, J. Crowther, P. Carbo and G. Mitchell (1998). Faecal indicator budgets discharging to the Ribble estuary. A report to Environment Agency (N. W. Region). Aberystwyth, CREH, University of Wales: 32pp (plus Figures and Tables).

Flint, K. P. (1987). "The long-term survival of *Escherichia coli* in river water." Journal of Applied Bacteriology **63**: 261-270.

Food Safety Authority of Ireland (2001). "Code of Practice For Food Safety in the Fresh Produce Supply Chain in Ireland." http://www.fsai.ie/publications/codes/cop4.pdf.

Food Standards Agency (2005). "Food and feed hygiene for farmers and growers." Food Standards Agency, London.

Food Standards Agency (2000). A report of the study of infectious intestinal disease in England. London, The Stationery Office.

Food Standards Agency (undated). "FSA Guidance on the Requirements of Food Hygiene Legislation." http://www.food.gov.uk/multimedia/pdfs/fsaguidefoodhygleg.pdf.

Foster, J. W. and H. K. Hall (1990). "Adaptive acidification tolerance response of Salmonella typhimurium." J. Bacteriol. **172**: 771-778.

Franz, E., A. D. van Diepeningen, O. J. de Vos and A. H. van Bruggen (2005). "Effects of cattle feeding regimen and soil management type on the fate of Escherichia coli O157:H7 and salmonella enterica serovar typhimurium in manure, manure-amended soil, and lettuce." Appl Environ Microbiol **71**(10): 6165-74.

Franz, E., A. A. Visser, A. D. Van Diepeningen, M. M. Klerks, A. J. Termorshuizen and A. H. van Bruggen (2007). "Quantification of contamination of lettuce by GFP-expressing *Escherichia coli* O157:H7 and *Salmonella enterica* serovar Typhimurium." Food Microbiol **24**(1): 106-12.

Fresh Produce Consortium (1998). "The Control of Microbial Hazards. A Produce Industry Guide." 38pp. London.

Froder, H., C. G. Martins, K. L. De Souza, M. Landgraf, B. D. Franco and M. T. Destro (2007). "Minimally processed vegetable salads: microbial quality evaluation." J Food Prot **70**(5): 1277-80.

Fujioka, R. S. and W. W. Ackermann (1975). "The inhibitory effects of MgCl2 on the inactivation kinetics of poliovirus by urea." Proc Soc Exp Biol Med. **148**: 1063.

Furtado, C., G. K. Adak, J. M. Stuart, P. G. Wall, H. S. Evans and D. P. Casemore (1998). "Outbreaks of waterborne infectious intestinal disease in England and Wales, 1992-5." Epidemiology and Infection **121**(1): 109-119.

Gandhi, M. a. C., M. L (2007). "Listeria: A foodborne pathogen that knows how to survive." International Journal of Food Microbiology **113**: 1-15.

Gantzer, C., L. Gillerman, M. Kuzetsov and G. Oron (2001). "Adsorption and survival of faecal coliforms, somatic coliphages and F-specific RNA phages in soil irrigated with wastewater." Water Science and Technology **43**: 117-124.

Geldreich, E. E. (1996). "Pathogenic agents in freshwater resources." Hydrological Processes **10**: 315-333.

Gerba, C. P. (1984). "Applied and theoretical aspects of virus adsorption to surfaces." Advances in Applied Microbiology **30**: 133-168.

Gerba, C. P. and G. E. Schaiberger (1975). "Effect of particulates on virus survival in seawater." Journal of the Water Pollution Control Federation **47**(1): 93-103.

Goodridge, L., C. Goodridge, J. Wu, M. Griffiths and J. Pawliszyn (2004). "Isoelectric point determination of norovirus virus-like particles by capillary isoelectric focusing with whole column imaging detection." Anal Chem **76**(1): 48-52.

Gordon, C. and S. Toze (2003). "Influence of groundwater characteristics on the survival of enteric viruses." J Appl Microbiol **95**(3): 536-44.

Gorski, L., J. D. Palumbo and R. E. Mandrell (2003). "Attachment of Listeria monocytogenes to radish tissue is dependent on temperature and flagellar motility." Applied and Environmental Microbiology **69**: 258-266.

Groves, S., N. Davies and M. Aitken (2002). A review of the use of water in UK agriculture and the potential risks to food safety. A report to the Food Standards Agency.: 133pp.

Guan, T. Y. and A. Holley (2003). "Pathogen survival in swine manure environments and transmission of human enteric illness - a review." Journal of Environmental Quality **32**: 383-392.

Guo, X., M. W. van Iersel, J. Chen, R. E. Brackett and L. R. Beuchat (2002). "Evidence of association of salmonellae with tomato plants grown hydroponically in inoculated nutrient solution." Applied and Environmental Microbiology **68**(7): 3639-3643.

Haas, C. N., J. B. Rose and C. P. Gerba (1999). Quantitative Microbial Risk Assessment. New York, John Wiley & Sons, Inc.

Haas, C. N., A. Thayyar-Madabusi, J. B. Rose and C. P. Gerba (2000). "Development of a dose-response relationship for *Escherichia coli* O157: H7." International Journal of Food Microbiology **56**(2-3): 153-159.

Hamilton, A. J., F. Stagnitti, R. Premier, A. M. Boland and G. Hale (2006). "Quantitative microbial risk assessment models for consumption of raw vegetables irrigated with reclaimed water." Appl Environ Microbiol **72**(5): 3284-90.

Hampton, P. (2005). Reducing administrative burdens: effective inspection and enforcement. London, HM Treasury.

Havelaar, A. H., M. van Olphen and J. F. Schijven (1985). "Removal and inactivation of viruses by drinking water treatment processes under full scale conditions." Water Science and Technology **31**(5/6): 55-62.

Hawkins, P. R., P. Swanson, M. Warnecke, S. R. Shanker and C. Nicholson (2000). "Understanding the fate of *Cryptosporidium* and *Giardia* in storage reservoirs: a legacy of Sydney's water contamination incident." Journal of Water Supply, Research and Technology AQUA **496**: 289-306.

Haydon, S. (2005). Trial of a couopled pathogen-stormflow model. 29th Hydrology and Water Resources Symposium, Canberra, Australia, Engineers Australia.

Hein, J., M. v. Lieverloo, E. J. M. Blokker, G. J. Medema, B. Hambsch, R. Pitchers, G. Stanfield, M. Stanger, P. Agutter, R. Lake, J. F. Loret and E. Soyeux (2006). Contamination during distribution. Microrisk. Microbiological risk assessment: a scientific basis for managing drinking water safety from source to tap. European Commission. http://217.77.141.80/clueadeau/microrisk/publish/cat_index_11.shtml

Hijnen, W. A. M., E. F. Beerendonk and G. J. Medema (2006). "Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: A review." Water Research **40**(1): 3.

Hillborn, E. D., J. H. Mermin, P. A. Mshar, J. L. Hadler, A. Voetsch, C. Wojtkunski, M. Swartz, R. Mshar, M. A. Lambert-Fair, J. A. Farrar, M. K. Glynn and L. Slutsker (1999). "A

multistate outbreak of *Escherichia coli* O157:H7 infections associated with consumption of mesclun lettuce." <u>Arch. Intern. Med. </u>**159**: 1758-1764.

Hilton, J. (2002). "Reducing foodborne dieases: meeting the Food Standards Agency's targets." <u>Nutrition and Science</u> **32**(2): 46-50.

Höller, C. (1988). "Long-term study of occurrence, distribution and reduction of *Campylobacter* sp. in the sewage system and wastewater treatment plant of a big town." <u>Water Science and Technology</u> **20**(11-12): 529-531.

Hoogenboezem, W., H. A. M. Ketelaars, G. J. Medema, G. B. J. Rijs and J. F. Schijven (2001). <u>*Cryptosporidium* and *Giardia*; occurrence in sewage, manure and surface water.</u> The Netherlands, Association of River Waterworks - RIWA.

Horman, A., R. Rimhanen-Finne, L. Maunula, C. H. von Bonsdorff, N. Torvela, A. Heikinheimo and M. L. Hanninen (2004). "Campylobacter spp., Giardia spp., Cryptosporidium spp., noroviruses, and indicator organisms in surface water in southwestern Finland, 2000-2001." <u>Appl Environ Microbiol</u> **70**(1): 87-95.

Horticultural Development Council (2005). "Keeping It Clean." <u>http://www.hdc.org.uk</u>.

House of Commons (2006). <u>Select Committee on Science and Technology. Eighth Report</u>. London, House of Commons.

Hunter, P. R. (1997). "Waterborne Disease Epidemiology and Ecology." <u>Wiley & Sons, Chichester.</u>

Hunter, P. R. (1998). <u>Waterborne diseases, epidemiology and ecology</u>. Chichester, UK., Wiley & Sons Ltd.

Hunter, P. R. and C. Quigley (1998). "Investigation of an outbreak of cryptosporidiosis associated with treated surface water finds limits to the value of case control studies." <u>Communicable Disease & Public Health</u> **1**(4): 234-238.

Hurst, C. J., W. H. Benton and K. A. McClellan (1989). "Thermal and water source effects upon the stability of enteroviruses in surface freshwaters." <u>Canadian Journal of Microbiology</u> **35**: 474-480.

Hurst, C. J. and C. P. Gerba (1980). "Stability of simian rotavirus in fresh and estuarine waters." <u>Applied and Environmental Microbiology</u> **39**: 1-5.

Hurst, C. J., C. P. Gerba and I. Cech (1980). "Effects of environmental variables and soil characteristics on virus survival in soil." <u>Applied and Environmental Microbiology</u> **40**(6): 1067-1079.

Hutchison, M. L., L. D. Walters, S. M. Avery, F. Munro and A. Moore (2005). "Analyses of livestock production, waste storage, and pathogen levels and prevalences in farm manures." Appl Environ Microbiol **71**(3): 1231-6.

Hutchison, M. L., L. D. Walters, S. M. Avery, B. A. Synge and A. Moore (2004). "Levels of zoonotic agents in British livestock manures." Lett Appl Microbiol **39**(2): 207-14.

Hutchison, M. L., L. D. Walters, T. Moore, D. J. Thomas and S. M. Avery (2005). "Fate of pathogens present in livestock wastes spread onto fescue plots." Appl Environ Microbiol **71**(2): 691-6.

Ibarra-Sanchez, L. S., S. Alvarado-Casillas, M. O. Rodriguez-Garcia, N. E. Martinez-Gonzales and A. Castillo (2004). "Internalization of bacterial pathogens in tomatoes and their control by selected chemicals." J Food Prot **67**(7): 1353-8.

Islam, M., J. Morgan, M. P. Doyle, S. C. Phatak, P. Millner and X. Jiang (2004). "Persistence of Salmonella enterica serovar typhimurium on lettuce and parsley and in soils on which they were grown in fields treated with contaminated manure composts or irrigation water." Foodborne Pathog Dis **1**(1): 27-35.

Itoh, Y., Y. Sugita-Konishi, F. Kasuga, M. Iwaki, Y. Hara-Kudo, N. Saito, Y. Noguchi, H. Konuma and S. Jumagai (1998). "Enterohemorrhagic *Escherichia coli* O157:H7 present in radish sprouts." Applied and Environmental Microbiology **64**(4): 1532-1535.

Iturriaga, M. H., E. F. Escartin, L. R. Beuchat and R. Martinez-Peniche (2003). "Effect of inoculum size, relative humidity, storage temperature, and ripening stage on the attachment of Salmonella Montevideo to tomatoes and tomatillos." J Food Prot **66**(10): 1756-61.

Iowa State University (2004). On-farm Food Safety:Guide to good Agricultural Practices (GAPs). http://www.extension.iastate.edu/store/ItemDetail.aspx?ProductID=6539.

Jablasone, J., K. Warriner and M. Griffiths (2005). "Interactions of Escherichia coli O157:H7, Salmonella Typhimurium and Listeria monocytogenes in plants cultivated in a gnotobiotic system." Int. J. Food Microbiol. **99**: 7-18.

Jacangelo, J. G., S. S. Adham and J.-M. Laine (1995). "Mechanism of *Cryptosporidium, Giaridia* and MS2 virus removal by MF and UF." Journal of American Water Works Association **87**(9): 107-212.

Jenkins, M. B., L. J. Anguish, D. D. Bowman, M. J. Walker and W. C. Ghiorse (1997). "Assessment of a dye permeability assay for determination of inactivation rates of

Cryptosporidium parvum oocysts." Applied and Environmental Microbiology **63**(10): 3844-3850.

Jenkins, M. B., D. D. Bowman and W. C. Chiorse (1998). "Inactivation of *Cryptosporidium parvum* oocsts by ammonia." Applied and Environmental Microbiology **64**(2): 784-788.

Jenkins, M. B., D. D. Bowman, E. A. Fogarty and W. C. Ghiorse (2002). "*Cryptosporidium parvum* oocyst inactivation in three soil types at various temperatures and water potentials." Soil Biology and Biochemistry **34**(8): 1101-1109.

Jin, Y. and M. Flury (2002). "Fate and transport of viruses in porous media." Advances in Agronomy **77**: 39-102.

Jin, Y., E. Pratt and M. V. Yates (2000). "Effect of mineral colloids on virus transport through saturated sand columns." Journal of Environmental Quality **29**(2): 532-539.

John, D. E. and J. B. Rose (2005). "Review of factors affecting microbial survival in groundwater." Environ Sci Technol **39**(19): 7345-56.

Johnson, G. (2006). "What's the forecast?" Farmers Weekly **1 December 2006**: 35.

Jolly, T. (2007). "Effects of restrictions." Farmers Guardian. **2 February 2007**.

Jones, D. L. (1999). "Potential health risks associated with the persistence of *Escherichia coli* O157 in agricultural environments." Soil Use & Management **15**(2): 76-83.

Jones, K. (2001). "Campylobacters in water, sewage and the environment." Symp Ser Soc Appl Microbiol(30): 68S-79S.

Jones, S., and Shortt, R. (2005). "Improving On-Farm Food Safety Through Good Irrigation Practices." http://www.omafra.gov.on.ca/english/crops/facts/05-059.htm.

Kabir, S. (1977). "Investigations on the outer membrane proteins of *Salmonella typhimurium*." Microbios. **20**(79): 47-62.

Karenlampi, R. and M. L. Hanninen (2004). "Survival of Campylobacter jejuni on various fresh produce." Int J Food Microbiol **97**(2): 187-95.

Kay, D., M. Wyer, J. Crowther, C. Stapleton, M. Bradford, A. McDonald, J. Greaves, C. Francis and J. Watkins (2005). "Predicting faecal indicator fluxes using digital land use data in the UK's sentinel Water Framework Directive catchment: the Ribble study." Water Res **39**(16): 3967-81.

Kay, D; Wyer, MD; Crowther, J; Wilkinson, J; Stapleton, C; Glass, P. (2005). "Sustainable reduction in the flux of microbial compliance parameters from urban and arable land use to

coastal bathing waters by a wetland ecosystem produced by a marine flood defence structure." Water Research. Vol. 39, no. 14, pp. 3320-3332

Kearney, T., M. Larkin and P. Levett (1993). "The effect of slurry storage and anaerobic digestion on survival of pathogenic bacteria." Journal of Applied Bacteriology **74**: 305-306.

Kinoshita, T., R. C. Bales, K. M. Maguire and C. P. Gerba (1993). "Effect of pH on bacteriophage transport through sandy soils." Journal of Contaminant Hydrology **14**(1): 55-70.

Knox, J. W. (2005). "Onus on water users to improve their efficiency." Farmers Weekly **May 6-12, 2005**: 50-51.

Knox, J. W., J. A. Rodriguez-Diaz, E. K. Weatherhead and K. Khan (2006). Climate change impacts on water for irrigated horticulture in the Vale of Evesham. Environment Agency.

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

Koivunen, J., A. Siitonen and H. Heinonen-Tanski (2003). "Elimination of enteric bacteria in biological-chemical wastewater treatment and tertiary filtration units." Water Res **37**(3): 690-8.

Koopmans, M. and E. Duizer (2004). "Foodborne viruses: an emerging problem." International Journal of Food Microbiology **90**(1): 23-41.

Koopmans, M., J. Vinje, M. de Wit, I. Leenen, W. van der Poel and Y. van Duynhoven (2000). "Molecular epidemiology of human enteric caliciviruses in The Netherlands." Journal of Infectious Diseases **181**(Suppl 2): S262-S269.

Kutz, S. M. and C. P. Gerba (1988). "Comparison of virus survival in freshwater sources." Water Science and Technology **20**: 467-471.

Li, Y., R. E. Brackett, J. Chen and L. R. Beuchat (2002). "Mild heat treatment of lettuce enhances growth of Listeria monocytogenes during subsequent storage at 5 degrees C or 15 degrees C." J Appl Microbiol **92**(2): 269-75.

Linden, K. G., G. Shin and M. D. Sobsey (2001). "Comparative effectiveness of UV wavelengths for the inactivation of *Cryptosporidium parvum* oocysts in water." Water, Science and Technology **43**(12): 171-174.

Little, C.L. and Gillespie, I.A. (2008). Prepared salads and public health. Journal of Applied Microbiology, **105** (6): 1729-1743.

Lodder, W. J. and A. M. de Roda Husman (2005). "Presence of noroviruses and other enteric viruses in sewage and surface waters in The Netherlands." Appl Environ Microbiol **71**(3): 1453-61.

Long, S. M., G. K. Adak, S. J. O'Brien and I. A. Gillespie (2002). "General outbreaks of infectious intestinal disease linked with salad vegetables and fruit, England and Wales, 1992-2000." Commun Dis Public Health **5**(2): 101-5.

Lopman, B. A., D. W. G. Brown and M. Koopmans (2002). "Human caliciviruses in Europe [Review]." Journal of Clinical Virology **24**(3): 137-160.

Lund, V. (1996). "Evaluation of *E. coli* as an indicator for the presence of *Campylobacter jejuni* and *Yersinia enterocolitica* in chlorinated and untreated oligotrophic lake water." Water Research **30**(6): 1528-1534.

MAFF (1996). Winter Storage Reservoirs. Ref PB 2512. London.

MAFF (1998). Air Code. Ref. PB 0618. London: 80.

MAFF (1998). Soil Code. Ref PB 0617. London: 66.

MAFF (1998). Water Code. Ref PB 0616. London.

MAFF (2000). A Study on Farm Manure Applications to Agricultural Land and an Assessment of the Risks of Pathogen Transfer Into the Food Chain. London, Ministry of Agriculture, Fisheries and Food.

Mbithi, J. N., V. S. Springthorpe and S. A. Sattar (1991). "Effect of relative humidity and air temperature on survival of hepatitis A virus on environmental surfaces." Appl Environ Microbiol **57**(5): 1394-9.

McMahon, M. A. and I. G. Wilson (2001). "The occurrence of enteric pathogens and Aeromonas species in organic vegetables." International Journal Of Food Microbiology **70**(1-2): 155-162.

Medema, G. J., M. Bahar and F. M. Schets (1997). "Survival of *Cryptosporidium parvum*, *Escherichia coli*, faecal enterococci and *Clostridium perfringens* in river water - influence of temperature and autochthonous microorganisms." Water Science and Technology **35**(11-12): 249-252.

Medema, G. J. and J. F. Schijven (2001). "Modelling the sewage discharge and dispersion of *Cryptosporidium* and *Giardia* in surface water." Water Research **35**(18): 4307-4316.

Metcalf, T. G., J. L. Melnick and M. K. Estes (1995). "Environmental virology: from detection of virus in sewage and water by isolation to identification by molecular biology--a trip of over 50 years." Annual Review of Microbiology **49**: 461-487.

Millard, P. S., K. F. Gensheimer, D. G. Addiss, D. M. Sosin, G. A. Beckett, A. Houck-Jankoski and A. Hudson (1994). "An outbreak of cryptosporidiosis from fresh-pressed apple cider." Journal of the American Medical Association **272**(20): 1592-1596.

Millis, N. F. (1988). "Microorganisms and the aquatic environment." Hydrobiologia **176/177**: 355-368.

Moeller, J. R. and J. Calkins (1980). "Bactericidal agents in wastewater lagoons and lagoon design." Journal of the Water Pollution Control Federation **52**: 2442-2451.

Molbak, K. and F. Scheutz (2004). Verocytotoxin-producing *Escherichia coli* and other diarrhoeagenic *E. coli*. Waterborne zoonoses: Identification, causes and control. World Health Organization. J. Cotruvo, A. Dufour, G. Reeset al. London, UK, IWA Publishing.

Monaghan, J. M. (2006). "United Kingdom and European Approach to Fresh Produce Food Safety and Security." HortTechnology **16**(4): 9-12.

Monis, P. T. and C. P. Saint (2001). "Development of a nested-PCR assay for the detection of *Cryptosporidium parvum* in finished water." Water Research **35**(7): 1641-1648.

Moore, J. A., J. D. Smyth, E. S. Baker, J. R. Miner and D. C. Moffitt (1989). "Modeling bacteria movemnet in livestock manure systems." Transactions of the ASAE **32**: 1049-53.

Moreland, V., A. Asahina, T. Unutoa and R. Fujioka (1998). "UV disinfection: to pilot or not to pilot?" Water Environment & Technology **10**(6): 47-51.

Morris, C. E., J. E. Monier and M. A. Jacques (1997). "Methods for observing microbial biofilms directly on leaf surfaces and recovering them for isolation of culturable microorganisms." Appl. Environ. Microbiol. **63**: 1570-1576.

Mukherjee, A., D. Speh, E. Dyck and F. Diez-Gonzalez (2004). "Preharvest evaluation of coliforms, Escherichia coli, Salmonella, and Escherichia coli O157:H7 in organic and conventional produce grown by Minnesota farmers." J Food Prot **67**(5): 894-900.

Mukherjee, A., D. Speh, A. T. Jones, K. M. Buesing and F. Diez-Gonzalez (2006). "Longitudinal microbiological survey of fresh produce grown by farmers in the upper midwest." J Food Prot **69**(8): 1928-36.

Murray, R. K., D. K. Granner, P. A. Mayes and V. W. Rodwell (1996). Harper's Biochemistry. Stamford, CT, Appleton & Lange.

Nachamkin, I., J. Engberg and F. Moller Aerstrup (2000). Chapter 3: Diagnosis and antimicrobial susceptibility of Campylobacter species. Campylobacter (2nd ed.). I. Nachamkin and M. J. Blaser. Washington, ASM Press**: 45-66.**

Nasser, A. M., R. Glozman and Y. Nitzan (2002). "Contribution of microbial activity to virus reduction in saturated soil." Water Research **36**(10): 2589-2595.

Nasser, A. M. and S. D. Oman (1999). "Quantitative assessment of the inactivation of pathogenic and indicator viruses in natural water sources." Water Research **33**(7): 1748-1752.

National Farmers Union (2005). Agriculture and Climate Change. http://www.nfuonline.com/documents/Policy%20Services/Environment/Climate%20Change/NFU%20Climate%20Change.pdf, accessed 16/3/07.

New England Extension Food Safety Consortium (2002). "On Farm Water Resources. Irrigation and Drinkable (Potable) Water." http://www.hort.uconn.edu/IPM/foodsafety/irrgwater.htm.

Nguyen-the, C. and F. Carlin (1994). "The microbiology of minimally processed fresh fruits and vegetables." Crit Rev Food Sci Nutr **34**(4): 371-401.

Noble, R. T., I. M. Lee and K. C. Schiff (2004). "Inactivation of indicator micro-organisms from various sources of faecal contamination in seawater and freshwater." J Appl Microbiol **96**(3): 464-72.

O'Brien, S. J., R. T. Mitchell, I. A. Gillespie and G. K. Adak (2000). The microbiological status of ready-to-eat fruit and vegetables. Discussion paper: Advisory Committee on Microbiological Safety of Food.

O'Connor, R. (2002). Report of the Walkerton Enquiry, Part One: the events of May 2000 and related issues (a summary). Ontario, Canada, Ontario Ministry of the Attorney General.

Obiri-Danso, K. and K. Jones (1999). "The effect of a new sewage treatment plant on faecal indicator numbers, campylobacters and bathing water compliance in Morecambe Bay." Journal of Applied Microbiology **86**(4): 603-614.

Obiri-Danso, K., N. Paul and K. Jones (2001). "The effects of UVB and temperature on the survival of natural populations and pure cultures of Campylobacter jejuni, Camp. coli, Camp. lari and urease-positive thermophilic campylobacters (UPTC) in surface waters." J Appl Microbiol **90**(2): 256-67.

Olson, M. E., R. M. O'Handley, B. J. Ralston, T. A. McAllister and R. C. Thompson (2004). "Update on Cryptosporidium and Giardia infections in cattle." Trends Parasitol **20**(4): 185-91.

Ongerth, J. E. and J. P. Pecoraro (1996). "Electrophoretic mobility of *Cryptosporidium* oocysts and *Giardia* cysts." Journal of Environmental Engineering **122**(3): 228-231.

Ormeci, B. and K. G. Linden (2002). "Comparison of UV and chlorine inactivation of particle and non-particle associated coliform." Water Science and Technology: Water Supply **2**(5-6): 403-410.

Paiba, G. A., J. W. Wilesmith, S. J. Evans, S. J. Pascoe, R. P. Smith, S. A. Kidd, J. B. Ryan, I. M. McLaren, S. A. Chappell, G. A. Willshaw, T. Cheasty, N. P. French, T. W. Jones, H. F. Buchanan, D. J. Challoner, A. D. Colloff, M. P. Cranwell, R. G. Daniel, I. H. Davies, J. P. Duff, R. A. Hogg, F. D. Kirby, M. F. Millar, R. J. Monies, M. J. Nicholls and J. H. Payne (2003). "Prevalence of faecal excretion of verocytotoxigenic Escherichia coli O157 in cattle in England and Wales." Vet Rec **153**(12): 347-53.

Park, S. F. (2002). "The physiology of Campylobacter species and its relevance to their role as foodborne pathogens." Int J Food Microbiol **74**(3): 177-88.

Parshionikar, S. U., S. Willian-True, G. Shay Fout, D. E. Robbins, S. A. Seys, J. D. Cassady and R. Harris (2003). "Waterborne outbreak of gastroenteritis associated with a *Norovirus*." Applied and Environmental Microbiology **69**(8): 5263-5268.

Pearson, A. D., M. Greenwood, T. D. Healing, D. Rollins, M. Shahamat and J. Donaldson (1993). "Colonization of broiler chickens by waterborne *Campylobacter jejuni.*" Applied & Environmental Microbiology **59**(4): 987-996.

Pedley, S., M. Yates, J. F. Schijven, J. West, G. Howard and M. H. Barrett (2006). Chapter 3. Pathogens: Health relevance, transport and attentuation. Protecting Groundwater for

Health: Managing the Quality of Drinking-water Sources. O. Schmoll, G. Howard, J. Chilton and I. Chorus. London, IWA Publishing.

Peng, M. P., L. Xiao, A. R. Freeman, M. J. Arrowood, A. A. Escalente, A. C. Weltman, C. S. L. Ong, W. R. MacKenzie, A. A. Lal and C. B. Beard (1997). "Genetic polymorphism among *Cryptosporidium parvum* isolates: evidence of two distinct human transmission cycles." Emerging Infectious Diseases **3**(4): 567-573.

Percival, S. L., R. M. Chalmers, M. Embrey, P. R. Hunter, J. Sellwood and P. Wyn-Jones (2004). Microbiology of Waterborne Disease., Elsevier Academic Press.

Petterson, S. R. (2002). Microbial Risk Assessment of Wastewater Irrigated Salad Crops. Civil and Environmental Engineering. Sydney, University of New South Wales. **PhD**.

Petterson, S. R., N. J. Ashbolt and A. Sharma (2001). "Microbial risks from wastewater irrigation of salad crops: A screening-level risk assessment." Water Environment Research **73**(6): 667-672 Errata: Wat. Environ. Res. 74(4):411.

Petterson, S. R., P. F. M. Teunis and N. Ashbolt (2001). "Modeling virus inactivation on salad crops using microbial count data." Risk Analysis **21**(6): 1097-1107.

Powell, K. L., R. G. Taylor, A. A. Cronin, M. H. Barrett, S. Pedley, J. Sellwood, S. A. Trowsdale and D. N. Lerner (2003). "Microbial contamination of two urban sandstone aquifers in the UK." Water Research **37**(2): 339-352.

Rangarajan, A., Bihn, E.A., Gravani, R.B., Scott, D.L. and Pritts, M.P. (2000). "Food Safety Begins on the Farm." http://www.GAPs.cornell.edu.

Rees, B., F. Cessford, R. Connelly, J. Cowan, R. Bowell, E. K. Weatherhead, J. W. Know, C. L. Twite and J. Morris (2003). Optimum use of water for industry and agriculture: Phase 3. Environment Agency R & D Report W6-056/TR2. Bristol, Environment Agency. http://publications.environment-agency.gov.uk/epages/eapublications.storefront/469f1ca4023b1e9a273fc0a802960680/Product/View/SW6&2D056&2DTR2&2DE&2DE#

Renou, C., J.-F. Cadranel, M. Bourlière, P. Halfon, D. Ouzan, H. Rifflet and et al. (2007). "Possible zoonotic transmission of hepatitis E from pet pig to its owner." Emerg Infect Dis **2007 Jul**.

Risk Policy Analysts (2000). Economic Instruments in Relation to Water Abstraction. London, Department for Environment, Food & Rural Affairs.

Robertson, L. J., A. T. Campbell and H. V. Smith (1992). "Survival of *Cryptosporidium parvum* oocysts under various environmental pressures." Applied and Environmental Microbiology **58**(11): 3494-3500.

Robertson, L. J. and B. Gjerde (2000). "Isolation and enumeration of Giardia cysts, cryptosporidium oocysts, and Ascaris eggs from fruits and vegetables." J Food Prot **63**(6): 775-8.

Robertson, L. J., C. A. Paton, A. T. Campbell, P. G. Smith, M. H. Jackson, R. A. Gilmour, S. E. Black, D. A. Stevenson and H. V. Smith (2000). "*Giardia* cysts and *Cryptosporidium* oocysts at sewage treatment works in Scotland, UK." Water Research **34**(8): 2310-2322.

Rockx, B., M. d. Wit, H. Vennema, J. Vinjé, E. d. Bruin, Y. v. Duynhoven and M. Koopmans (2002). "Natural history of human calicivirus infection: a prospective cohort study." Clinical Infectious Diseases **35**(3): 246-253.

Rocourt, J. and J. Bille (1997). "Foodborne listeriosis." World Health Stat Q **50**(1-2): 67-73.

Roser, D. and N. J. Ashbolt (2005). Source Water Quality Assessment and the Management of Pathogens in Surface Catchments in Aquifers. Draft Report. Cooperative Research Centre for Water Quality and Treatment Research Report.

Sagoo, S. K., C. L. Little and R. T. Mitchell (2001). "The microbiological examination of ready-to-eat organic vegetables from retail establishments in the United Kingdom." Letters in Applied Microbiology **33**(6): 434-439.

Said, B., F. Wright, G. L. Nichols, M. Reacher and M. Rutter (2003). "Outbreaks of infectious disease associated with private drinking water supplies in England and Wales 1970-2000." Epidemiology and Infection **130**(3): 469-479.

Sair, A. I., D. H. D'Souza and L. A. Jaykus (2002). "Human enteric viruses as causes of foodborne disease." Compr. Rev. Food Sci. Food Saf. **1**: 73-89.

Sattar, S. A., C. Chauret, V. S. Springthorpe, D. A. Battigelli, M. Abbaszadegan and M. LeChevallier (1999). *Giardia* cyst and *Cryptospordium* oocyst survival in watersheds and factors affecting incativation. Denver, CO and Toronto, ON, AWWARF and Ontario Ministry of Environment and Energy.

Savill, M. G., J. A. Hudson, A. Ball, J. D. Klena, P. Scholes, R. J. Whyte, R. E. McCormick and D. Jankovic (2001). "Enumeration of *Campylobacter* in New Zealand recreational and drinking waters." Journal of Applied Microbiology **91**(1): 38-46.

Schaffter, N. and A. Parriaux (2002). "Pathogenic-bacterial water contamination in mountain catchments." Water Research **36**(1): 131-139.

Schlech, W. F., 3rd, P. M. Lavigne, R. A. Bortolussi, A. C. Allen, E. V. Haldane, A. J. Wort, A. W. Hightower, S. E. Johnson, S. H. King, E. S. Nicholls and C. V. Broome (1983). "Epidemic listeriosis--evidence for transmission by food." N Engl J Med **308**(4): 203-6.

Schorr, D., Schmid, H., Rieder, HL., Baumgartner, A., Vorkauf, H. and Burnens, A. (1994). "Risk factors for *Campylobacter enteritis* in Switzerland." Zentralbl Hyg Umweltmed **196**(4): 327-337.

Scottish Agricultural College (2001). FSA Irrigation Survey. Forfar, Scottish Agricultural College.

Seo, K. H. and J. F. Frank (1999). "Attachment of *Escherichia coli* O157:H7 to lettuce leaf surface and bacterial viability in response to chlorine treatment as demonstrated by using confocal scanning laser microscopy." J. Food Prot. **62**: 3-9.

Seymour, I. J. and H. Appleton (2001). "Foodborne viruses and fresh produce [Review]." Journal of Applied Microbiology **91**(5): 759-773.

Sheikh, B., R. C. Cooper and K. E. Israel (1999). "Hygienic evaluation of reclaimed water used to irrigate food crops - A case study." Water Science and Technology **40**(4-5): 261-267.

Sheridan, J. J. and D. A. McDowell (1998). "Factors affecting the emergence of pathogens on foods." Meat Science **49**(1): S151-S167.

Shin, G.-A., K. G. Linden, M. J. Arrowod and M. D. Sobsey (2001). "Low-Pressure UV Inactivation and DNA Repair Potential of *Cryptosporidium parvum* Oocysts." Applied and Environmental Microbiology **67**(7): 3029-3032.

Shuval, H., Y. Lampert and B. Fattal (1997). "Development of a risk assessment approach for evaluating wastewater reuse standards for agriculture." Water Science and Technology **35**(11-12): 15-20.

Šimùnek, J., M. Šejna and M. T. van Genuchten (1998). The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat and multiple solutes in variably saturated media. Golden, Colorado, International Ground Water Modelling Centre, Colorado School of Mines.

Sinton, L., C. Hall and R. Braithwaite (2007). "Sunlight inactivation of Campylobacter jejuni and Salmonella enterica, compared with Escherichia coli, in seawater and river water." J Water Health **5**(3): 357-65.

Sinton, L. W., C. H. Hall, P. A. Lynch and R. J. Davies-Colley (2002). "Sunlight inactivation of fecal indicator bacteria and bacteriophages from waste stabilization pond effluent in fresh and saline waters." Applied and Environmental Microbiology **68**(3): 1122-1131.

Sivapalasingam, S., C. R. Friedman, L. Cohen and R. V. Tauxe (2004). "Fresh produce: a growing cause of outbreaks of foodborne illness in the United States, 1973 through 1997." J Food Prot **67**(10): 2342-53.

Skraber, S., C. Gantzer, A. Maul and L. Schwartzbrod (2002). "Fates of bacteriophages and bacterial indicators in the Moselle river (France)." Water Research **36**(14): 3629-3637.

Smibert, R. M. (1986). Genus *Campylobacter* Sebald and Veron 1963, 907[AL]. Bergey's Manual of Systematic Bacteriology. N. R. Krieg and J. G. Holt. Baltimore, Williams & Wilkins. **1:** 964.

Snelling, W. J., J. E. Moore, J. P. McKenna, D. M. Lecky and J. S. G. Dooley (2006). "Bacterial–protozoa interactions; an update on the role these phenomena play towards human illness." Microbes and Infection **8**(2): 578-587.

Sobsey, M. D. and J. S. Meschke (2003). Virus survival in the environment with special attention to survival in sewage droplets and other environmental media of fecal or respiratory origin. Draft - August 21, 2003. Geneva, WHO.

Sobsey, M. D., C. Wallis, M. Henderson and J. L. Melnick (1973). "Concentration of Enteroviruses from Large Volumes of Water." Appl Microbiol **26**(4): 529-534.

Sobsey, M. D., C. Wallis and J. L. Melnick (1975). "Studies on the survival and fate of enteroviruses in an experimental model of a municipal solid waste landfill and leachate." Applied Microbiology **30**(4): 565-574.

Solomon, E. B., H. J. Pang and K. R. Matthews (2003). "Persistence of Escherichia coli O157:H7 on lettuce plants following spray irrigation with contaminated water." J Food Prot **66**(12): 2198-202.

Solomon, E. B., C. J. Potenski and K. R. Matthews (2002). "Effect of irrigation method on transmission to and persistence of Escherichia coli O157:H7 on lettuce." J Food Prot **65**(4): 673-6.

Solomon, E. B., S. Yaron and K. R. Matthews (2002). "Transmission of Escherichia coli O157:H7 from contaminated manure and irrigation water to lettuce plant tissue and its subsequent internalization." Appl Environ Microbiol **68**(1): 397-400.

Stagg, C. H., C. Wallis and C. H. Ward (1977). "Inactivation of clay-associated bacteriophage MS-2 by chlorine." Applied and Environmental Microbiology **33**(2): 385-391.

Standing Committee on the Food Chain and Animal Health (2005). Annotated EC Guidance on the implementation of Articles 11, 12, 16, 17, 18, 19 and 20 of Regulation (EC) No 178/2002 on General Food Law.
http://www.food.gov.uk/multimedia/pdfs/gflreu1782002.pdf

Stanley, K. (1996). Seasonal variation of thermophilic campylobacters in farm animals and the farm environment. Lancaster, UK, Lancaster University. **PhD**.

Stanley, K. and K. Jones (2003). "Cattle and sheep farms as reservoirs of Campylobacter." J Appl Microbiol **94 Suppl**: 104S-113S.

Steets, B. M. and P. A. Holden (2003). "A mechanistic model of run-off-associated fecal coliform fate and transport through a coastal lagoon." Water Research **37**(3): 589-608.

Stenstrom, T. A., F. Boisen, F. Georgsen and *et al.* (1994). Waterborne outbreaks in Northern Europe. Copenhagen, Denmark, TemNord, Nordisk Minist.

Stern, N.J., Hiett, K.L., Alfredsson, G.A., Kristinsson, K.G., Reiersen, J., Hardardottir, H. Briem, H., Gunnarsson, E., Georgsson, F., Lowman, R., Berndtson, E., Lammerding, A.M., Paoli, G.M. and Musgrove, M.T. (2003). *Campylobacter* spp. in Icelandic poultry operations and human disease, Epidemiology and Infection **130**, 23–32.

Stine, S. W., I. Song, C. Y. Choi and C. P. Gerba (2005). "Effect of relative humidity on preharvest survival of bacterial and viral pathogens on the surface of cantaloupe, lettuce, and bell peppers." J Food Prot **68**(7): 1352-8.

Stuart, D. (2006). Reconciling Food Safety and Environmental Protection: A Literature Review. Salinas, CA. USA, Resource Conservation District of Monterey County.
http://caff.org/policy/documents/ReviewofFoodSafetyLiterature.pdf

Sturdee, A. P., A. T. Bodley-Tickell, A. Archer and R. M. Chalmers (2003). "Long-term study of *Cryptosporidium* prevalence on a lowland farm in the United Kingdom." Veterinary Parasitology **116**(2): 97-113.

Sulaiman, I. M., L. Xiao, C. Yang, L. Escalante, A. Moore, C. B. Beard, M. J. Arrowood and A. A. Lal (1998). "Differentiating human from animal isolates of *Cryptosporidium parvum*." Emerging Infectious Diseases **4**(4): 681-685.

Takeuchi, K., C. M. Matute, A. N. Hassan and J. F. Frank (2000). "Comparison of the attachment of Escherichia coli O157:H7, Listeria monocytogenes, Salmonella typhimurium, and Pseudomonas fluorescens to lettuce leaves." Journal of Food Protection **63**: 1433-1437.

Talibart, R., M. Denis, A. Castillo, J. M. Cappelier and G. Ermel (2000). "Survival and recovery of viable but noncultivable forms of Campylobacter in aqueous microcosm." Int J Food Microbiol **55**(1-3): 263-7.

Taormina, P., L. Beuchat and L. Slutsker (1999). "Infections associated with easting seed sprouts: An international concern." Emerging Infectious Diseases **5**: 626-634.

Tchobanoglous, G. and F. L. Burton (1991). Wastewater Engineering: Treatment, Disposal and Reuse. New York, NY, McGraw-Hill, Inc.

Templeton, M. R., R. C. Andrews and R. Hofmann (2005). "Inactivation of particle-associated viral surrogates by ultraviolet light." Water Research **39**(15): 3487.

Tian, Y. Q., P. Gong, J. D. Radke and J. Scarborough (2002). "Spatial and temporal modeling of microbial contaminants on grazing farmlands." Journal of Environmental Quality **31**: 860-869.

Tompkins, D. S., M. R. Millar and A. P. West (1988). "Isoelectric focusing of ureases from Campylobacter pylori and related organisms." J Clin Microbiol. **26**(12): 2678-2679.

Toze, S. (1997). Microbial Pathogens in Wastewater. Literature Review for Urban Water Systems Multi-divisional Research Program. CSIRO Land and Water Technical Report No 1/97. Perth, CSIRO Land and Water.

Tyrrel, S. F., J. W. Knox and E. K. Weatherhead (2006). "Microbiological water quality requirements for salad irrigation in the United Kingdom." J Food Prot **69**(8): 2029-35.

UKWIR (2003). A review of the fate of enteroviruses and indicator organisms across wastewater treatment processes. UKWIR Report Ref. 03/WW/11/6.

van Breemen, L. W. C. A., H. A. M. Ketelaars, W. Hoogenboezem and G. Medema (1998). "Storage reservoirs - a first barrier for pathogenic microorganmisms in the Netherlands." Water Science and Technology **37**(2): 253-260.

van den Berg, H., W. Lodder, W. van der Poel, H. Vennema and A. M. de Roda Husman (2005). "Genetic diversity of noroviruses in raw and treated sewage water." Res Microbiol **156**(4): 532-40.

Vatanyoopaisarn, S., A. Nazli, C. E. Dodd, C. E. Rees and W. M. Waites (2000). "Effect of flagella on initial attachment of Listeria monocytogenes to stainless steel." Appl Environ Microbiol **66**(2): 860-3.

Vinten, A. J., D. R. Lewis, M. McGechan, A. Duncan, M. Aitken, C. Hill and C. Crawford (2004). "Predicting the effect of livestock inputs of E. coli on microbiological compliance of bathing waters." Water Res **38**(14-15): 3215-24.

Vogt, R. L., H. E. Sours and T. Barrett (1982). "*Campylobacter enteritis* associated with contaminated water." Annals of Internal Medicine **96**(3): 292-296.

Wachtel, M. R., L. C. Whitehand and R. E. Mandrell (2002). "Association of Escherichia coli O157:H7 with preharvest leaf lettuce upon exposure to contaminated irrigation water." J Food Prot **65**(1): 18-25.

Wait, D. A. and M. D. Sobsey (1983). "Method for recovery of enteric viruses from estuarine sediments with chaotropic agents." Applied and Environmental Microbiology **46**(2): 379-385.

Walderhaug, M. O., S. G. Edelson-Mammel, A. J. DeJesus, B. S. Eblen, A. J. Miller and R. L. Buchanaw (1999). "Preliminary studies on the potential for infiltration, growth and survival of *Salmonella enterica* serovar Hartford and *Escherichia coli* O157:H7 within oranges." U. S. Food and Drug Administration **November 9, 1999**: 10.

Walker, M., K. Leddy and E. Hagar (2001). "Effects of combined water potential and temperature stresses on *Cryptosporidium parvum* oocysts." Applied and Environmental Microbiology **67**(12): 5526-5529.

Walker, S. E., S. Mostaghimi, T. A. Dillaha and F. E. Woeste (1990). "Modeling animal waste management practices: impacts on bacteria levels in run-off from agricultural lands." Transactions of the ASAE **33**(3): 807-17.

Wang, G. D. and M. P. Doyle (1998). "Survival of enterohemorrhagic *Escherichia coli* O157: H7 in water." Journal of Food Protection **61**(6): 662-667.

Warriner, K., F. Ibrahim, M. Dickinson, C. Wright and W. M. Waites (2003). "Interaction of Escherichia coli with growing salad spinach plants." J. Food Prot. **66**: 1790-1797.

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

Weatherhead, E. K., J. W. Knox, T. T. de Vries, S. Ramsden, J. Gibbons, N. W. Arnell, N. Odoni, K. Hiscock, C. Sandhu, A. Saich, D. Conway, C. Warwick, S. Bharwani, J. Hossell and B. Clemence (2006). <u>Sustainable water resources: A framework for assessing adaptation options in the rural sector. Tyndall Centre Technical Report 44</u>. Norwich, Tyndall Centre for Climate Change Research, UEA.

Weatherhead, E. K. and M. Rivas-Casado (2006). <u>Survey of Irrigation of Outdoor Crops in England</u>. Bedford, Cranfield University.

Webb, A. R., L. Kline and M. F. Holick (1988). "Influence of season and latitude on the cutaneous synthesis of vitamin D3: exposure to winter sunlight in Boston and Edmonton will not promote vitamin D3 synthesis in human skin." <u>J Clin Endocrinol Metab</u> **67**(2): 373-8.

Wei, C. I., T. S. Huang, J. M. Kim, W. F. Lin, M. L. Tamplin and J. A. Bartz (1995). "Growth and survival of Salmonella montevideo on tomatoes and disinfection with chlorinated water." <u>J. Food Prot.</u> **58**: 829-836.

Westrell, T. (2004). Microbial risk assessment and its implications for risk management in urban water systems. <u>Department of Water and Environmental Studies</u>. Linköping, Sweden, Linköping University.

Westrell, T., P. Teunis, H. van den Berg, W. Lodder, H. Ketelaars, T. A. Stenstrom and A. M. de Roda Husman (2006). "Short- and long-term variations of norovirus concentrations in the Meuse river during a 2-year study period." <u>Water Research</u> **40**(14): 2613.

Wheeler, J. G., D. Sethi, J. M. Cowden, P. G. Wall, L. C. Rodrigues, D. S. Topkins, M. J. Hudson and P. J. Roderick (1999). "Study of infectious intestinal disease in England: rates in the community, presenting to general practice, and reported to national surveillance." <u>British Medical Journal</u> **318**: 1046-1050.

WHO (1989). <u>Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture.</u> Geneva, World Health Organization: 74.

WHO (2004). <u>Guidelines for Drinking-Water Quality</u>. Geneva, World Health Organization: 238.

WHO (2006). <u>Guidelines for the safe use of wastewater, excreta and greywater</u>. Geneva, World Health Organization.

Wither, A., J. Greaves, I. Dunhill, M. Wyer, C. Stapleton, D. Kay, N. Humphrey, J. Watkins, C. Francis, A. McDonald and J. Crowther (2005). "Estimation of diffuse and point source microbial pollution in the ribble catchment discharging to bathing waters in the north west of England." Water Sci Technol **51**(3-4): 191-8.

Withers, B. and S. Vipond (1974). Irrigation: Design and Practice. Batsford, London.

Yates, M. V., C. P. Gerba and L. M. Kelley (1985). "Virus persistence in groundwater." Applied and Environmental Microbiology **49**(4): 778-781.

Yates, M. V., S. R. Yates, A. W. Warrick and C. P. Gerba (1986). "Use of geostatistics to predict virus decay rates for determination of septic tank setback distances." Applied and Environmental Microbiology **52**(3): 479-483.

Yu, K., M. C. Newman, D. D. Archbold and T. R. Hamilton-Kemp (2001). "Survival of Escherichia coli O157:H7 on strawberry fruit and reduction of the pathogen population by chemical agents." J Food Prot **64**(9): 1334-40.

Zimmer, J. L. and R. M. Slawson (2002). "Potential repair of *Escherichia coli* DNA following exposure to UV radiation from both medium- and low-pressure UV sources used in drinking water treatment." Applied and Environmental Microbiology **68**(7): 3293-3299.

Zuckerman, J. N. (2003). "Hepatitis E and the traveller." Travel Med Infect Dis **1**: 73-76.

Appendix 1.1 Health Protection Agency data on foodborne outbreaks

General foodborne outbreaks of infectious intestinal diseases associated with salad vegetables and fruit, England and Wales 1995 - 2005 (Health Protection Agency Centre for Infections Environmental and Enteric Diseases Department, August 2006)

Year	Organism	No. affected	No. positive	Month of outbreak	Suspect Vehicle*
1995	Escherichia coli O157	5	5	July	Lettuce/Tomatoes
1995	Norovirus	88	19	June	Salad (Mixed)
1995	Norovirus	15	1	March	Salad
1995	Norovirus	11	1	March	Salad (Raw)
1995	Unknown	23	0	September	Mushrooms (Dried)
1996	Campylobacter	16	3	April	Lettuce, Tomato
1996	Clostridium perfringens	11	3	December	Lentil Dahl, Chicken Drumsticks (Tandoori)
1996	Cl. perfringens	3	1	October	Rice (Pilau), Vegetable Curry
1996	Cl. perfringens	34	14	July	Chicken Curry, Vegetable Curry
1996	Cl. perfringens	39	23	May	Pork Curry, Chicken Curry, Vegetable Curry
1996	Norovirus	18	2	December	Salad (Tomato & Cucumber)
1996	Norovirus	42	3	August	Potato Salad
1996	Norovirus	193	7	April	Cold Food, Salad
1996	Salmonella Enteritidis PT 4	9	4	September	Mushroom Soup
1996	S. Enteritidis PT 4	35	5	June	Chocolate Marquise, Potatoes
1996	S. Enteritidis PT 4	7	6	August	Tuna & Pasta Salad, Coleslaw With Onion
1996	S. Enteritidis PT 4	40	20	August	Raspberry Bavarois, Egg Mayonnaise, Fruit Juice
1996	Shigella Flexneri	9	7	November	Salad Vegetables
1996	Unknown	4	0	September	Salad (Mixed Bean)
1996	Unknown	5	0	June	Chicken, Salad, Ice Cream
1996	Unknown	23	0	December	Potato Salad
1996	Unknown	9	0	August	Chicken Roll Sandwich, Pork Pie, Lettuce
1997	Cl. perfringens	35	18	June	Ham, Turkey, Salad (Mixed0
1997	E. coli O157	9	9	February	Salad (Mixed), French Fries
1997	S. Enteritidis PT 24	55	41	November	Cauliflower, Cheese Sauce
1997	S. Enteritidis PT 4	9	9	August	Pork Loin, Mayonnaise Made With Rse, Salad
1997	Unknown	29	0	February	Orange Juice
1998	Campylobacter	30	12	May	Lettuce, Mayonnaise (Garlic)
1998	S. Enteritidis PT 6a	13	10	May	Potato Salad, Mayonnaise
1998	S. Enteritidis PT 4	28	14	December	Stuffed Pepper, Spanish Omelette
1998	S. Enteritidis PT 4	10	5	October	Lemon Mousse Made With RSE, Bean Salad, Black Cherry Cheesecake
1998	S. Enteritidis PT 4	29	12	August	Sandwiches, Cold Savoury Salad
1998	Unknown	51	0	January	Fresh Fruit
1999	Norovirus	13	2	October	Salad, Cheese
1999	S. Java	55	17	November	Dessicated Coconut
1999	S. Hindmarsh	12	12	March	Lamb Doner Kebab, Salads, Sauces
1999	S. Enteritidis PT 4, 5 & 7	14	13	September	Aromatic Duck, Spring Onion, Cucumber
1999	Unknown	39	0	May	Salad

Year	Organism	No. affected	No. positive	Month of outbreak	Suspect Vehicle*
1999	Unknown	17	0	December	Chicken Drumsticks, Onion Bhaji
1999	Unknown	18	0	July	Cheese, Beef, Salad
2000	Campylobacter	18	18	June	Lettuce
2000	S. Enteritidis PT 6a	14	9	September	Cooked Turkey, Potato Salad
2000	S. Enteritidis PT 4	84	62	August	Pasta Salad, Coleslaw, Lemon Cheesecake (RSE)
2000	S. Enteritidis PT 4	87	31	July	Egg Fried Rice, Sweetcorn Soup
2000	S. Typhimurium DT 104	361	361	August	Lettuce
2000	S. Typhimurium DT 204b	140	140	August	Lettuce
2000	S. Typhimurium DT 170	37	30	June	Beef, Lettuce
2000	Unknown	11	0	December	Brussel Sprouts
2000	Unknown	11	0	June	Mixed Side Salad
2001	Campylobacter	30	12	March	Orange Juice, Pasta Salad
2001	Mixed aetiology	30	0	August	Roast Beef, Salad, Potatoes
2001	S. Newport	19	19	June	Pre Packed Salad
2001	S. Enteritidis PT 4	15	6	June	Duck, Seaweed
2001	S. Virchow	9	8	July	Salad
2002	Bacillus cereus	4	0	February	Dried Mushrooms
2002	Norovirus	40	5	December	Salad
2002	B. thuringiensis	2	0	October	Rocket Leaves
2003	B. cereus	30	0	July	Stilton & Broccoli Quiche, Mushroom Quiche, Tomatoes & Lettuce
2003	B. subtilis	9	0	June	Mixed Vegetables, Bombay Potatoes
2003	Escherichia coli	37	24	October	Salad/Lettuce
2003	S. Braenderup	90	17	February	Iceberg Lettuce
2003	S. Enteritidis PT 4	8	5	August	Salad
2003	S. Enteritidis PT 4	14	12	July	Rice Salad, Coleslaw
2004	Campylobacter	8	8	May	Side Salad
2004	S. Newport	146	146	August	Lettuce
2005	Norovirus	43	1	July	Three Bean Salad
2005	S. Enteritidis PT 6	5	3	July	Salad

*More than one food vehicle can be reported in any given outbreak

Appendix 1.2 Modelling water quality

A review of models was undertaken to assess and compare models that can predict microbiological water quality. For modelling of both surface and groundwater catchments, data requirements are generally high requiring detailed catchment hydrology and land use information, as well as water quality data for calibration of the model. Therefore, modelling water quality may not be a viable option on a single irrigator basis, but may be appropriate on regional basis to provide guidance to irrigators.

Modelling of the transport and fate of pathogens in surface water catchments has increased due to a number of water contamination incidents such as Milwaukee *Cryptosporidium* outbreak, and Sydney *Cryptosporidium* incident. Ferguson *et al.* (2003b) presented a review of catchment models that are used for, or can be adapted for use with, modelling the transport and fate of microorganisms. The most successful methods to date have employed a budgeting approach, e.g. Ferguson *et al.* (2004) and Crowther *et al.* (2003). The surface water models are reviewed in Table 1.

Models for the transport of pathogens in groundwater vary greatly in the data inputs required. The simplest models assume die-off is the only removal mechanism for pathogens (Yates *et al.*, 1986), and therefore the main data requirement is the distance and flow rate between the source and the bore. More complicated models may be used where the data is available. For example, Hydrus1D is frequently used for analysing experimental results (Šimùnek *et al.*, 1998).

ICREW

As part of the remit of Pilot Action 4 of the ICREW (Improving Coastal and Recreational Waters) project, two predictive models were developed to:

- aid investigations to improve and enhance the quality of bathing waters;

- provide near real time predictions on microbial water quality for the information and benefit of beach users; and

- predict the impact and duration of Short Term Pollution Incidents at Bathing Waters, allowing use of the Sample Discounting provisions in the 2006 Bathing Waters Directive (2006/7/EU).

The first was a deterministic model, MOHID Land developed by IST/Maretec. MOHID Land was developed specifically to address the transport and fate of microorganisms in catchments, including transport, dispersion and decay. The simulation incorporates 2D

surface run-off with sediment production, 1D stream network flow and infiltration and 3D subsurface flow.

The second was a stochastic model (Department for Environment Food and Rural Affairs *et al.*, 2006) designed to provide predictions of acceptable water quality based on readily available environmental data, and compare to available water quality data. The aim of this approach was to identify when samples did not need to be taken. A correlation analysis and a linear regression modelling approach were used in parallel. Correlation analysis investigated trigger values for environmental variables that represent a threshold for indicator organisms in water. Linear regression was used to assess the relationship between water quality and multiple environmental variables, including rainfall, flow, wind speed/direction, sunshine, UVA, UVB, total irradiance and tidal data.

The stochastic approach was applied to 19 UK bathing water sites, with the accuracy of predictions measured against monitoring data from 2005. The validation of the rainfall trigger levels showed that it was possible to predict failure at 10 sites. Trigger values for environmental variables were incorporated at four sites, only one of which resulted in improved prediction capabilities.

Table 1 Summary of surface water quality models, updated from (Ferguson, 2005)

Model	Advantages	Constraints	Applicability
MOHID Land	Integrates surface and subsurface transport on catchment basis Uses GIS approach	Requires large amounts of data for a wide range of input parameters	Predicts concentrations where there are significant interactions between surface and groundwater
ICREW	Few input parameters required Easy to calibrate and test	Qualitative result for calibrated catchments Need to have water quality data	Predicts water quality in relation to threshold values
Ferguson (2005)	Uses catchment land use GIS data to estimate indicator and pathogen concentrations for a catchment using IHACRES Includes point sources and diffuse pollution from wildlife and farms.	Requires large amounts of data for a wide range of input parameters.	Predicts loads of faecal indicators and bacterial and protozoan pathogens for base and high flow conditions
Crowther *et al.* (2003)	Uses catchment land use GIS data to estimate faecal indicator concentrations in streams	Does not include data on stocking rates or point sources Not linked to a hydrologic model Need to have water quality data	Predicts faecal indicator concentrations for streams in base flow or high flow conditions
Vinten *et al.* (2004)	Compares a soil transport model, regression analysis and a distributed catchment model (PAMIMO-C) to predict *E. coli* transport to receiving waters	Does not include point sources Does not account for salinity of receiving waters or sunlight intensity Soil transport model does not allow for surface water delivery	Likely to under predict microbial impacts on bathing water quality
IHACRES	Few input parameters required Easy to calibrate and test Can be used on regional basis	Model output is dependent on good quality rainfall and stream data Several catchments with stream data are needed for regionalisation	Rainfall-run-off model that can be applied locally to catchments with good datasets, or for ungauged/poorly gauged catchments through regionalisation
HSPF	Existing versions of this model include faecal coliforms	Requires large amounts of data for a wide range of input parameters Assumes that pathogens are transported with particles but the relationship is not quantified	Only applicable to catchments with comprehensive existing GIS and hydrological information that can be integrated with water quality data
STARS	Few input parameters required Easy to calibrate and test	Requires calibration – needs sufficient water quality data	Estimating sediment and chemical (e.g. salt) exports

BASINS	Can calculate run-off and pollutant loadings from point and non-point sources through stream reaches and reservoirs; uses GIS	A simple approach that uses USA data where quality assurance is suspect in some cases. User-friendly tools may five rise to inappropriate use of output data	A planning level catchment model that can integrate both point and non-point sources of pollutants
Jenkins	Simple process-based model for predicting indicator concentrations in water and sediment from diffuse sources	Not able to use GIS data No routing mechanism Model not validated	Predicts faecal coliform concentrations in water and sediment in small upland catchments
MWASTE	Predicts indicator concentrations in surface run-off from manure/agricultural areas Has the ability to run various management scenarios	Not able to use GIS data No routing mechanism Only includes indicator bacteria Only includes manure sources	Predicts faecal coliform and faecal streptococci concentrations in surface run-off from agricultural areas
COLI	Predicts faecal coliform concentrations in surface run-off from manure/agricultural areas Has the ability to run detailed management scenarios and includes catchment/land use features	Not able to use GIS data No routing mechanism Only includes indicator bacteria Only includes manure sources	Predicts faecal coliform concentrations in surface run-off from agricultural areas for single storm events
SEDMOD	Interface with a GIS platform facilitates data input Can prioritise relative contributions of non-point source pollutants	Requires large amounts of data for a wise range of input parameters	Useful for predicting the relative contribution of diverse livestock operations within a variety of land use types
GWLF	Few input parameters required	Some assumptions may not be valid e.g. decay and transport coefficients for pathogens Estimates of pathogen loads may be too low	Can be used to predict pathogen loads utilising first order decay kinetics
PROMISE and WATNAT	Simple emission and dispersion models that can predict the concentration of pathogens in receiving waters receiving point source pollution	Currently calibrated for regional data specific to the Netherlands Data not available to account for non-point source pollution from agricultural livestock	Currently only applicable for use within the Netherlands
Steets and Holden (2003)	A mechanistic model to describe the fate and transport of faecal coliforms in a coastal lagoon Accounts for advective flow, dispersion, decay and sedimentation and resuspension	Only includes indicator bacteria Only inputs are diffuse pollution	Able to predict water and sediment concentrations of faecal coliforms from diffuse sources dispersed into estuarine lagoons

Tian et al. (2002)	Interface with a GIS platform facilitates data input Calculated run-off and streamflow using WAM Sensitivity analysis of various scenarios used to test variables in the model	Only models E. coli bacteria Does not include direct deposition of faecal material to streams, inputs from wildlife or groundwater transport mechanisms	Only applicable to catchments with comprehensive existing GIS information Able to estimate E. coli loads, surface run-off and streamflow
Collins and Rutherford (2004)	Calculates run-off and streamflow using WAM Includes direct depositions from livestock Has a delivery index for pathogen transport to the stream network and includes subsurface transport Includes in-stream dynamics of deposition and resuspension Sensitivity analysis and water quality validation testing of the model and scenario analyses to evaluate effectiveness of riparian buffer zones	Does not include direct deposition from wildlife Data not yet available for some of the parameters (e.g. rates of direct deposition)	Estimates E. coli loads, surface run-off and streamflow for diffuse pollution in rural catchments
Dorner (2004)	Uses β-distributions to calculate pathogen prevalence in domestic animals and Γ-distributions to estimate pathogen shedding intensity	Does not yet include inputs from wildlife, sewage treatment works, or septic tanks. Does not yet include pathogen inactivation or stream routing	Probabilistic model to estimate maximum pathogen loads generated per day from domestic livestock in catchments
Haydon (2005)	Estimates *E. coli* concentrations in stream water during baseflow and stormflow conditions	Does not give good estimates of total loads, probably due to the simplified representation of the pathogen store component of the model	Simple model for the estimation of microorganism concentrations at peak flow from rainfall and flow data

IHACRES – Identification of unit hydrographs and component flows from rainfall, evaporation and streamflow
STARS – Sediment/chemical Transport with Advection, Resuspension and Settling
BASINS – Better assessment science integrating point and non-point sources model
HSPF – Hydrologic simulation program FORTRAN
MWASTE – model developed by Moore *et al.* (1989)
COLI – model developed by Walker *et al.* (1990)
SEDMOD – Spatially explicit Delivery Model
GWLF – Generalized watershed loading function
PROMISE and WATNAT – models used by Medema and Schijven (Medema *et al.*, 2001)
WAM – Watershed assessment model used by Tian *et al.* (Tian *et al.*, 2002) and Collins and Rutherford (Collins *et al.*, 2004)

Appendix 1.3 Quantitative Microbial Risk Assessment Results

Comparison with water quality

The results of the concentrations of the faecal indicator bacteria in surface water from the modelling compared with the data above are provided for in Table 1 with the distribution of faecal coliforms illustrated in Figure 1.

Table 1 Comparison of measured and modelled indicator bacteria concentrations in surface water (per 100 mL)

Statistic	Measured	Log_{10} Measured	Modelled	Log_{10} Modelled	Microrisk Dataset
Total coliforms					
Mean		3.98	18,746	3.98	
Std Dev		0.50	30,551	0.51	
Minimum	1,420	3.15	74	1.87	
Maximum	155,906	5.19	751,456	5.88	
50%	9,591	3.98	9,669	3.99	
95%			62,764	4.80	
Faecal coliforms					
Mean		3.42	5426	3.42	4.57×10^{10}
Std Dev		0.53	8989	0.53	1.94×10^{11}
Minimum	304	2.48	34	1.53	2.90×10^{3}
Maximum	52597	4.72	289237	5.46	1.57×10^{12}
50%	2538	3.40	2639	3.42	2.70×10^{7}
95%			19340	4.29	1.98×10^{11}
Faecal streptococci					
Mean		2.85	2073	2.86	
Std Dev		0.63	5324	0.63	
Minimum	95	1.98	3	0.53	
Maximum	18499	4.27	168497	5.23	
50%	582	2.76	731	2.86	
95%			7838	3.89	
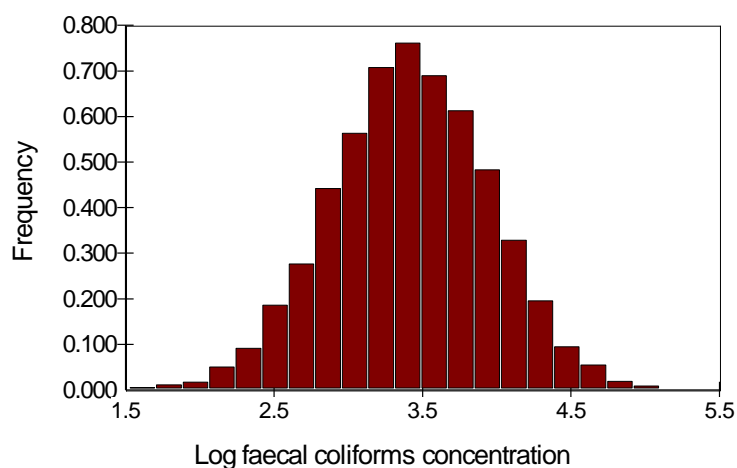
Figure 1 Log_{10} faecal coliforms distribution in surface water (per 100 mL)

The water quality at source is summarised in Table 2.

Table 2 Summary of water quality at source (per L)

Organism	Average	50%	80%	95%	Max	>10/ L
Faecal coliforms	54,736	26,118	71,225	189,810	2,304,484	100 %
E. coli O157	1,706	0	1,944	8,525	184,359	39 %
Campylobacter	242	60	340	995	19,267	55 %
Norovirus	15	0	0.3	70	3590	11 %
Giardia	3	0	0	14	738	6.6 %
Cryptosporidium	1.8	1.0	2.5	5.8	95	1.6 %

Norovirus was modelled as a function of prevalence, correlated to faecal coliforms concentrations, and concentration. The modelled distribution (Figure 2) provided a good fit of the available statistical parameters (Table 3), with the 50th percentile of the measured data equal to the 45th percentile in the modelled distribution.

Table 3 Comparison of measured and modelled Norovirus concentrations in river water (per L)

Statistic	Meuse river water (Westrell *et al.*, 2006)	Modelled distribution	Water quality distribution including presence/absence
Mean	33.3	32	14
Std Dev		101	68
Minimum		0	0
Maximum		1379	1393
50%	0.062	0.2	0
90%	81.4	89	12
95%	195	185	65
99%	577	503	341
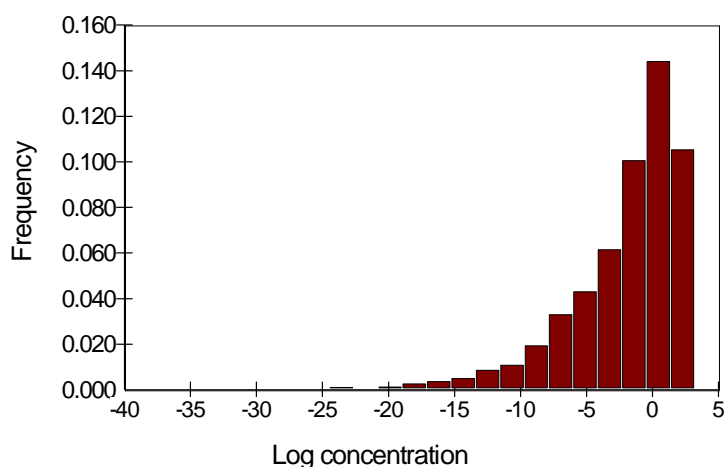
Figure 2 Distribution for $\log_{10}$ Norovirus concentration per L in surface water

E. coli O157 was modelled as 8% of the total *E. coli* count, where faecal coliforms were assumed to be *E. coli* (Figure 3).
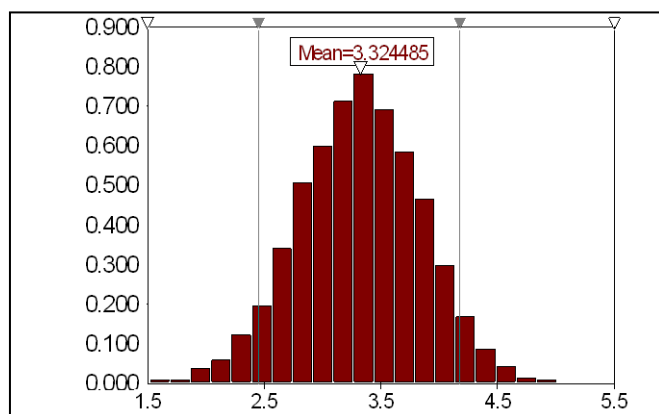
Figure 3 E. coli O157 distribution

The available data for correlation between concentrations of indicators and pathogens in surface water, namely *Giardia*, *Cryptosporidium* and *Campylobacter*, consisted of two databases: one with concentrations in sewage and one with concentrations in surface water. The faecal coliform concentrations reported in this study (Table 5.2) had a median value of 10^4 per 100mL, which was in between the median values for the sewage dataset (10^7 per 100mL), and river water dataset (10^3 per 100mL for *E. coli* and 10^4 for thermotolerant coliforms). Therefore the combined dataset was considered the most appropriate for covering the range of values in the model, and fitting the combined data resulted in a lower standard error than that for the river water dataset only. However, the modelled distribution provided a better fit for the river water dataset (Figure 4, Figure 7) than the combined dataset (Figure 5, Figure 8) in most cases.

There is limited data for water quality in England and Wales for comparison with the modelled pathogen concentrations. *Cryptosporidium* was reported for one site in River Avon in the south west where it had a mean of <0.01 oocysts per 10 L and a maximum of 1.2 oocysts per 10 L which is ten fold lower than the average modelled concentration of 1.8 oocysts per L (Table 2). Similarly at Lowenstock Reservoir, the average concentration was calculated as 0.01 per L. Overall, the *Cryptosporidium* distribution had a low standard deviation.

The impact of rainfall events on water quality is highlighted by Roser & Ashbolt (2005) who reported average concentrations in dry weather of < 0.1 and 0.11 oocysts per L at sites partially impacted by agriculture rising to 0.45 and 3.9 oocysts per L in wet weather. At a site in an urbanised catchment, oocysts concentrations rose from an average of 1.6 per L

in dry weather to 29.0 per L in wet weather, and in an intensive agricultural catchment from 0.19 to 3.1 per L.
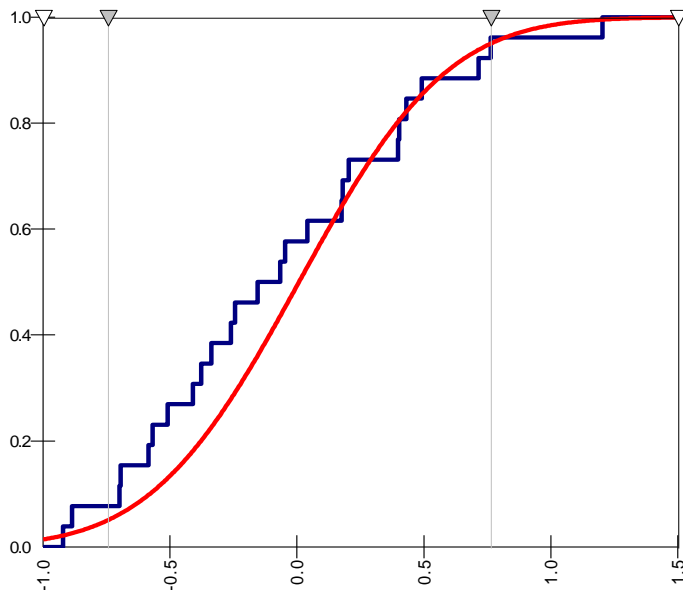
Figure 4 Comparison of modelled *Cryptosporidium* distribution (red) with log$_{10}$ cumulative density function for river water dataset (blue)
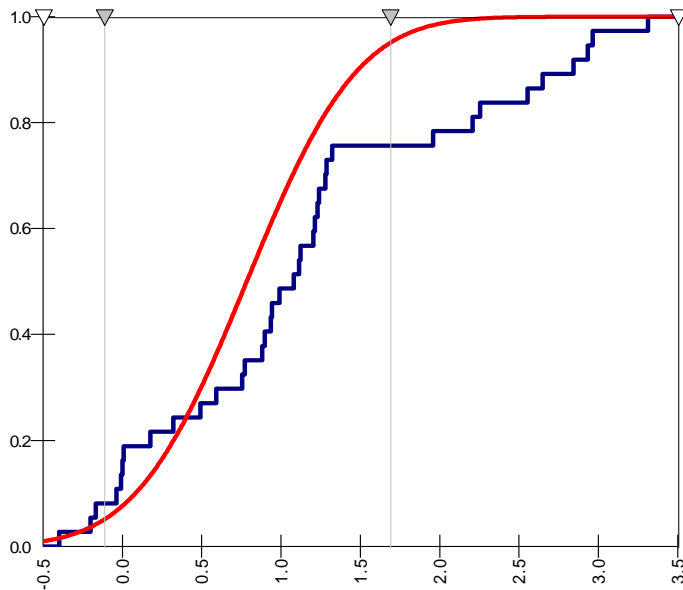
Figure 5 Comparison of modelled *Cryptosporidium* distribution (red) with log$_{10}$ cumulative density function for the combined sewage and river water dataset (blue)
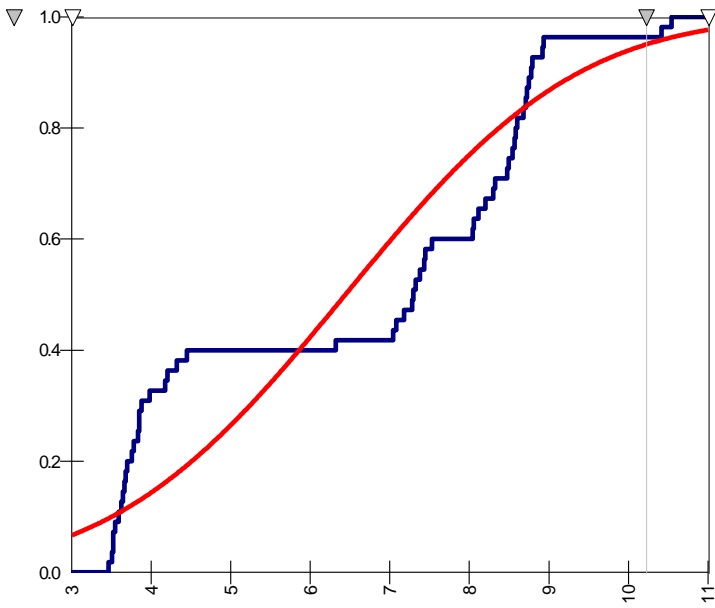
Figure 6 Comparison of modelled *Campylobacter* distribution (red) with $\log_{10}$ cumulative density function for the combined sewage and river water dataset (blue)
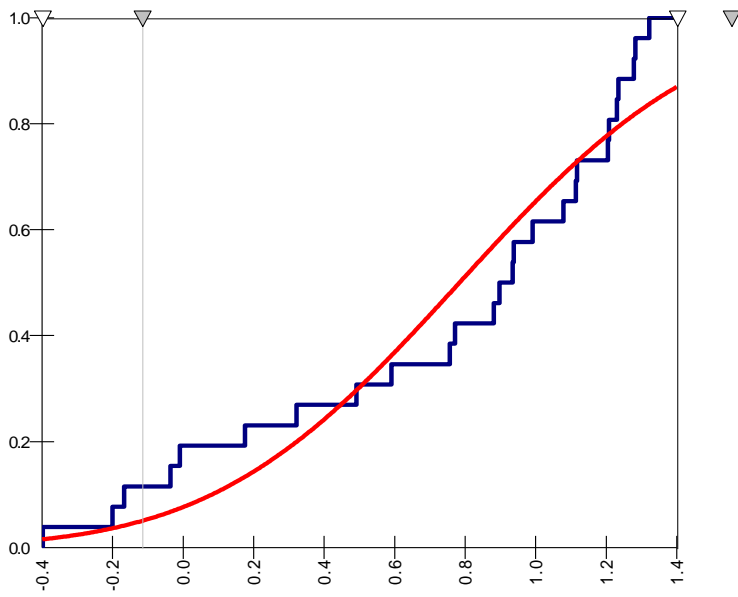
Figure 7 Comparison of modelled *Giardia* distribution (red) with $\log_{10}$ cumulative density function for the river water dataset (blue)
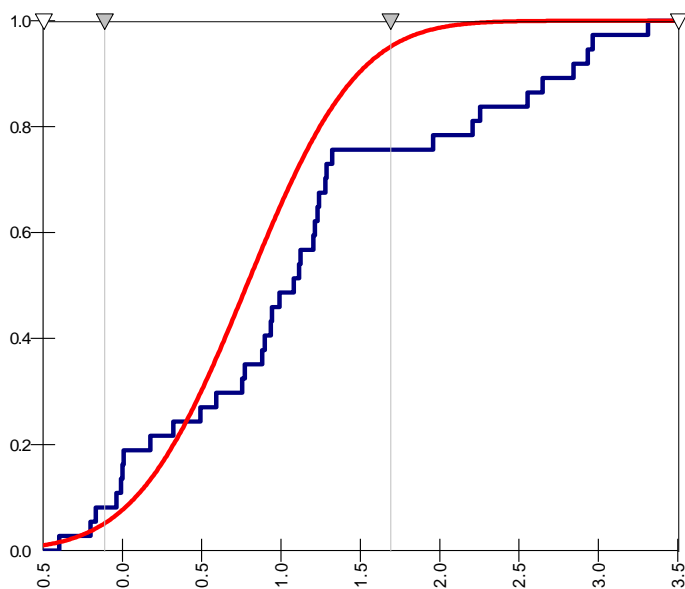
Figure 8 Comparison of modelled *Giardia* distribution (red) with $\log_{10}$ cumulative density function for the combined sewage and river water dataset (blue)

Sensitivity assessment

A sensitivity assessment was undertaken on this model to identify the parameters which most strongly predicted the resulting load at harvest. The rankings of the parameters (Table 4) was determined by summing the number of times the parameter appeared in the sensitivity rankings for load at harvest and $\log_{10}$ load at harvest for all pathogens and indicators modelled, multiplied by the inverse of the rank (i.e. ranked 1 was multiplied by 10).

Table 4 Ranking of most sensitive parameters by regression

Rank	Parameter
1	Harvest interval
2	Use of storage reservoir
3	Inactivation coefficient on vegetables
4	Presence of storage reservoir
5	$\log_{10}$ concentration in source water
6	$\log_{10}$ concentration of faecal coliforms in source water
7	Volume of irrigation water retained
8	Storage interval
9	Concentration in source water
10	Inactivation coefficient in water

The parameter which had the most impact on loads at harvest was the harvest interval, the time between the last irrigation and harvest. Harvest interval was ranked in the top three

for regression sensitivity for all parameters (pathogens and indicators) for log_{10} concentration at harvest, and in the top four for all pathogens for concentration at harvest.

The inactivation coefficients for microorganism in water and on vegetables were also identified as sensitive parameters. For indicators, the log regression sensitivity ranked the relevant inactivation coefficient in water as the second most sensitive parameter, with inactivation on vegetables as third.

Storage of water within a reservoir prior to use had a strong impact on the pathogen concentrations at harvest, with storage reservoir use, presence and storage interval all important factors.

The concentration of pathogens in the water source was one of the most sensitive parameters, with a positive correlation between log_{10} concentration at source and concentration at harvest typically on of the highest ranking parameters for pathogens in the sensitivity assessment. Norovirus, which was modelled with presence/absence based on a correlation with faecal coliforms, had a correlation between concentration at harvest and presence, as well as with concentration at source. Due to the linear relationship between *E. coli* O157 and faecal coliforms, there was a correlation between *E. coli* O157 at harvest and log_{10} faecal coliforms at source.

Log_{10} faecal coliforms per 100mls was ranked highly for those pathogens whose concentrations were predicted based on correlations with *E. coli*, namely, *Giardia, Cryptosporidium, E. coli* O157 and *Campylobacter*.

There was insufficient data available on the storage interval to develop an accurate distribution. Initially, this lack of data was modelled as a uniform distribution ranging from none to six months storage, however, as storage was therefore the most sensitive parameter and the probability of no recontamination within 6 months being improbable the distribution was altered to a lognormal distribution with an average of 10 ± 5 days. The lognormal model provided a significant reduction of the duration of storage, from an average of 90 ± 52 days in the uniform model, which resulted in a reduction in sensitivity of the model to the storage interval and the relevant inactivation rate.

Load of pathogens and indicators at harvest

The results are reported in terms of their distribution, as well as in terms of detection, where the detection limit is assumed to be 1 organism per 100 grams of produce for all organisms and types of produce. The load of pathogens and indicators at harvest were below detection in most cases (Table 5).

Table 5 Summary of loads at harvest (per gram lettuce)

Pathogen	Average	50%	80%	95%	Max	% above detection
Faecal coliforms	0.43	2.0e-14	0.002	0.90	189	16.8
E. coli O157	0.0052	0	1.1e-26	3.1e-4	5.0	2.2
Campylobacter	0.0030	1.2e-17	6.6e-5	0.014	0.79	6.5
Norovirus	1.7e-4	0	9.1e-10	9.0e-5	0.0061	0.4
Giardia	3.1e-5	0	0	2.0e-5	1.3e-2	0.02
Cryptosporidium	92e-5	3.5e-5	1.2e-4	3.6e-4	3.2e-3	0
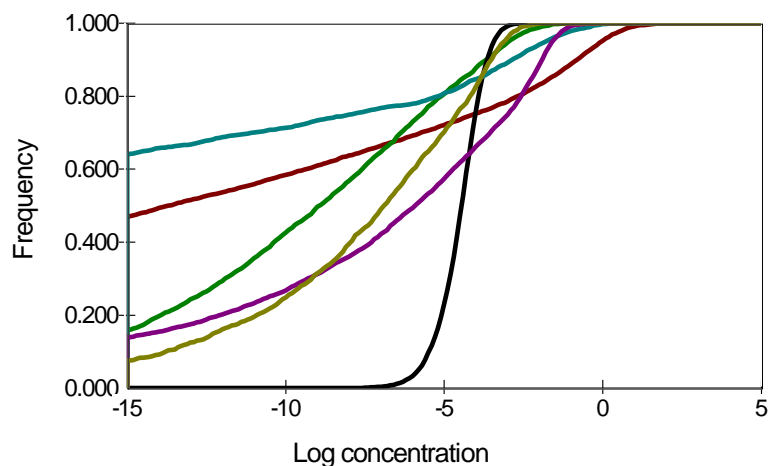
Figure 9 Cumulative distribution for organisms at harvest: faecal coliforms (brown), norovirus (green), *Cryptosporidium* (black), *E. coli* O157 (blue), *Campylobacter* (purple) and *Giardia* (khaki)

Vegetables

Table 6. Distribution of organisms at harvest on different vegetables

Vegetables	Organism	Average	50%	80%	95%	max	% above detection
Lettuce	Faecal coliforms	0.23	9.9e-14	3.5e-3	0.77	177	18
	Campylobacter	0.0026	6.0e-19	9.1e-5	0.013	0.40	6.0
	Norovirus	2e-4	0	1.5e-9	8.7e-5	0.071	0.51
	Cryptosporidium	.5e-5	3.5e-5	1.2e-4	3.2e-4	0.006	0
Broccoli	Faecal coliforms	2.2	3.2e-37	1.3e-21	4.6e-13	18068	0.13
	Campylobacter	9.4e-8	4e-25	1.2e-11	5e-8	1.3e-4	0
	Norovirus	1.2e-7	0	3e-10	2.3e-7	3.6e-5	0
	Cryptosporidium	4.5e-6	1.3e-9	5.3e-6	1.8e-5	6.3e-4	0
Baby spinach	Faecal coliforms	0.50	1.2e-5	0.20	2.3	88	36
	Campylobacter	5.2e-3	6.6e-14	3.6e-3	0.029	0.49	12
	Norovirus	3.6e-4	0	1.4e-7	6.6e-4	7.1e-2	0.8
	Cryptosporidium	1.2e-6	5.4e-5	1.6e-4	4.2e-4	6.3e-3	0
Cucumber	Faecal coliforms	1.4e-8	1.9e-37	6.6e-22	2.8e-13	4.6e-5	0
	Campylobacter	3.2e-7	1.9e-31	1.0e-13	3.7e-9	1.4e-3	0
	Norovirus	5.4e-8	0	2.3e-13	6.7e-9	7.8e-5	0
	Cryptosporidium	9.1e-7	2.7e-7	1.1e-6	3.8e-6	8.6e-5	0

Water quality
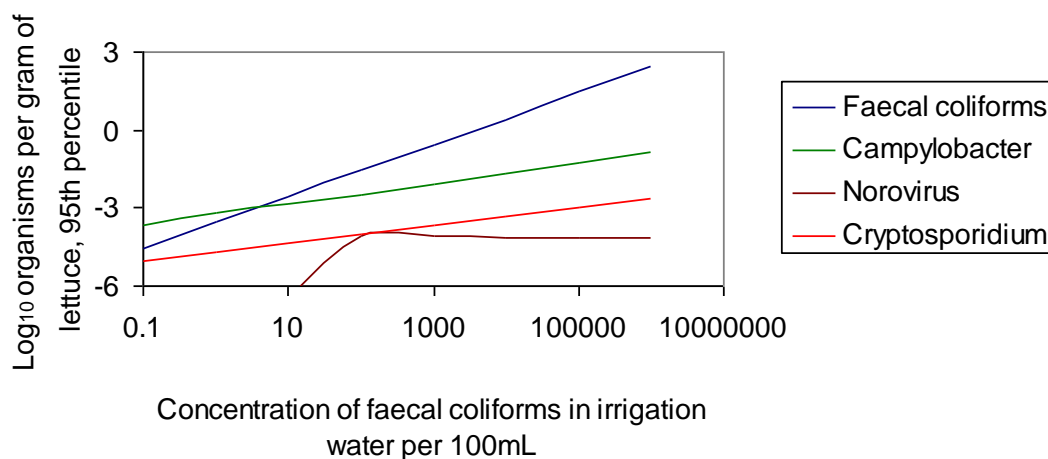
Figure 10 Comparison of $\log_{10}$ loads of the 95th percentile of organisms on lettuce at harvest for different initial indicator concentrations in water

Table 7 Comparison of loads at harvest with increasing faecal coliforms loads (Log$_{10}$ per 100 ml)

Initial log coliform	Average	50%	80%	95%	Max	% detection
Faecal coliforms						
-1	8.80E-06	2.70E-18	1.10E-07	2.60E-05	0.025	0.03
0	4.10E-05	5.50E-17	1.30E-06	2.90E-04	0.0014	0
1	4.20E-04	2.60E-16	1.40E-05	0.0029	0.11	0.46
2	0.0071	1.60E-15	9.90E-05	0.027	20.9	8.7
3	0.041	1.50E-14	0.0018	0.27	9.7	16.3
4	0.6	9.00E-14	0.0077	2.6	1548	19.6
5	4767	3.50E-12	0.13	29.2	4.6E+07	24.5
6	46	3.00E-11	1.5	278	6.1E+04	27.7
Campylobacter						
-1	3.70E-05	5.70E-20	1.50E-06	2.30E-04	0.0033	0
0	1.00E-04	1.00E-19	3.50E-06	6.30E-04	0.013	0.03
1	2.20E-04	1.30E-18	8.70E-06	0.0014	0.027	0.08
2	5.70E-04	1.10E-18	1.90E-05	0.0031	0.087	1.2
3	0.0015	8.10E-20	0.000049	0.008	0.24	4.3
4	0.0042	5.90E-19	9.80E-05	0.021	0.96	8.2
5	0.01	5.10E-17	3.60E-04	0.053	1.5	11.6
6	0.029	2.80E-16	8.10E-04	0.14	6.1	14.6
Norovirus						
-1	5.0E-05	0	0	4.6E-10	0.12	0.1
0	1.5E-05	0	0	0	2.5E-02	0.04
1	6.2E-05	0	0	3.2E-07	5.6E-02	0.16
2	2.1E-04	0	1.6E-09	8.8E-05	1.3E-01	0.5
3	1.9E-04	0	1.2E-09	8.8E-05	0.11	0.4
4	1.7E-04	0	1.1E-09	6.9E-05	0.077	0.42
5	1.9E-04	0	1.5E-09	6.9E-05	0.097	0.47
6	1.8E-04	0	2.0E-09	7.4E-05	0.11	0.43
Cryptosporidium						
-1	2.9E-06	1.6E-06	4.4E-06	9.8E-06	6.1E-05	0
0	5.9E-06	3.3E-06	9.0E-06	2.0E-05	1.7E-04	0
1	1.2E-05	6.7E-06	1.8E-05	4.3E-05	2.5E-04	0
2	2.6E-05	1.3E-05	3.8E-05	9.2E-05	6.7E-04	0
3	5.6E-05	2.6E-05	8.1E-05	2.1E-04	0.0015	0
4	1.2E-04	5.0E-05	1.7E-04	4.6E-04	0.0094	0
5	1.9E-04	1.1E-04	3.8E-04	0.0011	0.03	0.04
6	6.2E-04	2.2E-04	8.1E-04	0.0024	0.048	0.34

Survival
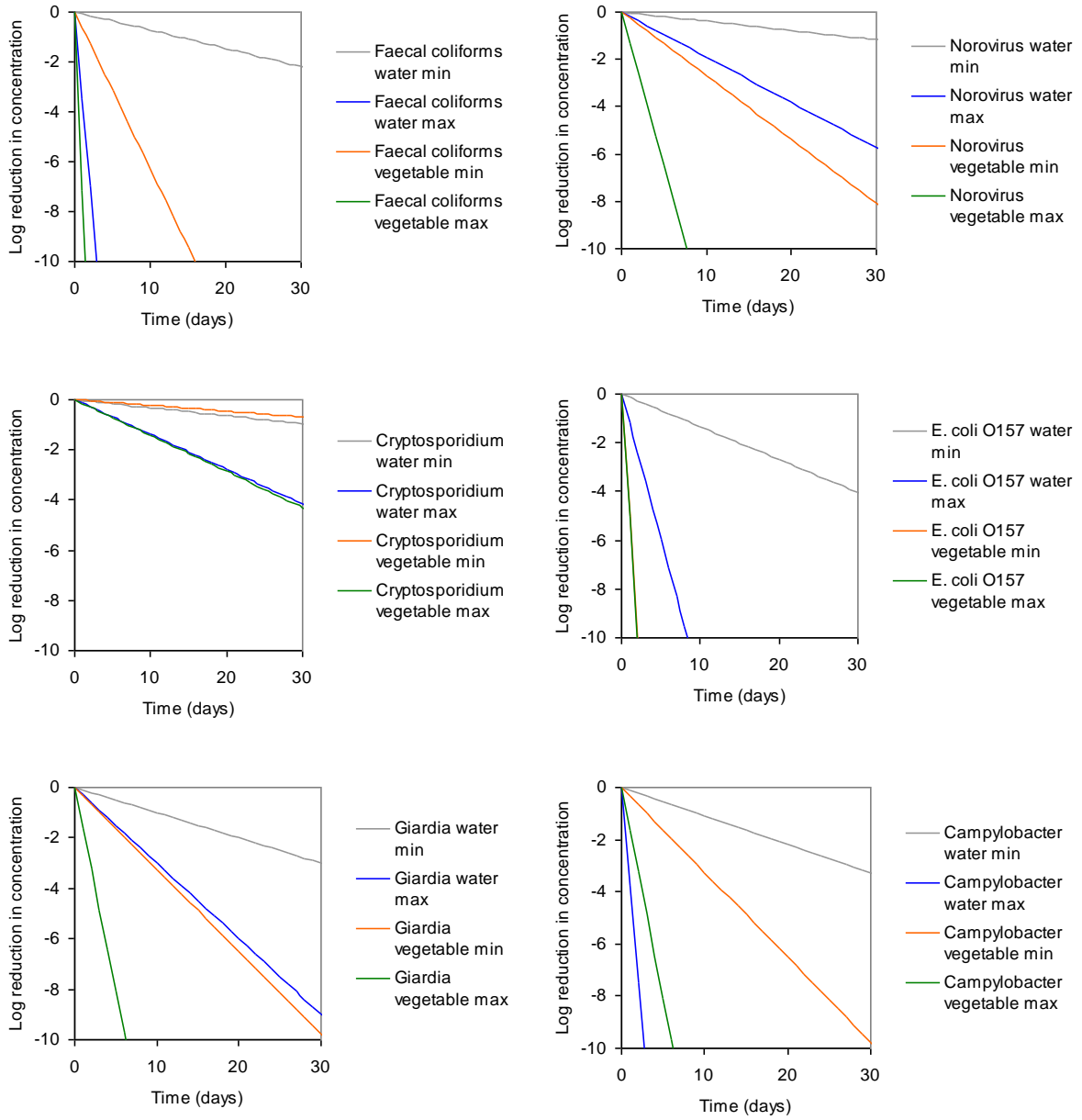
Figure 11 Modelled survival rates in water and on vegetables

Storage
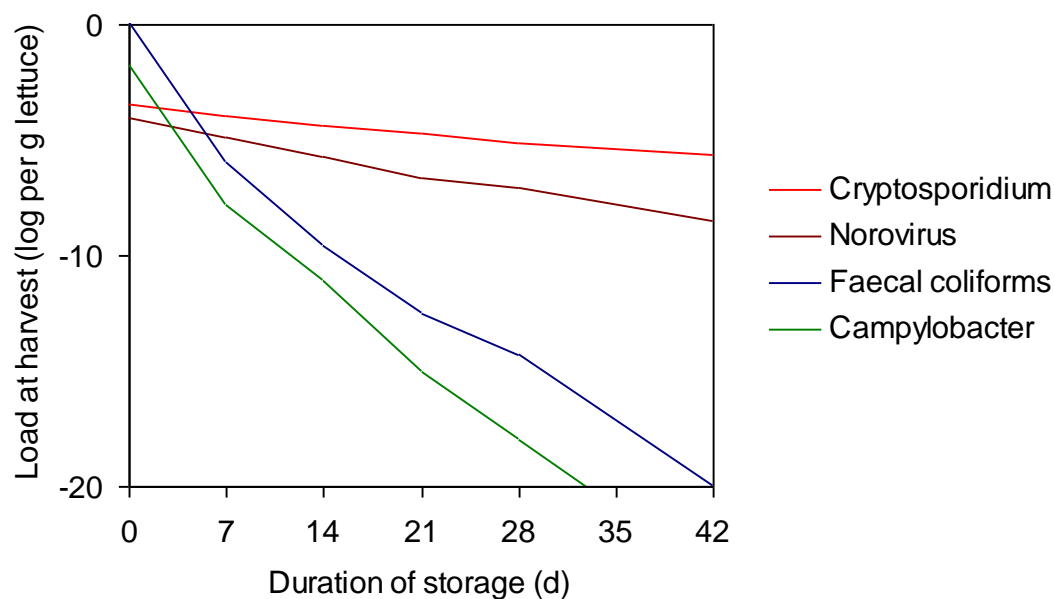
Figure 12 Comparison of log₁₀ loads of the 95ᵗʰ percentile of organisms on lettuce at harvest with storage of water in a reservoir before irrigation

Table 8 Comparison of loads at harvest with increasing duration of storage

Microorganism	Duration (d)	Average	95%	Max	>0.01
Faecal coliforms	0	0.62	1.3	1744	20.6
	7	0.002	1.1E-06	4.3	0.66
	14	7.7E-04	2.8E-10	2.3	0.3
	21	3.6E-05	2.8E-13	1.1E-01	0.073
	28	1.2E-05	4.9E-15	1.4E-02	0.052
	42	1.8E-07	9.2E-21	4.1E-04	0
Campylobacter	0	0.0034	0.016	1.5	6.9
	7	7.5E-06	1.6E-08	6.4E-03	0
	14	1.5E-06	9E-12	4E-03	0
	21	2.1E-07	9E-16	1E-03	0
	28	5.7E-09	1E-18	1E-05	0
	42	2.6E-10	1.4E-24	6.5E-07	0
Norovirus	0	1.8E-04	0.000087	0.068	0.45
	7	3.4E-05	1.4E-05	3.5E-02	0.04
	14	9.3E-06	1.8E-06	5.5E-03	0
	21	3.9E-06	2.2E-07	5.6E-03	0
	28	1.8E-06	8.3E-08	2.3E-03	0
	42	2.5E-07	3.2E-09	3.5E-04	0
Cryptosporidium	0	1.0E-04	3.6E-04	1.2E-02	0.0027
	7	2.9E-05	1.1E-04	2.9E-03	0
	14	1.1E-05	4.3E-05	8.9E-04	0
	21	4.1E-05	1.8E-05	4.2E-04	0
	28	1.8E-06	7.9E-06	1.9E-04	0
	42	4.4E-07	2.2E-06	8.4E-05	0

Harvest interval

Inactivation rate coefficients are generally higher on vegetables than in water, hence, the reduction in pathogens between the last irrigation and harvest, was expected to be slightly higher than in storage.
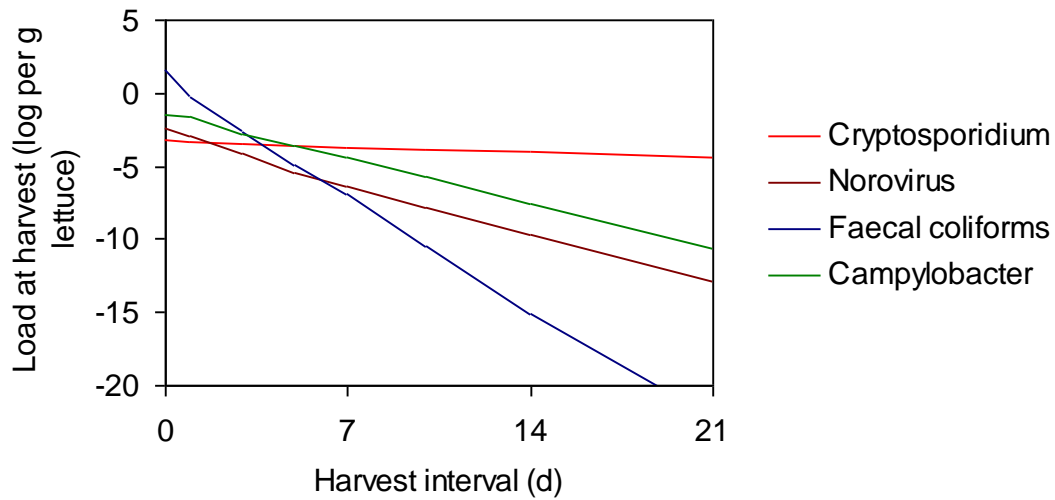
Figure 13 Comparison of log$_{10}$ loads of the 95th percentile of organisms on lettuce at harvest with duration of harvest interval

Table 8 Comparison of loads at harvest with increasing time to harvest

Orgs	Time (d)	Average	95%	Max	>0.01
Faecal coliforms	0	8.7	33.3	4103	89.1
	1	0.16	0.5	69.3	36
	3	9.2E-03	1.9E-03	11.9	2.6
	5	6.6E-02	1.3E-05	575	0.59
	7	0.68	1.3E-07	6404	0.42
	10	2.0E-02	3.7E-11	89.5	0.18
	14	1.3E-01	8.9E-16	909	0.072
	21	2.8E+03	6.9E-23	2.7E+07	0.062
Campylobacter	0	2.4E-02	3.3E-02	1.6	39.8
	1	4.7E-03	2.1E-02	0.68	11.9
	3	4.0E-04	1.8E-03	7.3E-02	0.6
	5	5.6E-05	2.4E-04	3.4E-02	0.05
	7	9.3E-06	3.6E-05	3.0E-03	0
	10	8.2E-07	1.7E-06	6.0E-04	0
	14	1.9E-08	3.0E-08	9.0E-06	0
	21	8.5E-11	2.6E-11	7.6E-09	0
Norovirus	0	1.1E-03	4.5E-03	0.18	3
	1	3.2E-04	1.1E-03	6.9E-02	0.67
	3	3.4E-05	6.7E-05	7.0E-03	0
	5	6.8E-06	3.5E-06	6.4E-03	0
	7	1.3E-06	4.2E-07	8.0E-04	0
	10	1.3E-07	1.5E-08	1.0E-04	0
	14	8.3E-09	2.4E-10	1.1E-05	0
	21	6.6E-11	1.4E-13	6.3E-08	0
Cryptosporidium	0	1.9E-04	6.7E-04	9.0E-03	0
	1	1.6E-04	5.3E-04	9.6E-03	0
	3	1.1E-04	3.7E-04	3.5E-03	0
	5	7.8E-05	2.8E-04	3.8E-03	0
	7	5.7E-05	2.1E-04	5.1E-03	0
	10	3.7E-05	1.4E-04	2.9E-03	0
	14	2.2E-05	9.1E-05	1.8E-03	0
	21	1.0E-05	4.5E-05	9.6E-04	0

Ratios of indicators to pathogens

Table 9 Relationships between the concentration of faecal coliforms and select pathogens

Pathogen	Scenario	Average ± std deviation	Range	Proportion of ratios		
				Equal to 0	Between 0 and 1	Greater than 1
Nv	In water	0.001 ± 0.01	$0 - 0.7$	61	39	0
	Harvest	10^{35}	$0 - 10^{37}$	62	16	12
Campy	In water	0.01 ± 0.04	$0 - 0.8$	44	56	0
	Harvest	10^{35}	$0 - 10^{37}$	45	17	38
Cryptosporidium	In water	0.0001 ± 0.002	$10^{-7} - 0.003$	0	100	0
	Harvest	10^{35}	$10^{-7} - 10^{37}$	0	72	28

Distribution for pfcl/E19
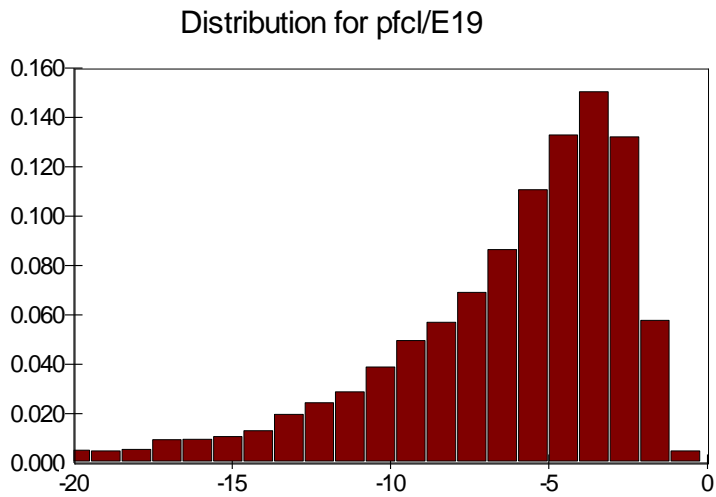
Figure 14 Log$_{10}$ norovirus to faecal coliforms, in water

Distribution for pfcl/G19
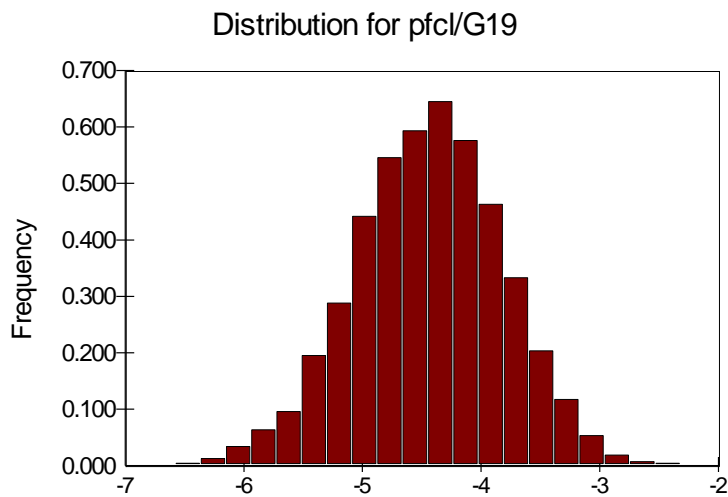
Figure 15 Log$_{10}$ *Cryptosporidium* to faecal coliforms, in water

Distribution for pfcl/J19
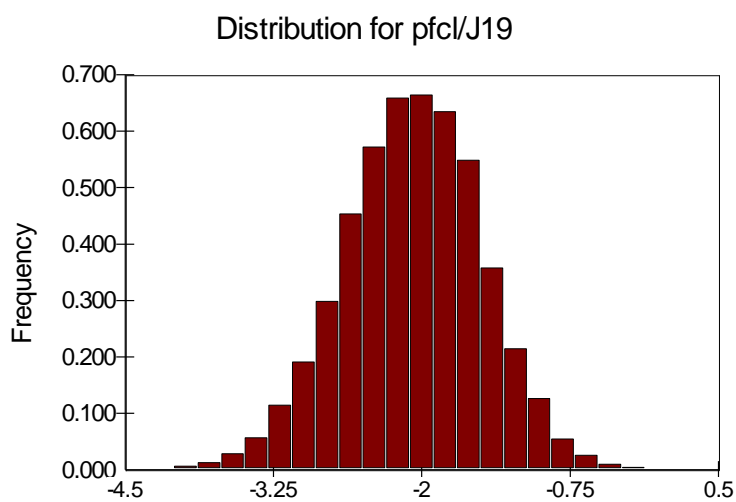
Figure 16 Log$_{10}$ *Campylobacter* to faecal coliforms, in water

Multiple irrigation events
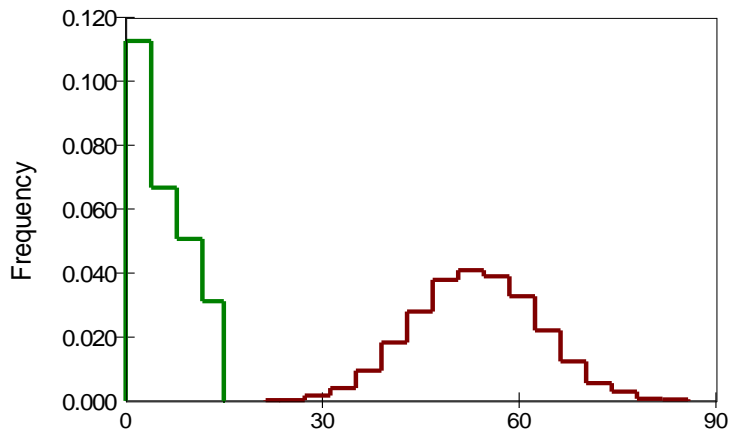
Figure 17 Comparison of the time (days) between harvest and irrigation of the first and last of seven events
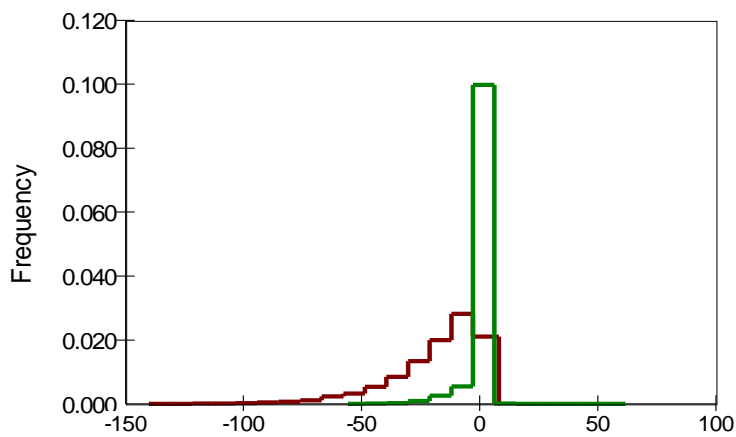
Figure 18 Comparison of log$_{10}$ faecal coliforms load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)
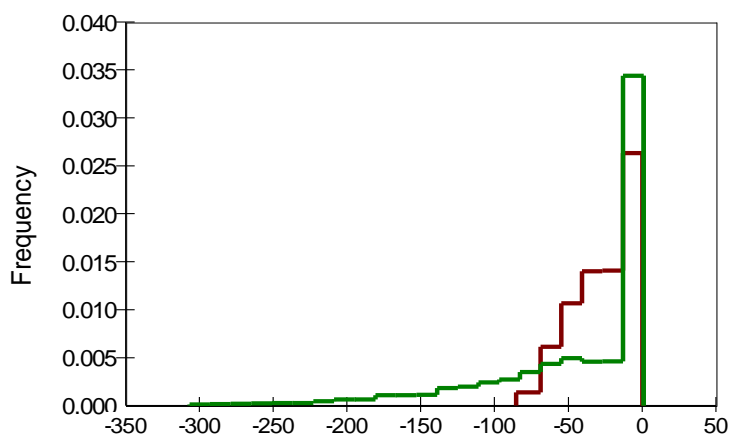
Figure 19 Comparison of log$_{10}$ *E. coli* O157 load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)
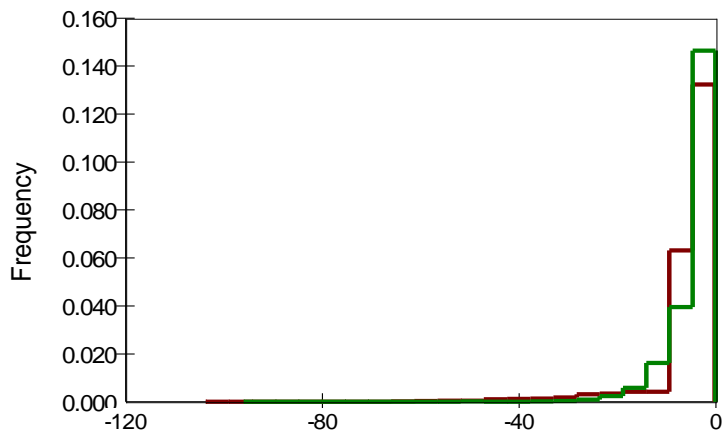
Figure 20 Comparison of log₁₀ *Campylobacter* load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)
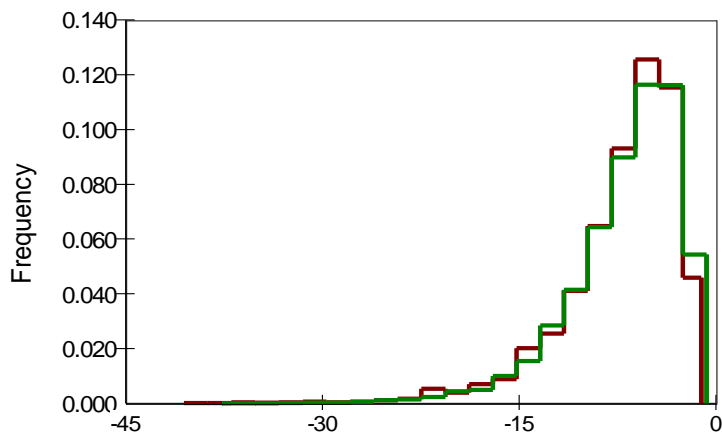
Figure 21 Comparison of log$_{10}$ Norovirus load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)
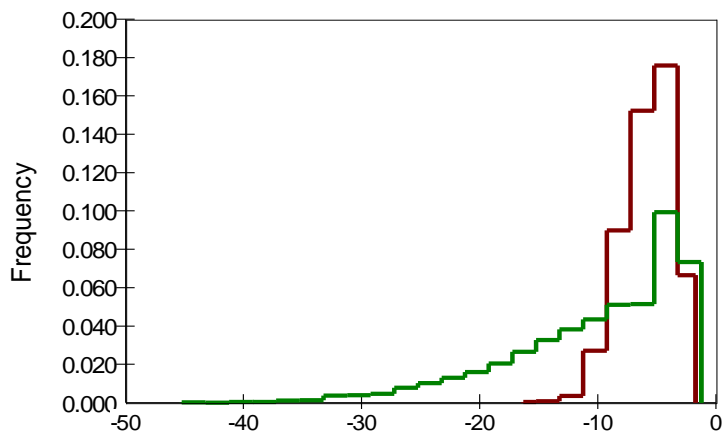
Figure 22 Comparison of log$_{10}$ *Giardia* load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)
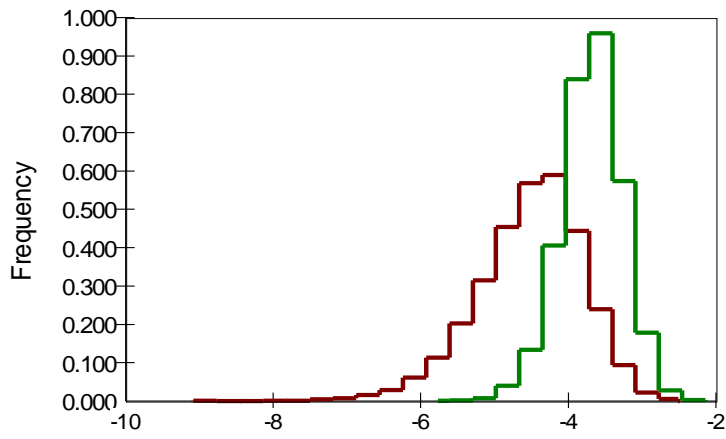
Figure 23 Comparison of log$_{10}$ *Cryptosporidium* load per gram at harvest from the last irrigation (brown) and the cumulative load from seven irrigations (green)

Section 2.
Report to the University of Surrey

B17005 Review of the use of irrigation water in UK agriculture

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Important note
While all reasonable care has been taken in the preparation of this wide-ranging review, we cannot guarantee the accuracy of all the information contained herein and do not accept any responsibility for errors and omissions. No views, particulars or statements of fact should be relied upon. No liability to third parties can be accepted.

Contents

1. Introduction

Irrigation is the application of water to a growing crop. Most usually it is carried out for the purposes of increasing yield and quality, but it may also be used for specialised applications such as frost protection in the case of blackcurrants. Irrigating crops is expensive, but may be cost effective when compared with the potential reduction in returns which can occur through loss of yield and quality with no irrigation. It has increasingly become necessary to irrigate crops to meet the demands of retailers and processors to achieve quality, consistency of product and continuity of supply particularly for fruit and vegetables. Statistics indicate that despite the area of field vegetables having fallen by around a quarter over the ten years to 2005, the area irrigated increased by 18% and output fell less than 1% (Defra, undated).

While this review focuses on the microbiological quality of irrigation water and irrigation practices used in this country, it is important to recognise that large parts of the domestic fruit and vegetable markets are supplied from overseas (Defra, undated). In the case of fruit, home production accounts for about 10% of the total tonnage marketed each year, and for vegetables it is about 55%. Exotic produce, together with supplies to make up for seasonal gaps in home supplies will account for part of these imports. Part will also comprise crops which are competing with domestic output to supply the home market. The proportion of the domestic market being supplied by UK growers has been declining in recent years for some crops in particular such as lettuce, where imports now exceed 50% of total supplies (Defra, undated).

The principal source of data on irrigation is contained in the Defra "Survey of irrigation of outdoor crops" (the Irrigation Survey). Data from the 1995 survey were used in the previous study of agricultural water use and food safety (Groves, Davies and Aitken 2002), but since then, results from two further surveys in 2001 and 2005 have become available (the latter in draft and subject to revision at the time of writing). Both these were carried out for Defra by Cranfield University (Weatherhead and Danert 2002 and Weatherhead and Rivas-Casado 2006). Information from the survey on areas irrigated and volumes of irrigation water applied by crop category are included in Appendix 1.

2. Irrigation practices

This section of the report addresses the current irrigation practices in the UK. These practices will influence how and when water, with any associated pathogens, is applied. This section covers:

- types of irrigation system used
- extent of use of different methods
- irrigation methods used in the horticultural sector
- amount and timing of water applied.

Information on sources of data, areas irrigated and volumes applied, are included in Appendix 1.

2.1 Types of irrigation system used

There are three basic categories of water application practice: overhead irrigation, surface irrigation and sub-irrigation; each with its inherent advantages and hazards affecting its value for any particular situation (Withers and Vipond, 1974). In the context of microbiological risks, particularly for 'ready-to-eat' (RTE) crops, overhead irrigation is of particular interest due to the direct application of water to aerial parts of the plant.

Irrigation methods vary in their potential to introduce human pathogens to crops. Factors influencing this include:

- method of application (overhead or soil applied)
- droplet size, and
- even-ness of application.

Overhead irrigation methods vary in performance on factors which may be relevant to microbiological risks such as droplet size and even-ness of application. Large droplet size may increase the risk of pathogens attached to soil particles being splashed onto the crop, while uneven application may contribute to over-irrigation. Over application can also lead to ponding and soil-splash from machinery.

The types of irrigation system in use in the UK were described by Groves *et al.* (2002) and a fuller description is contained in the Defra Best Practice Guides (2003). These publications do not refer to 'sub-irrigation' which is practiced in certain parts of the country. Nor does sub-

irrigation feature as a separate category in the Defra Survey of irrigation of outdoor crops (see Appendix 1). The Chilled Food Association (CFA) refers to 'underground' irrigation in its microbiological guidance for produce suppliers (Chilled Food Association, 2002), citing this method as an example of lowest relative risk. Key features of the main irrigation application systems are set out below.

2.1.1 Hosereel Systems

Hosereels are by far the most important method used for overhead application. They are flexible and adaptable. They can irrigate fields of varying shapes and sizes and can easily be moved from field to field. They are very popular and are used on more than 85% of outdoor irrigated crops (Weatherhead and Rivas-Casado, 2006). Hosereels can be used with either rainguns or booms.

Rain guns

Rainguns are the main type of irrigators used with hosereel systems. They are less expensive but accuracy and evenness in application (uniformity) is not as good as with booms. They can realistically achieve 80-85% Coefficient of Uniformity (%C of U) but can be as low as 40-60 % (Defra, 1999). This is particularly the case if the equipment is not operating efficiently or is not set up correctly, and if conditions are windy causing drift. Droplet sizes are larger with rainguns than booms and this may give more soil splash.

Booms

Booms can regularly achieve 90% C of U (Defra, 1999), giving greater accuracy in application and so are potentially more beneficial for yield and quality. Another advantage of boom irrigators is the smaller droplet size, reducing impact on the soil (ADAS, 2005) and giving less splash. The advantages of booms in respect of evenness, droplet size and splash may have some advantages over rainguns for potential pathogen loadings on the crop.

2.1.2 Centre pivot and linear move gantrys

These systems are large, highly automated and expensive, although the labour requirement is less than with hosereel systems. Droplet size depends on nozzles but can be very fine, and so have still less risk of splash. Apart from their cost, the disadvantage with these systems is that they tend to require regular shaped fields and they are difficult to transport on public highways (ADAS, 2005). They are most suited to large scale operations.

2.1.3 Sprinklers

Sprinkler systems are relatively accurate and may be set up to give small droplets. They are used in particular on high value horticultural crops, where greater control and automation is needed (Knox *et al.,* 2006), on perennial crops and on some protected crops such as winter lettuce.

2.1.4 Trickle/drip systems

Trickle (sometimes referred to as drip) irrigation waters the roots and not the aerial parts of the crop. Systems can be laid on the surface or buried. They are widely perceived as expensive in terms of capital outlay, operation and maintenance and are more commonly used in the UK for the following types of crops:

- perennial crops where the system can stay in place for a number of years, e.g. orchards, raspberries, strawberries;
- particularly high value crops which can carry the cost of laying and taking up the system e.g. baby sweetcorn;
- crops where the frequency of application can offer particular advantages e.g. runner beans;
- crops in glasshouse production, where the systems employed often use artificial media such as rockwool in place of soil.

In principle, trickle irrigation does have a number of advantages, including improved placement of water and uniformity, and also allows for more frequent timing and scheduling of irrigation. Typical ranges of reported application efficiency for trickle and other systems are given by Knox and Weatherhead (2003). Trickle systems, together with centre pivot/linear move, were cited as the most efficient.

Trickle is used only to a very limited extent in UK field scale production. Knox and Weatherhead (2003) refer to mixed experiences amongst farmers, citing problems with insufficient lateral soil wetting on some soils. In water-scarce environments such as south-east Spain and Morocco trickle systems are used more widely (Monaghan, *pers. comm.).*

2.1.5 Flood and Furrow

Flood irrigation is where water is allowed to flow across the surface of a graded field in a controlled way. Furrow irrigation is a variant of this where water is allowed to flow in furrows across the surface of land which is very level. These methods are used in some

overseas countries, for example the USA. Neither are known to be practiced in the UK, not being mentioned in either the Defra Irrigation Survey or Best Practice Guides. They are not to be confused with uncontrolled and unplanned flooding, which may involve heavily contaminated water.

2.1.6 Sub-irrigation

Sub-irrigation involves the passing of water into the soil at depth until capillary action raises it to the root zone (Withers and Vipond, 1974). As the name suggests, water is delivered to the roots from below. It can be carried out by raising water levels in drainage ditches so that water flows into the outfall pipes of under-drainage systems. It is carried out in areas such as the East Anglian Fens, where water levels are usually managed by the statutory Internal Drainage Boards. We were informed that this technique is used on salad crops such as lettuce, as well as mainstream arable crops.

2.2 Extent of use of different irrigation methods

Methods of irrigation are linked to crop types and overall statistics are strongly influenced by potatoes, which account for the largest share of the irrigated area in England (52% in 2001, 43% in 2005), and where rainguns predominate.

Table 2.1 Irrigation methods (percent of irrigated area) in England 2001 and 2005 (Weatherhead and Danert, 2002; Weatherhead and Rivas-Casado, 2006)

Method of irrigation	(Weatherhead and Danert, 2002)	(Weatherhead and Rivas-Casado, 2006)
Hose-reel and raingun	72%	67%
Hose-reel and boom	16%	19%
Centre pivot and linear	3%	4%
Sprinkler/spray lines	4%	5%
Trickle/drip	5%	5%
Other	<<1	<<1

Source: Defra Irrigation Survey of Outdoor Crops 2005

The 2005 Survey of irrigation of outdoor crops carried out for Defra (Weatherhead and Danert, 2002; Weatherhead and Rivas-Casado, 2006) (Table 2.1) indicates that rainguns are used on around two thirds of the irrigated area, but that booms are becoming more popular, largely at the expense of rainguns. Booms now account for almost 20% of the area irrigated. Trickle irrigation accounted for 5% in both 2001 and 2005.

The 2005 Irrigation Survey reports a drop in the number of holdings and area used for trickle (Table 2.2). It is suggested that this may be partly related to the exclusion of farms irrigating <1ha. from the 2005 survey (Weatherhead and Rivas-Casado, 2006).

Table 2.2 Number of holdings and area (ha) equipped/used for trickle irrigation in England, 1982-2005 (Weatherhead and Rivas-Casado, 2006)

	1982	1984	1987	1990	1992	1995	2001	2005
Number	890	640	490	600	720	820	910	425*
Area (ha)	2040	1550	1330	1420	1970	4120	7040	5444

Source: Defra Irrigation Survey of Outdoor Crops 2005. Up to 1995 data refers to holdings and area equipped for trickle; for 2001 and 2005 data refers to trickle systems used. * Reduction in numbers may be partly related to restriction to farms irrigating 1 ha or more for 2005.

The breakdown of irrigation methods by Catchment Abstraction Management Strategy (CAMS) unit (Table 5, Appendix 1) reveals wide variations. Comparing these figures with those in Table 4, Appendix 1, points to high levels of raingun use of 90-100% in those units where potatoes account for a high proportion of the irrigated area and vice versa. Similarly, the high level of trickle usage (30%) in CAMS unit 58 (Medway) would appear to be associated with the larger share in the area irrigated accounted for by fruit production. Generally though, interpretation of the data is constrained by the large number of cells for which data has been withheld, particularly in the fruit sector. (For details of CAMS units, see Appendix 2).

2.3 Irrigation methods used on particular crops in the horticultural sector

Irrigation practices can be highly specific to individual crops in the horticultural sector and the Defra Irrigation Surveys have a number of limitations for the purposes of this report. They do not provide crop-specific data in the horticultural sectors, grouping crops into broad categories such as orchard fruit, small fruit, and vegetables; they cover only outdoor crops, whereas a number of RTE crops are permanently protected (e.g. tomatoes, cucumbers, peppers); and they are not able to provide figures for the method of irrigation used for the different crop categories.

Information for the salad sector as a whole is given by Tyrrel *et al.* (2006) based on the results of a postal survey carried out for the Horticultural Development Council (HDC) in 2003. Tyrrel presents some of the information from the survey, which was sent to all registered UK growers of RTE salad and leafy crop vegetables. The survey covered 11 species of salad crops (lettuce, spinach, salad onion, other baby leaf salad, celery, culinary herbs, endive, rocket, Chinese leaf, watercress and radish) and the survey data covered 60% of the UK salad crop area. It reported that the majority of UK salad crops (>99%) are irrigated by mobile overhead methods (hose reels fitted with rain guns or booms and portable sprinklers) (Tyrrel *et al.* (2006)). While ADAS (ADAS, 2003) commented that some

growers of salads have found field-scale trickle well suited to their requirements, the survey suggests that this is a very small percentage.

A study of trickle irrigation in England and Wales by Knox and Weatherhead (2003), included estimates of the areas of crops that were trickle irrigated based on data for pipe sales obtained from an industry survey. The study found that the use of trickle is particularly prevalent for soft fruit and runner bean sectors, and to a lesser extent on orchard fruit, sweetcorn and celery. The trickle irrigated areas represented sizeable proportions of the crop area for apples, pears, plums, sweetcorn and celery (20-25%), and cherries and blackcurrants (40-50%), and very high percentages for runner beans, strawberries and raspberries (70-80%). For lettuce and green onions the figures were 5% and 1% respectively.

The use of trickle irrigation on crops such as strawberries and raspberries, which often undergo minimal preparation before consumption, may help reduce the microbiological risk. However, it is not clear whether the use of trickle in these crops is driven by agronomic reasons or concerns about microbial contamination of the crop, or a combination of the two.

Estimates of the proportion of the crop irrigated and irrigation methods used have been obtained from crop specialists in individual crop sectors. As would be expected, indoor salad crops e.g. cress, cucumber, protected lettuce, pepper and tomatoes are all irrigated. High levels of irrigation use – up to 100% of the crop - were also reported for many outdoor salad crops e.g. lettuce, radish and spinach, echoing the findings of the salad survey (see above). In the case of fruit, the proportion of the crop irrigated tended to vary with the type of fruit being grown. The proportion was lowest for orchard (top) fruit (apples, cherries, pears and plums) where the estimates ranged between 5 – 25 %, depending on crop, but with dessert apples and cherries at the higher end of the range. For soft fruit, it ranged from 60 - 90%, with blueberries, blackberries, hybrid berries, raspberries and strawberries at the upper end of the range and bush fruit (blackcurrants, gooseberries and red and white currants) at the lower end.

Trickle irrigation is generally well used for many RTE crops, particularly where protected, and where considerations influencing the choice of method can be very different. Here the irrigation installations can be more permanent and are easier to manage in some respects, even when the crops are annual. Examples of crops to which these types of

consideration apply are tomatoes, cucumbers, and sweet peppers. Sprinklers are reported as being used on indoor lettuce. Salad cress is also grown in glasshouses and is irrigated using booms and mains water with extra chlorination. Overhead irrigation from booms or sprinklers is generally used for outdoor grown salad crops. Being annual crops they tend to be less well suited to trickle irrigation.

Strawberries and cane fruit are largely trickle irrigated. One cultivation method used for strawberries, particularly for the fresh market, uses raised beds covered with polythene sheeting, with trickle irrigation pipework laid under the plastic so leaves and fruit do not come into contact with the irrigation water. There is also a move to using raised beds and ridges with buried trickle irrigation pipes, but without polythene sheeting to reduce pest problems.

Some soft fruit crops are irrigated using different irrigation methods at different times during the growing season. Raspberries and strawberries for example are irrigated using sprinklers at the time of crop establishment, and in the case of some raspberries for frost protection in the spring, but trickle irrigation is used at other times, including during cropping. Sprinklers are used on some blackcurrants for frost protection in spring, and along with some other crops grown for both fresh and processing markets, such as redcurrants, trickle is reported to be more prevalent on fruit intended for the fresh market.

Trickle irrigation and low level sprinklers below the level of the canopy are used for orchard fruit where this is irrigated. Overhead sprinklers are used on some apples for protecting the blossom from frost.

In general irrigation is less prevalent for crops which are normally cooked before eating, although this is not the case for leeks and runner beans which are reported to be largely irrigated. For the root vegetables, onion, parsnip and carrot, the proportion irrigated was reported to be of the order of 60-85%. For brassicas (broccoli, cabbage, cauliflower, and brussels sprouts) it was of the order of 30-40%.

Irrigation methods are also different from those used for RTE crops. Many non-RTE crops are grown at field scale and the methods used tend to reflect the main methods shown in the Defra irrigation surveys, with a predominance of overhead hosereel systems. The share of booms in the survey is increasing (see above) and these are reported to be favoured by vegetable growers giving greater accuracy and reduction in soil splash on product, although they are more difficult and slower to move.

2.4 Amount and timing of water applied

2.4.1 Amount of water applied

The amount of irrigation water applied will influence the potential loading of pathogens on the crop at harvest in the event that pathogens are present in the water. Each crop will have its own typical water requirement, which will be met by rainfall available water from the soil and irrigation, or in the case of protected crops the whole requirement will be met by irrigation. The irrigation requirements for outdoor crops will vary with climatic conditions, with reported requirements varying between those quoted on an 'average' year (Groves *et al.,* 2002) and on a 'dry' year basis (Rees *et al.,* 2003). The amount applied to some crops could more than double in a very dry season (Groves *et al.,* 2002), although comments provided by growers for this study about average and dry year irrigation needs suggest a smaller increase, for example, 50% for outdoor strawberries, 25% for whole-head lettuce and 25-30% for baby leaf salad.

The process of deciding how much water to apply and when to apply it is termed irrigation scheduling. The correct amount of water to apply is influenced by a range of factors, including crop species and variety, growth stage, rainfall, evapo-transpiration and the water availability of the soil. Where irrigation water is contaminated with pathogens, increased irrigation can increase the number of pathogenic organisms applied to the crop. Scheduling for efficiency in water use should help to avoid excess water being applied.

A number of approaches to scheduling are available to support growers' decisions. They broadly fall into the following categories:

* direct techniques, where instrumentation is installed into the soil to measure the soil moisture content
* indirect techniques, involving computer or manual calculations of irrigation requirements, calculating the balance between water being added to the soil and that being lost'
* judgement of the grower based on subjective observation of the weather, the crop and the moisture content of the soil.

The first two categories of scheduling techniques listed above – soil instrumentation and balance sheet methods – are regarded as scientific approaches and often referred to as 'scientific scheduling'.

Table 2.5 Scheduling method (% of irrigated area) 2001 and 2005 (Weatherhead and Rivas-Casado 2006).

Scheduling method	2001	2005
Water balance calculations (manual or computer)	23	25
Direct soil measurement	29	35
Grower judgement not based on measurement	48	34
Other		6
Total	100	100

Source: Defra Irrigation Survey of Outdoor Crops 2005

The 2005 Irrigation Survey indicates a sizable increase in the uptake of 'scientific' scheduling techniques (direct and indirect methods) since 2001, these now being used on 60% of the irrigated area (Table 2.5). Most of this has been due to the uptake of direct soil measurement techniques. Grower judgement accounts for just over one third of the irrigated area.

2.4.2 Timing of irrigation applications and harvest interval

The timing of applications and the period between the final application and harvest can be important factors in the microbial quality of produce due to pathogen die-off. This is particularly the case for spray irrigated RTE crops.

Requirements will be specific to particular crops and even crop varieties. Example irrigation schedules for a range of vegetables are given in the Defra Best Practice Guide for Field Vegetable Crops (ADAS, 2003). The timing of applications will be determined by a range of factors accommodated within the irrigation schedule, including crop growth stage and the weather.

Applications will tend to be more frequent under dry conditions with high evapotranspiration, but depth of rooting and soil type are also likely to affect frequency. Shallow rooting crops, for example baby leaf brassicas, salad onions and spinach, require more frequent applications, as do crops grown on sandy soils with less water availability. On these soils, irrigation has to be more precise and frequent to grow high quality vegetables to a guaranteed harvest schedule (ADAS, 2003).

There may be major differences in the timing of applications according to whether crops are spring, summer or autumn grown, and when they are harvested. Carrots for example may be summer or winter harvested and crops are harvested in sequence to provide continuity of supply over an extended period. In the case of crops maturing during the drier summer months, a large proportion of the total water requirement can be in the later growth stages.

This can be as high as 80% in the last two weeks before harvest in some short rotation crops.

The period between the final application and harvest is referred to as the 'harvest interval'. This varies according to crop and a range of other factors including soil, weather, time of the year when harvested and agronomic considerations. For protected crops, which tend to be trickle irrigated, irrigation will be a semi-continuous process and there may be no distinct harvest interval. Many of these crops are also multiple harvested. In the case of cucumbers for example, these will be irrigated many times a day when grown commercially in rockwool (Monaghan, *pers. comm).*

For outdoor crops, the harvest interval will tend to be shorter under dry conditions with high evapo-transpiration. This was reported by a number of growers to be the case during the hot, dry weather in summer 2006, when irrigation was used to hydrate shallow-rooted salad crops in particular. Where crops are machine–harvested (the majority), the interval may also be influenced by the length of time it takes for the soil to recover its bearing capacity to allow harvesting machinery to operate in the crop wheelings. This will depend on soil type. Crops which can be harvested in autumn and winter such as carrots, cabbage and broccoli may not have been irrigated for a number of weeks prior to harvest. In the case of broccoli, irrigation is not recommended within 3 weeks of harvest as a disease prevention measure, while it was reported that purple sprouting broccoli is irrigated at establishment only.

Groves *et al.* (2002) included "typical" minimum harvest intervals for a wide range of crops likely to be eaten both raw and cooked. For the most part these ranged from less than one day for glasshouse crops to 1-7 days for most outdoor crops, with 0-7 days for strawberry, rhubarb, spinach and outdoor lettuce. Longer typical harvest intervals of 30 days were reported for brussels sprouts and bulb onions, and 90 days for overwintered carrots, as opposed to 7 days for green-top carrots.

Tyrrel *et al.* (2006) reported a more detailed breakdown in the salad sector, which showed a wide range of minimum harvest intervals within each crop. These were generally less than 5 days, and in the case of celery, salad onion, and baby leaf other than spinach, was one day or less for half the respondents in the survey. The longest minimum harvest intervals were 6-10 days for these three crops while for lettuce, spinach and culinary herbs they were longer than 10 days.

2.5 Conclusions

Irrigation is increasingly carried out on RTE crops for quality purposes. However, it is not possible to ascertain the areas of individual crops irrigated from the Defra Irrigation Survey, which gives figures only for the broad categories of vegetables, small fruit and orchard fruit. The Defra survey is also for outdoor crops only, whereas a number of RTE salad crops are grown under cover in glasshouses and some soft fruit crops eg strawberries and raspberries are grown in polytunnels, at least for part of the year.

RTE salad crops grown under cover will clearly be irrigated and crop experts contacted for this study indicated that these are predominantly trickle irrigated.

In the case of salad cress and indoor lettuce overhead irrigation methods are used. In the case of outdoor RTE salad crops, indications are that these are generally irrigated, and a survey of UK salad crops reported that more than 99% are irrigated by mobile overhead methods (Tyrrel, 2006). A study of trickle irrigation (Knox and Weatherhead, 2003) found that trickle was used for a sizeable part (20%) of the celery crop. Sub-irrigation is carried out in the East Anglian Fens, an important salad growing area.

The proportion of soft fruit irrigated varied according to crop, but where irrigated, is largely by trickle. This is also the case for top fruit, although the proportion of the crop being irrigated is substantially less than for soft fruit.

In general, irrigation is less prevalent for crops which are normally cooked before eating. These crops are very often grown at field-scale and overhead methods are generally used.

The duration of the harvest interval varies according to crop and to other factors such as soil, weather, the time of the year when harvested and agronomic considerations. The salad survey reported by Tyrrel (2006) was able to indicate the extent of various minimum harvest intervals applied in 2003. These were categorised from <1 to >10 days and the results indicated that half of the baby leaf (excluding spinach), salad onion and celery crops had harvest intervals of 1 day or less, and that none of the remaining half exceeded 10 days.

3. Sources of water for irrigation

The source of water used for irrigation can be an important indicator of its microbiological quality, with surface water generally considered to pose the highest risk of contamination and mains water the lowest. A limited range of sources is available, and many growers will have little or no choice as to which of these sources is available to them in a particular location.

This section of the report covers:

- water sources available
- sources used for irrigation
- spatial distribution of sources used
- sources used in the horticultural sector,
- timing of abstraction
- storage in reservoirs
- water quality monitoring
- mitigation.

3.1 Water sources available

The two main sources are groundwater and surface water which together account for about 95% of irrigation water use. The remaining 5% is largely accounted for by mains water, recycled water and harvested water.

3.1.1 Surface water

Surface waters are open waters. They include streams, rivers and other watercourses, ponds, lakes and mineral workings such as sand, gravel or clay pits which fill up with water when extraction of minerals ceases and which can then be used for irrigation. They may also include reservoirs and open tanks, whatever the source of the water used to fill them. Surface water quality can be very variable and these waters are generally considered least reliable microbiologically.

Many rivers regularly receive treated sewage effluent, and in summer this can make up a substantial proportion of the total flow. However, discharges of untreated sewage are also permitted during periods of heavy rainfall when the design capacity of combined (foul and surface) sewer networks is exceeded. The frequency of discharges from combined sewer overflows (CSOs) ranges from once in 5 years to 100 times a year (Environment

Agency (EA), *pers. comm.).* The microbial quality of the diluted sewage discharge is likely to be similar to treated sewage (EA, *pers. comm.).* Blockages of sewers can also occur and are more frequent in dry weather when there is no additional dilution from rainfall, unlike the situation when CSOs operate. Blockages can create discharges with higher microbial concentrations (10 – 100 times greater) (EA, *pers. comm.),* and these may cause spikes in pathogen loads in surface waters which may be used for irrigation.

Pollution from livestock also poses a microbiological risk. This can occur from land which is being grazed or receiving manures, particularly following heavy rainfall, and from livestock with access to streams. The contamination of water sources can also result from sporadic pollution incidents due to equipment or management failures.

The number of serious water pollution incidents (defined as "major" or "significant") recorded by the Environment Agency in England and Wales has been declining and was at its lowest ever in 2005, the latest year for which data are available at the time of writing (Environment Agency, 2007). Sewage pollution contributed 185 of the 661 Category 1 & 2 ('serious') incidents, and 3653 Category 3 less serious incidents, the majority being crude sewage (Environment Agency, 2007). Agriculture was responsible for 112 Category 1 and 2 incidents, and 554 Category 3 incidents, although not all agricultural incidents will be from livestock manures and so carry variable microbial loads.

Of the Category 1 and 2 'serious' agricultural incidents, 72% of these were from dairy, beef and sheep farming which tends to be concentrated in the west and north of England, away from the main irrigation areas (Defra, 2005). Pig and poultry farming, which is more evenly distributed but with higher numbers on the eastern side of the country (Defra, 2005), contributed 8% of these serious incidents. Of the Category 3 agricultural incidents, 60% were from dairy, beef and sheep farming.

Work carried out for Defra to identify the average agricultural contribution to faecal indicator organisms (FIO) pollution at bathing waters found that this was 30%, although this concealed significant variations at high and low river flow (Defra, 2007). This was based on the faecal coliforms loads found in three clusters of bathing waters in the North-West, Yorkshire/Lincolnshire, and North Devon and Somerset (ADAS *et al,* 2005). A more recent study showed that the agricultural contribution to FIO loadings pollution typically varied between 25-50% under high river flow conditions (Defra, 2007). There will also be

substantial variation between catchments according to the nature and extent of agricultural activities and the human population.

3.1.2 Groundwater

Groundwater (from boreholes, wells and springs) is generally considered to be of good microbiological quality. Deep groundwater is generally protected by the filtering effect of both the soil and the rock matrix through which it passes, often over a period of decades, although there can be exceptions. These may occur for example, where the sources are shallow, the aquifer is fractured, where contaminating material is discharged close to the borehole or where the wellhead has not been adequately protected or maintained.

3.1.3 Mains water

Mains water quality is closely monitored by the Drinking Water Inspectorate to ensure compliance with drinking water standards. It is expensive but may be appropriate in some situations or as an emergency source. Water companies have no statutory obligation to provide commercial supplies, so the availability of mains water cannot be regarded as guaranteed.

3.1.4 Recycled water

Recycled water is likely to be of variable quality, depending on the process. Water which has been used in packhouses is directed to fields and reservoirs on some units to supplement the main supply if the processing facilities are nearby, although this is not thought to be a common situation (Chilled Food Association (CFA), *pers. comm.).* Re-use of water from sewage treatment works ('wastewater') for crop irrigation is not normally practiced in this country.

3.1.5 Harvested water

Harvested water is the collection of water that would otherwise have gone into drains or soil. It can be collected from fields, but more usually is from areas such as roofs and glasshouses. If collected from hard surfaces used by vehicles, contamination such as by oil is a risk. Whether storage takes place in closed tanks or in open reservoirs may also influence quality.

3.1.6 Reservoirs

Water from any source may be stored in reservoirs prior to use, and this may have significant effects on quality. This could involve improvement or deterioration depending on a range of factors including the quality of the original source, the exposure to contamination

and a range of environmental factors. For example, mains and groundwater would be prone to deterioration, particularly where stored in the open, while surface water has been found to improve.

3.2 Sources used for irrigation

Environment Agency (EA) statistics relating to water abstraction licences submitted to Defra each year include information from spray irrigators in England and Wales on their annual abstractions of ground and surface water (EA, *pers. comm.).* The EA data does not include sources other than surface and groundwater, and for information on minor sources it is necessary to refer to the Defra surveys, which relate to volumes of water applied.

The Defra Irrigation Surveys (Table 3.1) show that surface water and groundwater together supplied between 93-95% of the water applied to outdoor crops in England in 1995, 2001 and 2005. The surface water component of this varied between surveys from 54 to 58% and the groundwater from 36 to 41%. Mains water, rainwater collected from roofs and other surfaces, recycled water and other minor sources have accounted for the balance, which in 2005 was around 5%.

The use of mains water is reported as having fallen markedly from 4.3 - 4.4 Mm^3 (3%) in both 1995 and 2001 surveys to 0.8 Mm^3 (<1%) in 2005. The use of mains water was also low in 1987, another low irrigation use year (Weatherhead (Cranfield University), *pers.comm.)* The 2005 data also suggests that the use of harvested water is falling, but that the use of recycled water is rising. What is included in 'other' is not clear. In some cases it refers to seepage reservoirs (intercepting spring water). However, it is thought that it may include abstractions from reservoirs (most farmers in the 'other' category also had reservoirs) and abstractions from canals and inter-farm transfers (Weatherhead, *pers. comm.).*

Table 3.1 Volumes of water applied ('000m^3) 1982-2005 (Weatherhead and Rivas Casado, 2006)

Source	1982	1984	1987	1990	1992	1995	2001	2005
Surface water	34390	57210	19250	74070	41820	90860	75760	50343
Ground water	16680	32420	11800	50540	28470	61620	47810	38184
Public mains	2040	3840	1100	3860	2620	4390	4300	813
Rain collected			included in other				2050	617
Re-used water			included in other				670	986
Other	1830	3540	1470	5330	2160	4880	710	1939
Total	54940	97730	33630	133790	75070	146960	131300	92883

Source: Defra Irrigation Survey of Outdoor Crops 2005. Surface water includes ponds, lakes, gravel or clay workings, rivers, streams or other water courses. Ground water includes wells, bore holes and springs rising on the holding. Data up to 1992 for England and Wales, data for 1995, 2001 and 2005 for England only.

The ratio of surface water to groundwater is broadly of the order of 3:2 in both sets of statistics (see Table 3.2). Once stored in an open reservoir however, water effectively becomes surface water and the statistics may understate the amount of 'surface water' used for irrigation.

Table 3.2 Share of Surface water and Groundwater 1995-2005 derived from EA Returns and Defra Irrigation Surveys

	EA Irrigation returns		Irrigation surveys	
Year	Surface water		Surface water	
1995	56%	44%	60%	40%
1996	55%	45%	na	na
1997	52%	48%	na	na
1998	51%	49%	na	na
1999	51%	49%	na	na
2000	64%	36%	na	na
2001	62%	38%	61%	39%
2002	57%	43%	na	na
2003	55%	45%	na	na
2004	59%	41%	na	na
2005	na	na	57%	43%

Sources: EA abstraction statistics (EA, *pers. comm.*), and the Defra Survey of Irrigation of Outdoor Crops (Weatherhead and Rivas-Casado, 2006)

3.3 Spatial distribution of sources used

Spatial information on sources is available at regional level from both EA and Defra data. EA abstraction statistics (EA, *pers.comm.)* in Table 3.3 indicate that abstraction for spray irrigation is concentrated in its Anglian Region, accounting for 56% of the total, followed by the Midlands Region with 18%. Surface water sources accounted for 59-60% of abstractions in these regions. Groundwater is the principal source in the North East (70%), North West (7 1%) and Thames Regions (56%).

Table 3.3 Water abstracted for spray irrigation, by EA Region 2004

Region	(M litres/day)	%	Surface (%)	Groundwate (%)
North West	7	3	29	71
North East	11	5	30	70
Midlands	40	18	59	41
Anglian	126	56	60	40
Thames	10	4	44	56
Southern	16	7	69	31
South West	11	5	80	20
Wales*	6	3	66	34
Total	225	100	59	41

Source: EA irrigation returns. * EA Wales. Totals do not add due to errors in rounding.

The Defra Irrigation Survey on usage (Weatherhead and Rivas-Casado, 2006) also gives an indication of the extent of use of minor sources in the different EA Regions and shows that mains supplies feature quite significantly in the Thames (17%) and Southern (7%) Regions (Table 3.4).

Table 3.4 Volumes of water applied by source and EA region 2005 (Weatherhead and Rivas-Casado, 2006)

EA Region	Water Source					
	Surface	Ground	Mains	Harvested	Re-use	Other
North-west	57%	w	w	w	w	w
NE	48%	52%	w	w	w	w
East Anglia	50%	45%	0%	1%	w	3%
Midlands	58%	41%	w	w	w	w
Thames	60%	23%	12%	w	w	w
Southern	72%	19%	7%	w	w	w
South-west	65%	24%	w	w	w	w
Wales*	95%	w	w	w	w	w
Total	54%	41%	1%	1%	1%	2%

Source: Defra Irrigation Survey of Outdoor Crops 2005. * EA Wales. (w = withheld for confidentiality reasons. This occurs where there are only a small number of respondents' data in a cell. Growers are informed prior to participation in the survey that only aggregated data, from which their own responses cannot be identified, will be published.)

The breakdown by CAMS unit available in the 2005 Irrigation Survey (Weatherhead and Rivas-Casado, 2006) indicates that considerable differences exist between CAMS units, and that some units are much more dependent on a particular source e.g. units 15,16, 25, 40, 64 and 90 on surface (Appendix 1). The EA database would also be able to provide data for CAMS units. Data at this level may help to inform a general assessment of the quality of water used in particular geographical areas.

A survey of irrigation carried out in 2001 by the Scottish Agricultural College (SAC) indicated that groundwater was used less in Scotland (15%) than in England, and that surface water was primarily used (85%), with no respondents using public supply (Ioris, 2004). Most irrigation occurs along the East Coast, and around Ayrshire (Ioris, 2004). Sewage effluent has usually been found to be the main source of polluted coastal waters in Scotland, although in the livestock farming dominant area of southwest Scotland, all bathing waters are also potentially impacted by FIOs from farmland (Aitken et al., 2004). Most bathing water 'failures' in Scotland occur in the south west and appear to be associated with high flows following rainfall, with CSOs and run-off both identified as the origin of faecal indicator organisms (Taylor et al., 2004).

3.4 Sources used in the horticultural sector

There is little information on the sources used for individual crops or crop sectors. The Defra Irrigation Surveys are not able to provide any such analysis since some holdings will irrigate multiple crops using water from more than one source (Weatherhead, *pers. comm.).*

An indication of the position in the salad sector in the UK is available from the survey carried out for HDC in 2003 (Tyrrel *et al.,* 2006) (Table 3.5). Even allowing for the fact that this survey included the whole of the UK and not just England as is covered by the Irrigation Survey, it suggests that there may be a greater reliance on surface water in the salad sector than is suggested for outdoor crops as a whole. It is understood that the salad survey included an estimate of the breakdown by water source and irrigated area by salad crop type.

Table 3.5 Sources of water used for irrigation of salad crops and sources used for outdoor crops

Water source	Percentage of Surveyed Salad Area in UK, 2003 (Tyrrel *et al.,* 2006)	Percentage on Outdoor Crops in 2005 Irrigation Survey in England (Weatherhead and Rivas-Casado, 2006)
Surface water	71	54
Groundwater	24	41
Public mains	5	<1
Other	<0.5	4

Crop specialists contacted for this survey indicated that frequent use is made of harvested rainwater for protected crops, there being an obvious link with the availability of large roof catchments. Higher costs for mains supplies and lack of supply pressure are cited as factors contributing to a move away from mains. However, harvested water is not usually available in sufficient quantities, and some topping up is required, usually with groundwater or mains water. For cress, mains water reinforced with additional chlorination is reported to be used.

3.5 Timing of abstraction

The time of the year when surface water is abstracted may be significant from a microbiological perspective, but timing of abstraction is not always within a grower's control. Conditions attached to some abstraction licences define the period during which water may be taken, and may include conditions regarding minimum water levels and flows below which abstraction is not permitted. With the recognised changes to the climate and inevitable implications for rainfall events such prescribed flow conditions are likely to become increasingly prevalent, with emphasis on abstraction being permitted at times of high flows in surface waters throughout the year (EA *pers. comm.).*

Leaving aside rainfall events which may cause both surface run-off from agricultural land and CSOs to operate, water abstracted for reservoir replenishment during winter would generally be expected to be of better quality than water taken in summer when flows are lower. This is because winter flows tend to be higher, giving more scope
for dilution of any pathogen load. Abstraction licence conditions which may tend to increase the proportion of water abstracted after rainfall events causing manure run-off or CSOs to operate could have implications for microbial loads.

Data could not be obtained on the quantities of water abstracted for direct use and storage from the EA returns for the purposes of this study, although the period and purpose of abstraction are in principle available from the EA database subject to the availability of resources for its interrogation (EA, *pers. comm.).*

Some information on timing of abstraction is available from a study of economic instruments for water abstraction for Defra (Risk Policy Analysts, 2000), which found that summer abstraction was higher in the eight catchments surveyed. The study reported that 10% of respondents were abstracting solely during the winter, 3% in winter and summer, and 72% in summer only. 12% were reported as not using their licence, although no reasons were given for this. There are some years when irrigation is not required, such as when rainfall meets crop requirements or when non-irrigated crops are grown). It also found that, of the 40% of survey respondents having reservoirs, two thirds abstracted only during the summer. In large parts of the east and south-east of England the main way of obtaining new abstraction licences in recent years has been through construction of reservoirs relying on high flow winter abstracted water, suggesting the possibility of a shift in abstraction timing since the RPA study.

3.6 Reservoir storage

The most common type of reservoir used for irrigation is off-stream, often surrounded by raised banks to contain the water. Impounding reservoirs, formed by the construction of a dam across a stream, are much less common in the UK.

A reservoir will perform essential, and very often multiple, functions for a grower. It may for example enable an irrigator, who is otherwise unable to obtain supplies, to obtain water at times when flows are high. It may serve as a buffer between different parts of the irrigation system requiring different pressures or help meet irrigation demand at peak times, where the abstraction rate permitted by the licence is not sufficient. Or it may serve as a reserve should direct abstractions from surface or groundwater be limited or suspended by the EA at times of water shortage. Defra's 'Winter Storage Reservoirs' leaflet refers to reservoirs as a source of wildlife and amenity benefits, or as a sporting benefit if a fishery is incorporated into the design (MAFF, 1996).

Reservoirs may influence the microbiological quality of water as a result of changes that occur during storage, and quality may improve or decline, depending on a range of factors. These include the quality of water used to fill the reservoir, environmental conditions

(eg water temperature, UV and pH), the duration of storage and the potential for contamination by wildlife, which may serve to offset pathogen declines. There are thought to be advantages for the storage of surface water in particular, where it provides the opportunity for pathogen die-off and predation. Reservoirs also allow surface water to be abstracted in winter months when river flows are generally higher and when concentrations of pathogens may be lower (apart from when rainfall events cause spikes in microbial loads). Quality considerations are generally secondary to that of water management, although one grower refers to winter storage facilities as a means of ameliorating poor surface water (Tyrrel, 2005).

Evidence for declines in pathogen numbers during storage is provided by investigations carried out into changes in pathogen numbers during reservoir storage for public water supplies. These reservoirs are similar in principle to irrigation reservoirs, although generally larger than those located on farms. One study in the Netherlands reported reductions in enterovirus counts by factors of 400-1000 during storage utilising 3 reservoirs in series with an average residence time of 7 months. (Havelaar *et al*, 1995). Another Netherlands study found reductions in pathogen numbers of 1.7-3.1 log 10 units and was influenced by residence times extending up to 52 weeks (van Breeman *et al*, 1998). It was recognised that the water was exposed to pathogen inputs from wildlife (waterfowl).

Groves *et al.* (2002) found no readily available information on the quality of water sourced from irrigation reservoirs, or on changes in quality during storage, but cited laboratory work regarding the survival of pathogens in water obtained from reservoirs which showed that low temperatures enhanced survival. A research review carried out for the Groves study included a statement by ADAS that *ad hoc* testing of reservoirs indicated a one to two log reduction in faecal coliforms during the three-month summer irrigation period.

One practice cited by Groves *et al.* (2002), was that of reservoir water being released into watercourses to support abstraction in another location. The subsequent abstraction is effectively a direct abstraction from river water, and any benefits of reservoir storage may be lost or diminished. The EA has details of licences which permit this, but considers that the extent of the practice would be hard to determine (EA, *pers.comm.*).

The residence time of water in storage during which pathogen die-off may occur is likely to be highly variable. Some abstraction licences allow filling or topping up of reservoirs during the summer, while others authorise reservoir filling during winter only and/or to periods

when flow or water level conditions are met. A large part of the capacity on some farms may also be carried over to successive seasons, while on other farms, turnover may be more rapid.

The source of water stored in reservoirs is not covered in the Defra Irrigation Survey but it is clear that reservoirs are used to store groundwater, recycled water, harvested water and mains water as well as surface water. Storage can reduce quality of good quality water such as groundwater and mains water, since it becomes vulnerable to contamination from wildlife. Growers may however find it necessary to hold groundwater in surface reservoirs due to restrictive conditions attached to some abstraction licences. These may include abstraction rates set below peak irrigation demand and which may also be vulnerable to restrictions being imposed during periods of drought when growers will particularly need access to water. Similar considerations may also apply to mains supplies.

Wildlife attracted to reservoirs includes wildfowl and other water birds. Gulls in particular, are believed to have a negative impact on water quality. In studies cited by Stuart (2006) for example, 2% of gulls in England were found to be carrying *E .coli* O157:H7 and 12.9% were carrying *Salmonella,* most likely from nearby sewage outfalls in that instance. Growers made reference to conflicting drivers in terms of biodiversity and microbiological quality, and reservoir design was reported as being considered with the EA as a potential way forward to discourage use of reservoirs by aquatic birds (CFA *pers comm.).*

An indication of the usage of water from winter storage reservoirs for the 2005 growing season is available from the 2005 Defra Irrigation Survey (Weatherhead and Rivas-Casado, 2006), although there were partial responses on winter storage reservoir questions (Weatherhead, *pers.comm.).* The survey reported that 30% of the water used came from such reservoirs and that 50% of the reservoir capacity was used in what was a wet year in irrigation terms. The survey also found that 42% of survey respondents had winter storage reservoirs with considerable variation between CAMs units (see Table 7, Appendix 1).

The survey of the salad sector (Tyrrel *et al.,* 2006) provides information on the role of reservoirs in that sector. This found that 37% of the water used on salad crops came from reservoirs, made up of 29% from surface water and 8% from groundwater. Protected crops are not covered by the Defra surveys, but industry experts indicate that some growers

store substantial quantities of roof water in reservoirs or in large covered tanks for crop irrigation.

3.7 Water quality monitoring

Growers indicated that irrigation water quality was monitored to demonstrate due diligence, but were not always sure how to respond to the results of analyses. A variety of monitoring practices is evident.

Target organisms: Most samples were analysed for the faecal indicator organisms *E. coli* and faecal coliforms, although in some cases aerobic colony count, faecal streptococci, *Salmonella* and *Pseudomonas* were also included.

Frequency: The frequency of monitoring varied between growers. In some cases, the minimum of one sample per year is taken. The larger growers contacted employed more extensive and systematic sampling, with repeat samples often at monthly or two monthly intervals. Where timing was given, it was during the irrigation season.

Sampling point: The location of the sampling point also varied with some growers taking samples from the source or reservoir, while others sampled at the irrigator. A few growers sampled at a range of points through their system. Water company monitoring data from a nearby surface water abstraction point is sometimes accessed.

Tyrrel (Tyrrel *et al.,* 2006) reported that data acquired from growers for the HDC salad study, albeit limited, suggest that surface water sources would typically meet the WHO guideline limit of < 1000 faecal coliform bacteria/100ml.

3.8 Mitigation

Growers contacted for this study identified a number of mitigation measures. Certain larger salad growers have begun to use ultraviolet (UV) disinfection to routinely treat water, although growers cited the high cost of this. Chemical treatment e.g. chlorination had also been considered, but there was a perception of consumer aversion to this. The high energy use and environmental impact involved with such treatments would also appear to be an issue with potential wider policy implications.

Growers were also asked what mitigation measures were available in the event of a poor analytical result. Options cited were to stop irrigation, to flush out storage tanks, pipework

and equipment where this was the source of contamination, and to switch source. Testing of produce and where necessary withholding from sale, was regarded as a final fallback by some.

One grower has explained that physical filtration is being evaluated as a water treatment technique, (Tyrrel, 2005). Aeration of reservoirs to improve water quality and the use of floating pumps to minimise abstraction of contaminated sediment were included in other examples cited, along with more general management water practices such as storage, timing of abstractions, use of trickle and management of the harvest interval (Tyrrel, 2005).

The possibility of covering reservoirs to prevent their use by aquatic birds was addressed by Groves *et al.* (2002) who concluded that while this may be appropriate for very small reservoirs, it would prove both technically difficult and potentially very expensive for large reservoirs.

Employing a dual system using higher quality water for more sensitive situations may be a mitigation option for some growers. Groundwater, however, may not always be available. It is not present in some areas, or if it is, it may already be fully committed. It is also likely to be less available in future. Switching to mains water supplies may be an option for some growers, but may not be viable for others for a number of reasons. For example, there may be low mains pressure at times, and commercial supplies may be interruptible during drought periods when growers most need it. The rate of utilisation may also exceed the rate of supply, in which case it will need to be stored prior to application which may then lead to deterioration in quality.

There is no obligation on water companies to provide new supplies for commercial use, and their infrastructure may not be adequate. Use of mains water supplies also involves environmental costs, and water supply and treatment is one of the sectors responsible for the highest greenhouse gas emissions in the UK. Defra has indicated that it would be opposed in principle to the increased use of mains water for irrigation on environmental grounds unless it was demonstrated to be an appropriate and proportionate option (Defra, *pers. comm.).*

Relocating production to a site where water of sufficient quality could be obtained may be a feasible option for some growers, for example for larger growers who rent land,

sometimes over wide areas, and have operations that can accommodate these kind of changes.

3.9 Conclusions

Surface water and groundwater are the two principal sources used for irrigation, broadly in the ratio of 3:2. Together these two sources account for some 95%, with mains water, recycled water, harvested rainwater and other minor sources comprising the remaining 5%.

There is regional variation in water sources used for irrigation, which will in part reflect availability, for example if productive and accessible aquifers are prevalent in the region and are not fully committed. EA statistics show that in the EA's Anglian, Midlands and Southern regions, the main areas where irrigation is practiced, surface water is the dominant source, accounting for 60%, 59% and 69% of irrigation abstractions respectively in 2004. The Defra Irrigation Survey, however, indicates considerable variation between different CAMS units in the same EA region. For example, in those units with the largest areas of irrigated vegetables in the EA Anglian region (units 20, 21 and 24, which account for some 43% of the total area of irrigated vegetables in the survey), groundwater is the main source.

Harvested rainwater is reported to be used for protected crops, topped up with other sources, and mains water with additional chlorination for cress. The survey of outdoor salad crops (Tyrrel *et al.,* 2006) indicated that 71% of the irrigated area used surface water as a source, 41% of which had been stored prior to use.

Water is abstracted for both direct use and for storage. No recent information on timing of abstraction was available for this study, but a study carried out some time ago indicated that a minority of growers (13%) abstracted water in winter, which is likely to have been destined for storage.

Storage reservoirs are used *inter alia* to provide a secure water source, independent of abstraction restrictions at the time of irrigation. All sources of water are used for reservoir storage, although the majority are believed to be used to store surface water. Once stored in an open reservoir, all sources effectively become surface water from a quality point of view. The residence time in storage, which can influence microbiological quality, is not known and is likely to be highly variable, depending on abstraction licence conditions, flows and seasonal demand. Some growers can only fill reservoirs in winter,

while others may do so in summer and winter. In 2005 (a wet year), 30% of irrigation water was reported in the Irrigation Survey as being drawn from winter storage reservoirs. For salad crops, the 2003 survey reported 37% of the irrigated area used water drawn from reservoirs, with 78% of this water from surface water sources.

Irrigation water quality is monitored to demonstrate due diligence, and generally includes analysis for *E. coli* and faecal coliforms. Frequency of monitoring varies from one sample per year to more extensive and systematic sampling. Water samples may be taken at source, reservoir, or point of use, or combinations of these.

4. Future changes in irrigation

Irrigation of RTE crops, particularly vegetables, has been increasing in recent years. Water resources however are limited and for some time there has been little summer surface water available for new licences in almost the whole of central and southern England, and in parts, no winter surface water either (Defra, 2002). Climate change is predicted to further reduce the resources available, and to increase the need for irrigation, Climate change may also increase demand for salad crops and fruit, as may consumer trends towards 'healthier' eating, which it is government policy to encourage.

Demand for water for public supply is expected to increase significantly adding to existing pressures particularly in southeast England. In addition, new policies and legislation are being implemented to address the imbalance of supply and demand and to provide increased protection for natural ecology and biodiversity. These are likely to require additional water being retained to support flows, leaving less water available for abstraction and giving rise to possible cuts in some irrigators' abstraction licences.

This combination of pressures is expected to worsen progressively over a long period and may lead farmers and growers to make changes in their cropping, production areas, irrigation practices and water sources as they adapt to new circumstances. This section looks at the pressures and their likely effects on irrigation. It is set out as follows:

- policy and legislation
- climate change
- potential impact on irrigation and water management practices.

4.1 Policy and legislation
A series of droughts in the late 1980s and 1990s in England revealed a number of problems with both the availability of water for public supply and for maintaining flows and the ecology of rivers. This was addressed in the government policy consultation 'Taking Water Responsibly' (DETR, 1999), and in a further consultation entitled 'Directing the Flow' (Defra, 2002) which established priorities for future water policy based on the principles of sustainable development. Defra is currently developing a new 'Water Strategy' putting climate change at the centre of its policy.

4.1.1 Policies and legislation for demand management

Following 'Taking Water Responsibly', Catchment Abstraction Management Strategies (CAMS) were introduced in 2001 and these are progressively being drawn up for the whole of England. CAMS have the objectives of providing a consistent and structured approach to water resources management, recognizing both abstractors' reasonable needs for water and environmental needs (EA, 2001).

The availability of water resources throughout England and Wales is emerging as part of the CAMS process. Maps produced by the EA in 2000 (Defra, 2002) showed that no further summer surface water was available to be licensed across almost the whole of central and southern England south of Sheffield (EA, 2001), and that no further winter surface water was available in some important irrigation areas in the south and east. The map for groundwater indicated that no further water was available over the majority of south-eastern England. The CAMS process is currently updating this assessment and the overall results are expected to be available later in 2007. A recent EA consultation document classifies much of southern England, extending into the south Midlands and southern parts of East Anglia, as an area of 'serious' water stress where the household demand for water is a high proportion of the current effective rainfall (EA, 2007).

The position emerging from CAMS is that many catchments are licensed for more water to be abstracted than is available, and some are 'over-abstracted' as well as 'over-licensed'. New licences will not be generally granted in these areas, nor in those classified as having 'no water available'. Some reduction in volumes licensed for abstraction will be necessary to achieve a sustainable situation where catchments are over-licensed or over-abstracted (EA, 2001).

Historically, revocation or variation of abstraction licences without the agreement of the licence holder meant that abstractors were eligible for compensation if conditions to their licence were changed. Changes to the law introduced in the Water Act 2003 (Anon, 2003) may make it easier for the EA to keep licensed quantities in balance with the current assessments of the available water resource. Irrigators, however, will be exposed to increased uncertainty regarding their access to water.

The position with regard to trickle irrigation also changed in the Water Act 2003. Hitherto, abstraction licences were not required for trickle irrigation, but from 2008 licensing for trickle irrigation abstractions is planned to be introduced in England. It is anticipated that the

legislation will restrict the growth of trickle where it is being used to avoid licensing, but may benefit it in other situations, particularly if licence trading is taken up, and that trickle irrigation to continue to grow as a proportion of all irrigation (Knox and Weatherhead, 2003).

4.1.2 Policies and legislation for environmental protection

New standards of environmental protection have been established in policies and legislation in recent years. Some of these are likely to require increased quantities of water to be allocated to environmental needs, leaving less available for abstractors, while others will be directed towards improving water quality and are likely to reduce microbiological contamination.

Examples of environmental objectives to be achieved under these policies and legislation are the requirements of the Birds and Habitats Directives for the protection of designated sites and species, and the PSA (Public Service Agreement) target for 95% of Sites of Special Scientific Interest (SSSIs) to be in favourable condition by 2010. Some of these sites are rivers and wetlands at risk from abstraction, and achieving the required objectives for these includes maintaining suitable hydrological regimes. Their catchments are likely to extend substantially beyond the boundaries of the designated sites. Some commentators see the Birds and Habitats Directives as the legislation likely to have most impact on irrigation (Bidwells, undated), although some consider that the impact of SSSIs will be greater than SACs (Jolly, 2007).

Some legislation directly addresses microbiological standards, such as the Bathing Waters, Shellfish and Water Framework Directives, while some addresses other parameters which link to faecal contamination, such as the, Nitrates and Integrated Pollution Prevention and Control (IPPC) Directives. The full implications of these environmental requirements on the availability and quality of water for irrigation are not yet clear.

Bathing Waters Directive

This Directive (CEC, 1976) has recently been revised and stricter microbiological standards are to be introduced (CEC, 2006). It is anticipated that measures to reduce agricultural and sewage inputs may be necessary in some catchments. The quality of irrigation water may be improved where these measures coincide with waters used for irrigation.

Shellfish Waters Directive

Like the Bathing Waters Directive (BWD), microbiological objectives are essential for the achievement of the objectives of this Directive (CEC, 1979). Although the affected

catchments may differ, the measures required are similar to the BWD, and benefits for irrigation waters could arise in the same way.

EU Water Framework Directive

The WFD (CEC, 2000) is a far-reaching piece of legislation covering both qualitative and quantitative aspects of the water environment, and incorporating some existing EU water legislation such as the Nitrates, Shellfish Waters and Bathing Waters Directives. The objective is to achieve 'good ecological status' for surface waters or 'good status' for groundwaters. The first WFD 'Programme of Measures' for achieving this is to be settled by the end of 2009 and put into effect by December 2012.

Measures to address pollutants affecting the ecology of water bodies, such as phosphate, are likely to have an impact on faecal pollution and may reduce pathogen numbers in water. Some agricultural measures are already being implemented in about 60 catchments under Defra's England Catchment Sensitive Farming Delivery Initiative, including installation of fencing and bridges to prevent livestock accessing watercourses. A wider range of measures to reduce levels of contaminants, including microbiological pollution, are under development by Defra at the time of writing. Raw sewage discharges such as from sewer misconnections, are also planned to be addressed under this Directive.

WFD measures to address concerns about river flows and groundwater levels may directly affect the quantities of water available for abstraction from both groundwater and surface water, particularly during summer months when flows tend to be lower. Where this results in higher flows, it should provide increased dilution for microbial pollution entering water bodies.

WFD also sets objectives for water pricing policies, one of which is to provide adequate incentives to use water resources efficiently. The Directive recognises the importance of water pricing and the role it can play in curbing water usage to ensure that water resources are sustainably exploited.

Nitrates Directive

This Directive (CEC, 1991) addresses nitrate from agricultural sources and requires designation of areas vulnerable to nitrate pollution. Currently 55% of England, 3% of Wales, 15% of Scotland and all of Northern Ireland are in areas designated as requiring action

under this Directive. A sizeable extension of the designated areas and more rigorous measures are expected to be implemented in England in 2008.

A component of the strengthened measures aimed at reducing nitrate losses to groundwater and surface water is an extension of the control which limits the overall application rate of organic manures and the timing of slurry and poultry manure applications. This will potentially reduce microbiological loadings in water during periods when applications to land are not allowed ('closed periods') during autumn and early winter. The resultant shift in the timing of applications may lead to higher microbial loadings in run-off and drainage at other times, particularly in late winter and spring, and this will leave less time for pathogen die-off in water abstracted for storage during this period. The extended closed periods requiring slurry and poultry manure to be stored for longer periods will allow greater opportunity for pathogen die-off before application to land.

Urban Waste Water Treatment Directive

This directive (CEC, 1991) is aimed at reducing discharges of nutrients to 'sensitive areas' from larger sewage treatment works. Any effects on microbial concentrations is incidental and varies with the treatment process (see main report).

IPPC Directive

Larger housed pig and poultry units are subject to the Integrated Pollution Prevention and Control Directive (CEC, 1996). The rules applicable to these units set certain requirements for manure spreading which are intended to minimise the risk of water pollution which may also help reduce microbial loadings.

4.1.3   Government policy for diet and nutrition

Improving diet and nutrition is a key feature of the Government's prevention strategy to reduce early deaths from cancer and heart disease. Iincreasing consumption of fruit and vegetables is part of this and the current recommendations are that everyone should eat at least 5 portions of these per day (Department of Health, 2007).

If successful, this policy will lead to an increase in demand for fruit and vegetables, some of which may be met by growers in the UK. Since many of these crops require irrrigation, such changes in consumption may translate into increased demand for irrigation water in parts of the UK where supplies of water are likely to be limited.   In such areas, some of the demand may be met by reallocation of the available water from other irrigated crops,

and there may be some scope for rainwater harvesting where crops are grown under cover.

4.2 Climate change

A major uncertainty in predicting climate change is the level of future emissions of greenhouse gases, and the extent to which these will be controlled. Some predictions look as far as the 2080s or even the next century, but with high uncertainty. Projections for the 2020s have much smaller ranges of uncertainty.

It has not been practical to review the very extensive literature available on climate change and this study has therefore drawn on a report prepared and published by the National Farmers Union (NFU) dealing with the effects on agriculture (National Farmers Union, 2005). The NFU report involved the review of almost 200 publications, together with a number of other publications on climate change and irrigation from Cranfield University, the Tyndall Centre for Climate Change and the former Ministry of Agriculture, Fisheries and Food.

4.2.1 Summary of expected changes to the UK climate

Predictions of the most likely climate change effects include:

- *Temperature.* Temperature increases in the range 0 .1° C to 0 .3° C (low emissions) to 0 .3° C to 0 .5° C (high emissions) per decade are expected. Warming is expected to be greater in summer and autumn than winter and spring, and greater in the south-east than the northwest. The thermal growing season will be extended. Higher temperatures could increase evapo-transpiration and increase the need for irrigation.

- *Rainfall.* A shift is expected in the current pattern from summer to winter. The reduction in summer is expected to exceed the increase in winter, leading to a net reduction in rainfall of up to 10%. As with temperature, the change is likely to be greater in the south-east than in the north-west. Winter rainfall will become more variable, but summer rainfall less variable, especially in the south and west. An increase in the frequency of very dry summers and very wet winters is likely.

- *Relative humidity.* Humidity is likely to increase, but due to the rise in temperature, relative humidity will decrease throughout the year, increasing potential evapo-

transpiration.

- *Soil moisture deficit.* Higher temperatures and evapo-transpiration will increase soil moisture deficits, reduce recharge and flows, and lead to increasingly severe water shortages. Higher soil moisture deficits will increase cracking on clay soils, leading to increased flows by-passing the soil layer and less filtering effects, increasing the risk of microorganisms reaching aquifers (MAFF, 2000).

- *Weather extremes.* The frequency of extreme events is expected to increase, such as droughts, leading to greater demand for irrigation. More intense rainfall events increase the risk of run-off and sewer overflows, and could impact on soil splash.

- *Increase in sea-level.* Sea-level is expected to continue to rise. 57% of grade 1 soils in England are located below the 5 m contour including the Fens, one of the main irrigation areas. Rising sea levels increase the risk of salinity incursion into groundwaters, which could affect supplies of suitable irrigation water.

- *Increased CO_2 concentrations.* It has been shown that increased CO_2 concentrations can lead to increased yields through a fertilisation effect. It is not yet clear whether this will happen on a significant scale in practice. It is thought that the effects of increases in CO_2 and temperature will be broadly neutral.

4.2.2 Summary of potential impacts on agriculture

Impacts are expected to include the following:

- *Crops demanded:* A changing climate may have effects on consumer preferences and hence the types of food growers are required to produce. There could, for example, be an increase in crops eaten raw such as salads.

- *Crops grown:* The changing climate may raise the yield potential for existing crops and allow new crops to be grown. For example, new crops include peaches, apricots and olives. Vines, onions, legumes, sweetcorn and carrots are expected to benefit from the changes. Some existing crops may suffer from the lack of sufficient cold weather in winter, e.g. top fruit and cauliflower, or from conditions which are too hot in summer e.g. salad crops.

- *Irrigation demand:* As soils become drier, crops grown in existing locations will

require additional water. The increases predicted by Downing *et al.,((*2006)), indicate that by the 2020s 'dry' year irrigation demand in the EA's Anglian, Midlands and Southern Regions will increase by 26-29% for vegetables, 35-41% for orchard fruit and 8-9% for small fruit. A study of irrigated horticulture in the Vale of Evesham suggests that climate change would increase 'dry' year water demand by 13% for vegetables, 0-20% for top fruit and 25-29% for small fruit by the 2020s (Knox *et al.,* 2006).

- *Distribution of cropping:* The availability of water for irrigation and the effect of lower soil moisture levels may mean that some existing areas become less suitable for the type of crops currently being grown. This may result in crops being grown in different areas of the country compared to where they are currently produced. Any spatial change in the distribution of irrigated crops may affect the microbiological risk profile of irrigation water available to irrigators.

4.3 Potential impact on irrigation and water management practices

Increasing demand for water, combined with its reduced availability, are expected to be major drivers of future changes in irrigation. Principal responses to these pressures are likely to include increasing the efficiency of water use, concentrating the use of available water on high value crops, and seeking access to alternative and to additional supplies of water.

4.3.1 Increasing water efficiency

Measures identified in this report, and recognised by farmers in studies of adaptation to climate change (Knox *et al.,* 2006) include:

- improving existing irrigation equipment and operating it effectively
- changing to more accurate irrigation equipment
- improving irrigation scheduling
- irrigating at night (subject to crop constraints).

The NFU reported (National Farmers Union, 2005) that a 10% efficiency gain could be achieved from improving overhead irrigation methods, a further 10% through better scheduling, and that a switch to trickle might increase efficiency by 20 to 30% in total.

4.3.2 Higher value crops

Limited availability and increasing cost of water is likely to result in water use increasingly being concentrated on higher value crops, which will include many RTE crops.

4.3.3 Seeking access to alternative and additional supplies

The combination of pressures from increased irrigation requirements and less reliable supplies will require growers to examine alternative strategies. These are likely to include seeking alternative sources, and making more use of winter-abstracted water at times of high flows, although Defra does not envisage that an increase in reservoir capacity is likely to bring supply and demand into balance (Defra, 2002). Water licence trading, simplified by the Water Act 2003, or pooling licences, may enable better utilisation of licensed quantities. At the extreme, it could mean that irrigators move their production to parts of the country such as in the north and west which are expected to be less affected by climate change, although the scope for this will depend on the availability of suitable land in new areas.

Some of these approaches may have a positive effect on the quality of irrigation water used. For example, the increased use of winter storage offers a greater opportunity for pathogen die-off. The use of treated waste-water takes place in a number of countries overseas, including in Europe (European Environmental Agency and WHO 2002).

Surplus winter/high flow water

Surface water abstractions are likely to move increasingly to periods of high flow, generally in winter, with water being stored. However, reliance on stored water (reservoirs) is expensive and is likely to require a degree of certainty about water being available in the future to justify the investment required. The potential of reservoirs was identified by the House of Commons Science and Technology Committee (House of Commons, 2006), which also recognized the cost of such facilities was a major issue. The Committee considered that granting aid to farmers agreeing to reduce summer abstraction was justifiable, noting that reservoirs had been supported by government grants in the past.

Investment in reservoirs is considered to have a payback time in the region of 20 years (Weatherhead *et al.,* 2006), and the change in licensing arrangements whereby time limited licences may not be renewed in the future, or indeed may be revoked, is a concern for growers in this respect. Under the new licensing arrangements, the normal period of a licence will be 12 years with a presumption of renewal. Licences can be issued for up to 24 years where a number of stringent tests can be satisfied, but the legislation also

provides for licences being revoked without compensation where serious or significant environmental damage results from the abstraction and six years notice is given. The business risk associated with investment in reservoirs under the new legislation compared to that previously may mean that some farmers who may have constructed reservoirs may now decline to accept this additional risk.

The question has also been raised of whether constructing reservoirs could sometimes be a 'mal-adaptation' to climate change if (winter) river flows decline (Weatherhead *et al.,* 2006). Lower surface water flows have been modelled in winter as well as summer under some future climate scenarios in some catchments (Weatherhead *et al.,* 2006) as drier soils absorb more rainfall and reduce the contribution to river flows.

Licence trading

The transfer of water from locations where licences are under-used to areas where there is irrigation demand is an option made possible by the new licensing arrangements. The scope for switching may, however, be limited. It is likely to be constrained within local catchments and moving licences downstream rather than upstream may be more favoured for surface water. Using unused licence capacity may also lead to some catchments becoming over-abstracted and this may not be allowed. There are also concerns about the approval of such arrangements if it results in an overall increase in use.

Alternative sources

The scope for switching or augmenting supplies from alternative sources such as mains appears quite limited. Mains water is expensive and water companies have no obligation to provide supplies for this purpose. Using mains supplies for irrigation may also not fit well in Defra's emerging 'Water Strategy' on account of the environmental costs associated with water treatment (Defra, *pers.comm.).*

Water harvesting, the collection of rainfall which has not entered the water resource (groundwater or surface water) does not currently require an abstraction licence, but conventional sources such as from roofs and hard standings are unlikely to produce the volumes required for larger scale irrigation operations. There may be possibilities for harvesting water from land, particularly from soils requiring underdrainage. Clearly, harvesting also requires the construction of storage facilities if worthwhile quantities are to be made available for summer use.

The re-use of municipal waste water from domestic and industrial use after treatment at a sewage treatment works, is often suggested as a possible response to pressure on water resources. The World Health Organisation has produced guidance on the appropriate microbiological standards for such water when used for crop irrigation (WHO, 2006). The practice of reusing wastewater is increasing in EU countries, primarily to alleviate the lack of water resources in certain regions such as southern Europe (European Environmental Agency and WHO 2002) and it is also used in Sweden, where it is stored for 3 months to reduce bio-hazards before being used for irrigation (Johnson, 2006).

The safe use of lower quality water for irrigation is being addressed by an EU funded project, SAFIR, which is currently investigating ways of using such water for irrigation of vegetables, including the development of novel treatment and application technologies. UK participating organisations are the Natural Environment Research Council (NERC) and the London School of Hygiene and Tropical Medicine. SAFIR is intended to ensure a sustainable use of water resources by taking pressure off and protecting high quality supplies required for drinking by using lower quality water (eg wastewater), and at the same time ensuring the production of safe and high quality vegetable crops. Recent research and technological advances are to be combined in hardware and management tools, including a prototype small-scale water treatment plant, improved irrigation equipment, new single crop irrigation management systems (including decision support) and an assessment of the food safety and farmer health risks of the improved irrigation system (SAFIR, 2007).

The re-use of waste-water was considered in the House of Commons Science and Technology Select Committee Report (House of Commons, 2006), which recognized there may be a problem with the public attitude towards water re-use and cited the view of Dr Paul Jeffrey of Cranfield University that "any sub-potable quality water is viewed with suspicion by the public". A study by Weatherhead *et al.*, (2006), reported that the use of treated water from a primary sewage treatment plant was considered by one farm but abandoned as unfeasible due to difficulties with possible contamination of produce and supermarket quality control.

The re-use of water from other processes on farms, such as vegetable washing, is encouraged but packhouses are often centralised and not necessarily in the vicinity of all of the land where the water is required.

The scale of the potential for re-use of packhouse waste water and treated sewage effluent is considered rather small (Weatherhead *et al,* 2006). There is also the consideration that discharges from sewage treatment works to rivers are an important component of surface water flow to help maintain ecological status during dry periods of the year.

4.3.4 Adaptation responses

Surveys have reported that farmers and growers in different areas have different approaches to obtaining access to more water. In the Vale of Evesham, the preferred methods were found to be using mains water, harvesting water from roofs and land, and re-use of water. Reservoirs were recognised as a viable option but there was a reluctance to invest given short-term economic uncertainty and the changing reliability of local water resources (Knox *et al.,* 2006). In Norfolk, farmers in two catchments preferred individual reservoirs and changing cropping patterns, while in Lincolnshire, one large group of farmers have set up a water transfer scheme while retaining their individual licences, and another group have pooled their licences. Another Lincolnshire scheme involves building a large reservoir to serve a number of tenanted farms (Weatherhead *et al.,* 2006). A reservoir serving a number of farms has also been constructed in north Norfolk (Abram, 2005).

4.4 Conclusions

Climate change is clearly expected to have major effects on agriculture, as well as the availability of water resources for irrigation. A generally drier climate during the growing season, as is currently predicted for substantial parts of the UK, is likely to increase irrigation requirements. However, increasing demand from abstraction for public water supply, arising particularly from demographic changes, is likely to result in increasing competition for water resources, particularly in the south and east of England.

Even without climate change, the management of water resources is itself in a period of change with the new legislation introduced in the Water Act 2003 (Anon, 2003) and the introduction of CAMS. These changes are intended to place the abstraction licensing regime on a more sustainable basis, and enable licensed abstractions to be brought into balance with available resources. Resources currently available for abstraction are likely to reduce as a result of further initiatives and legislation, although the impact of the Water Framework Directive (CEC, 2000) is difficult to predict at this stage of implementation. The scope for alternative sources appears relatively limited.

In addition to these climate and legislative changes, consumers are likely to demand more salad crops and fruits which can be eaten raw and which may require higher quality irrigation water. Options for high quality irrigation water may be restricted: high quality groundwater supplies may be in shorter supply in the future due to reduced recharge and competing demands; and mains water may be less available for irrigation. The EU SAFIR project (see above) is seeking to develop water saving irrigation systems and management methods, which include treatment, irrigation and decision support, that allow safe use of low quality water resources for vegetables.

5. Statutory controls (legislation), non-statutory controls and guidance

This section identifies and describes legislation and guidance for growers relating to the control of contamination of produce by pathogens in irrigation water. It is set out as follows:

- statutory controls/legislation
- guidance and protocols available to growers.

5.1 Legislation

There is no food safety legislation in the UK which specifically refers to irrigation water *per se*, although water quality is referred to in EU Food Hygiene Regulation 852/2004 Annex 1 (see below). Irrigators are however subject to legislation governing the safety of the final product introduced in both the UK and Europe.

5.1.1 Food Safety Act 1990 (Anon, 1990)

This Act establishes offences of rendering food injurious to health, selling food not of the nature or substance or quality demanded and falsely describing or presenting food. It provides for the defence of due diligence if defendants can prove they have taken all reasonable precautions and exercised all due diligence to avoid committing an offence. This defence has had a marked effect on the way retailers manage risk to their brands through the food chain (Monaghan, 2006).

5.1.2 EU General Food Law Regulation (178/2002)

This lays down the general principles and requirements of food law. It establishes that food business operators (which include primary producers) have a duty to ensure that food satisfies the requirements of food law relevant to their activities. The rationale for this is that the food business operator is best placed to devise a safe system for ensuring the food it supplies is safe (Standing Committee on the Food Chain and Animal Health, 2005). It also creates legal responsibilities for safety, traceability and withdrawal, recall and notification to competent authorities of unsafe food.

5.1.3 EU Food Hygiene Regulation (852/2004)

Primary producers are subject to the requirements of Annex I of Regulation (EC) 852/2004. Annex I, II(2) of that Regulation establishes the over-arching requirement that a primary producer is to "As far as possible, ... ensure that primary products are protected against contamination, having regard to any processing that primary products will

subsequently undergo." Although primary producers are not required to put in place HACCP (Hazard Analysis and Critical Control Point) procedures, growers do need to follow good hygiene practice and manage their operations in a way that controls food safety hazards (Food Standards Agency, undated). They also need to demonstrate that food safety measures are in place (Food Standards Agency, 2005).

The Regulations require food business operators producing plant products "to use potable water or clean water whenever necessary to prevent contamination;" (Annex 1, 5 (c)). "Potable" is defined as "Water meeting the minimum requirements laid down in Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption (CEC, 1998); "clean water" is defined as "Water that does not contain micro organisms, harmful substances or toxic marine plankton in quantities capable of directly or indirectly affecting the health quality of food." (Food Standards Agency, 2006).

Certain provisions of the hygiene legislation are included in the cross compliance obligations, (Defra, 2005; Defra, 2006) which farmers receiving the Single Farm Payment under Common Agricultural Policy (CAP) Reform are required to follow (EC 1782/2003).

The Regulation provides for the development of guides to good hygiene practice and the control of hazards in primary production to assist producers in complying with the legislation. In the UK, guides have been proposed for fresh produce and horticulture. It is understood that as at the date of writing, these have not progressed beyond the proposal stage.

The Microbiological Criteria for Foodstuffs (EC Regulation 2073/2005) provides criteria for sprouted seeds along with products such as pre-cut fruit and vegetables, pasteurised fruit juices and carcases, which apply at the end of processing (process hygiene criteria) and when the product is placed on the market (food safety criteria).

5.2 Guidance

There is no official national guidance for farmers and growers setting out best growing practices for food safety. Instead, the guidance considered in this study largely originates from a variety of non-governmental sources linked to the fresh produce sector (see section 5.2.2 below). The situation in the UK differs from that in some overseas countries where there is often official government or government-sponsored guidance on microbiological risks for irrigation and good practices.

The principal source of guidance in this country is from the crop assurance scheme for fruit and vegetables, Assured Produce (AP) in the form of protocols and guidance notes. Some food retailers have also established their own codes of practice and grower protocols for their suppliers, although these are not publicly available.

5.2.1 Guidance from official sources

Food Standards Agency

As the competent authority, the FSA has produced guidance on the requirements of the new food hygiene legislation, explaining the scope of the regulations and how they apply to different sectors (Food Standards Agency, December 2005). It has also published more user-friendly information for producers in the form of a question and answer page on its website and a leaflet entitled 'Food and feed hygiene for farmers and growers – what you need to know' (Food Standards Agency, 2005). These explain in general terms what farmers and growers need to do to comply with the legislation, but do not detail practices which might be used to achieve them.

Defra

Although Defra has a number of publications on irrigation, these tend not to focus on food safety aspects. Defra's 'Irrigation Best Practice Guides', prepared by ADAS (2003; 2005) are essentially technical guides covering water management and methods of application. They each include a section on water quality, but these tend to focus on chemical parameters and plant pathogens. The sections on legislation make no reference to food safety laws, although it should be recognised that these guides were published prior to the introduction of the Food Hygiene Regulations.

The guide for vegetables provides most information on the food safety aspects of irrigation and includes information which does not appear elsewhere in the guidance reviewed. For example, in referring to the need for risk-assessment of water sources, it suggests this should include periods when contamination is most likely, and identifies the problem of obtaining representative samples of river and stream water due to fluctuating bacterial loading. It also refers to river water showing a decline in pathogen loads over time if stored prior to application, whereas in other guidance, surface water sources – including reservoirs - may be classified in the same risk category, regardless of whether water is stored. However, while the guide states that drip irrigation may result in reduced bacterial

loadings, it does not include this in the list of factors to be considered when comparing different application systems. One of the factors it does include is irrigation management, including maximizing night-time irrigation (see also below). It advises that water stored in tanks should be covered to prevent contamination.

Defra also publishes a number of booklets related to irrigation, although none of these discuss microbial food safety aspects directly. Its 'Winter Storage Reservoirs' booklet (MAFF, 1996) includes conservation, amenity and sporting activities as "secondary uses" and "benefits" of reservoirs. No reference is made to potential effects on microbial loadings.

Environment Agency

The EA publication 'Waterwise on the farm' (EA, 2007), published in conjunction with NFU, Defra and LEAF, includes guidance on efficient use of irrigation water which may also have implications for food safety. It encourages using scheduling techniques (which may help to avoid over-application), reusing packhouse water if it is of sufficient quality, and irrigating at night to save water. The advice to irrigate at night differs from recommendations in the USA to apply overhead irrigation in the morning to allow rapid drying and exposure to ultraviolet light to reduce pathogen survival (Rangarajan, 2000).

5.2.2 Guidance from industry and the private sector

Guidance for growers on the control of microbial contamination is available from a variety of bodies with links to the fresh produce sector. Some, such as that produced by some trade bodies to assist members, is voluntary, whereas compliance with assurance schemes protocols (Assured Produce (AP) and EUREPGAP) is mandatory for participants. Some retailers also have their own guidelines as part of their trading arrangements with suppliers. The following guidance was reviewed:

Chilled Food Association

The Chilled Food Association (CFA) represents manufacturers of the majority of chilled prepared food, including fresh produce such as bagged prepared salads. Suppliers to

CFA members are required to develop a HACCP (Hazard Analysis Critical Control Point) plan. To assist growers in the development of HACCP in the field, the CFA published microbiological guidance for growers entitled 'Microbiological Guidance for Suppliers to Chilled Food Manufacturers' (Chilled Food Association, 2002).

Parts of the CFA guidance dealing with water and irrigation have been incorporated into the Guidance Notes to the AP Generic Protocol, including the tables giving examples of relative risks for water sources and irrigation methods. Another table gives examples of relative risks for different types of raw RTE crops (according to whether they are leaf, stem or root).

The CFA goes further than some guidance, for example in providing explanation of risk assessment and where it sits in the overall context of risk analysis and management in the business. It also includes an example of a conceptual decision tree.

Horticultural Development Council

The HDC is a grower-funded statutory body commissioning near-market research, development and technology transfer for the benefit of the UK horticultural industry. All horticultural producers above certain turnover thresholds are required to join and pay a levy of 0.5% of turnover. Membership is open to others on payment of the requisite fee.

HDC has a wide range of publications available to members. One, on hygiene practices to reduce microbial contamination of RTE crops, has practical application to the food safety aspects of irrigation. Another, on the use of slow sand filters for removing plant pathogens from irrigation water by biofiltration, may also have relevance.

The former, entitled 'Keeping it clean' (Horticultural Development Council, 2005) is in DVD form. It works alongside the AP guidelines and takes growers through the stages to be considered to reduce the risk of microbial contamination. It also draws growers' attention to the Irrigation Best Practice Guides published by Defra. To coincide with the launch of the DVD, HDC ran a series of 9 workshops around the country. These explained the rationale for the new AP guidelines, and included a practical approach to risk assessment, together with discussions about pragmatic solutions available to minimise risks. HDC will consider reviewing this material when further scientific information is available, such as from current research it is funding into quantifying the risk of pathogen contamination in field-grown salads through irrigation water (Project FV 292). This is due for completion in 2008 (HDC, *pers. comm.)*.

Fresh Produce Consortium

The Fresh Produce Consortium (FPC) is the UK's fresh produce trade association. It covers, *inter alia,* the distribution and handling of UK produced fresh produce after it leaves the farm gate. Its membership covers the complete spectrum of industry businesses including growers, importers, wholesalers, retailers, distributors, processors, packers, food service companies and other allied organisations.

FPC guidance entitled, "The control of microbial hazards – a produce industry guide" (Fresh Produce Consortium, 1998), which included pre-harvest as well as post-harvest practices. A 1999 version of this guidance was reviewed by Groves *et al.* (2002), who described it as providing "considered and structured advice on irrigation water quality". However, the guidance is no longer available. FPC may re-publish it in 2008 (FPC, *pers. comm.).*

Campden and Chorleywood Food Research Association

Guidelines on the use of HACCP are available from Campden and Chorleywood Food Research Association (CCFRA) (Campden and Chorleywood Food Research Association, 2000). An extract from an earlier version, 'Assured Crop Production – a practical guide to developing a quality management system for primary food production", has been incorporated into an annex to the Assured Produce Guidance Notes (Assured Produce, 2006). The revised edition 'HACCP in agriculture and horticulture' covers foodborne pathogens and includes examples for field vegetables and top-fruit.

CCFRA also produces HACCP documentation software, designed to assist with HACCP record keeping. It uses flowcharting and associated note-making tools with general guidance on HACCP supported by a worked example. It does not provide detailed information and advice on specific hazards and control measures.

Both the manual and the software are commercial products, and have not been reviewed for this study.

5.2.3 Assurance Schemes
The development of quality assurance schemes is one way in which primary producers have responded to the need to reinstate consumer confidence in food safety and to provide due diligence defence (Monaghan, 2006). Assurance schemes require members to comply with protocols. Membership of the relevant assurance scheme is compulsory for growers supplying some customers.

Assured Produce

The AP scheme is a crop assurance scheme for fruit and vegetables. AP estimates that it covers 75-80 % of the fresh produce and potato sector by farmgate value (AP, *pers. comm.)* and as such is the principal source of guidance available to UK growers. Its declared objective is to address the concerns and needs of consumers, retailers, processors and growers for safe food of good quality at affordable prices, whilst maintaining a profitable and competitive UK horticultural sector.

AP establishes standards, which are detailed in its 'Generic Crop Protocol Standards' (Assured Produce, 2006). This is supplemented by 'Generic Protocol Guidance Notes' (Assured Produce, 2006) giving background information to the standards, and also by 50 individual crop-specific protocols for 2007 (Assured Produce, 2006). AP explains that the crop protocols outline current commercially acceptable best practice for each specific crop, although they are not intended to be a "growers' guide". The crops covered in 2007 are listed in Appendix 3.

The Generic Protocol covers the processes involved in crop production from initial site selection up to the farm gate, including produce handling and packing facilities where these are on the farm. It covers quality, environmental and health and safety issues as well as food safety, but explains that food safety, along with health and safety, always take precedence over quality and environmental controls.

Microbiological aspects affecting irrigation do not appear solely in the irrigation section, but in different sections, including General Introduction, Planning and Records, Site Selection, and Irrigation. In the Guidance Notes, they are largely dealt with in a section entitled Microbial Food Safety. Some of the individual crop protocols include microbial aspects, while some refer back to the Generic Protocol. The crop protocols also include a list of questions presented as "Control Points". These comprise the audited part of the of the crop protocol (AP, *pers. comm.).* Some lists include questions relating to microbial aspects.

The AP scheme includes "critical failure points" (CFPs), "strongly recommended" control points and "should" questions, which are to be aimed for as they are considered Good Agricultural Practice. All CFPs must be complied with to attain full member status, and two of these relate to irrigation or the quality of water resources. For "strongly recommended" control points, a percentage compliance (90%) is currently required, but from the

beginning of 2008 these will become "must" standards requiring 100% compliance in order for a participant to gain certification (AP, *pers. comm.).* One of these is that members undertake a Hazard Analysis to identify Critical Control Points in their production process, including *inter alia* any microbial hazards. Statements containing "should" are assessed during the AP assessment, but do not attract a score and their compliance does not form part of the certification/approval decision. Compliance with the standards is audited annually by independent companies.

AP standards have been successfully benchmarked against the requirements of the EUREPGAP assurance scheme (see below). At the time of writing, the current AP Generic Protocol is dated January 2007. New EUREPGAP standards came into effect in 2007 and AP standards are currently being re-benchmarked against the revised EUREPGAP standard (Assured Produce, 2007).

The AP assurance scheme has been evaluated by the FSA's UK Technical Group against the requirements of the new hygiene legislation and is considered to meet them (Assured Produce, 2007). It has been agreed by AP with Assured Food Standards (the umbrella body for UK farm assurance schemes), FSA and LACORS (the Local Authorities Coordinators of Regulatory Services) that enforcement inspections should be targeted at non-assured farms (25% annual inspection rate, as compared to 2% for assured farms) (Assured Produce, 2007).

EUREPGAP (now GLOBALG.A.P.)

The EUREPGAP assurance scheme has been developed at a European level by retailers belonging to the Euro-Retailer Produce Working Group in partnership with agricultural producers. EUREPGAP establishes good agricultural practices and procedures, together with common certification standards. It is primarily designed to maintain consumer confidence in food quality and food safety, but also includes wider environmental, efficiency and health and safety goals. (EUREPGAP changed its name to GLOBALGAP from September 2007.)

The scheme sets out control points and compliance criteria, which are divided into 'major musts', 'minor musts' and 'recommendations'. All 'major musts' have to be complied with, together with a minimum of 95% of the applicable 'minor musts'. No minimum percentage of compliance is set for recommendations.

Rather than there being additional crop-specific protocols as with AP, fruit and vegetables are grouped together under one document in EUREPGAP. The control points and compliance criteria are included in a number of documents, including the 'Fruit and Vegetables' document (EUREPGAP, 2007), the 'Crops Base' document (EUREPGAP, 2007) and the 'All Farms' document (EUREPGAP, 2007).

There are various provisions relating to irrigation. A 'major must' (i.e. mandatory) is that untreated sewage water must not be used and that treated sewage water must comply with WHO guidelines (WHO, 1989; WHO, 2006). The 2007 version includes some new compliance criteria for this control point, which makes clear that growers need to look beyond factors in their own control in assessing the quality of their water supply. This is as follows (with the 2007 addition italicised):

"Untreated sewage water is not used for irrigation/fertigation. Where treated sewage water is used, water quality complies with the WHO published 'Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture' 1989 (WHO, 1989). *Also, when there is doubt if water is coming from a possibly polluted source (because of a village upstream etc.) the grower has to demonstrate through analysis that the water complies with the WHO Guideline requirements or the local legislation for irrigation water ...."*

Compliance is audited by independent Certification Bodies, and certification is based on EN 45011 or ISO/IEC Guide 65. Existing national or regional Quality Assurance schemes that successfully complete their benchmarking process are recognised as technically equivalent to EUREPGAP.

NFU Watercress Association

The Association has a Code of Practice aimed at ensuring hygienic production and includes the microbial quality of water. Compliance is mandatory for members, and is enforced by physical inspection as well as paper audit. Association members represent about 95% of UK production.

5.2.4 Retailers

A number of retailers have protocols for crop production as part of their trading arrangements with suppliers, but details of most of these were not available for the purposes of this study. However, Marks and Spencer's (M&S) 'Field to Fork' code of practice has

been described in the literature (Monaghan, 2006), although it is understood that 'Field to Fork' is being reviewed at the time of writing.

Like crop assurance, retailer protocols include wider issues than food safety. They also vary. Some express requirements in terms of high level objectives, while others provide more information and specify levels of irrigation water quality which should be achieved, for example <1000 faecal coliforms/100 ml. In some cases the requirements can be prescriptive, for example regarding frequency of water sampling.

5.3 Conclusions

While there is no food safety legislation in the UK having direct application to irrigation practices per se, irrigators are subject to legislation governing the quality of water used to prevent contamination and the safety of the final product. Legislation requires, *inter alia,* that growers need to follow good hygiene practice, manage their operations in a way that controls food safety hazards, and demonstrate that food safety measures are in place.

Guidance largely originates from a variety of non-governmental sources linked to the fresh produce sector. The principal source is the crop assurance scheme for fruit and vegetables, Assured Produce. Some food retailers have also established their own codes of practice and protocols.

The situation in the UK differs from that in some overseas countries where there is often official government or government-sponsored guidance on good practices and microbiological risks for irrigation, e.g. Australia.

6. Evaluation of the Guidance

There is no comprehensive set of official national guidance for irrigation and food safety in the UK and growers for the most part are dependent on industry-led guidance. This will largely be through membership of an assurance scheme such as AP or through trading arrangements with their customers.

This section looks at strengths and weaknesses inherent in guidance being delivered in this way, and the extent to which guidance available to growers addresses the hazards.

6.1 Strengths and weaknesses

Both AP and the major food retailers cover a large proportion of the fresh produce market and are in powerful positions to drive change. UK multiple retailers are believed to have an 80% fresh produce market share (Monaghan, 2006), while on the production side, AP estimates it covers 75 to 80% of fresh produce and potatoes measured by farm gate value (AP, *pers. comm.).* The central role and importance of AP is recognized by buyers, many of whom require their suppliers to be members of AP and to comply with its standards. This includes retailers which may also have their own schemes.

Delivery of guidance through an assurance scheme such as AP has the advantage of securing grower 'buy in' to food safety issues and AP, with its 75-80% coverage of fresh produce output, has clearly achieved this to a high level. The importance of farmer engagement appears to have been recognized, and was seen as a key factor in supplier acceptance and implementation of the M & S 'Field to Fork' code of practice (Monaghan, 2006).

Assurance schemes and retailer protocols can provide a framework for independent auditing of compliance requirements. The effectiveness of an audit process in furthering food safety will clearly depend on the aspects of production being audited for compliance, and the required levels of compliance. AP will move to requiring 100% compliance with all standards from 2008, and it will only be the 'should' good practice points that remain outside certification (AP, *pers. comm.).*

At least one major retailer has opted in its own guidelines to require growers to report any non-compliance with microbiological levels specified as needing investigation.

Reliance on a range of industry initiatives such as assurance schemes and retailer codes of practice and guidelines potentially means that not all produce entering the market

will have been produced to the same standard. This is not meant to imply that some product is not meeting food safety needs. However, it does mean that some produce may not have been produced under an assurance scheme or retailer guidelines. The cost of assurance schemes are not always economic for smaller producers (NFU, *pers. comm.),* and smaller growers may be less likely to have trading arrangements with large retailers.

Grower protocols tend to deal with a wide range of crop issues, including efficient use of resources, pesticide management, pollution, health and safety and conservation as well as food safety. This has the advantage of enabling growers to see food safety as an essential component of the whole production process and the make-up of their end product, but a potential downside is that attention to food safety could be diluted. AP does nevertheless make it clear to growers in both its Generic Protocol and the accompanying Guidance Notes, that food safety (along with health and safety) takes precedence over quality and environmental controls. Another consequence of crop protocols dealing with a wide range of issues is that compliance requirements and good practice for irrigation and water quality may be dispersed throughout the scheme documentation.

An assurance scheme with widescale coverage such as AP would appear to have a clear advantage in communicating guidance to the industry and encouraging its take-up. AP's guidance is also freely available on the internet and so has the potential to influence non-members. This is clearly a powerful position from which to influence grower practices, reinforced as it is by its compliance procedures for members. Its system of crop-specific protocols also offers the scope to tailor guidance more closely to individual crop types and risk.

6.2 Extent to which the guidance addresses the hazards

A number of risk factors relating to irrigation can influence the prevalence of microbial contaminants on fresh produce at the point of harvest. These include factors such as the source of irrigation water and its management, the method of application, the characteristics of the crop to which it is applied, the amount of water applied and the length of time between the final irrigation and harvest (the harvest interval). The extent to which these risks are addressed in the different guidance available to UK growers varies. The following section provides an overview of this, illustrated with examples from particular guidance.

The approach taken in the UK to managing risk from irrigation has largely focused on risk assessment. However, compared with some overseas countries, less explanation is generally available to UK growers as to how they should carry out a risk assessment and the factors to take into account. While the guidance comments on individual risk factors, there is relatively little linking of these and without this it may be difficult for growers to assess the risk posed by particular combinations of factors. The combined risk is unclear and different farmers may come to different conclusions when faced with the same or similar sets of conditions. Some overseas guidance provides decision support tools to aid growers in these operational decisions and it is widely reported that one major retailer is developing a software decision support system for its own growers.

There has been a move towards the adoption of HACCP in some guidance. Hazard analysis in the form of HACCP is strongly recommended by AP, and will become mandatory from the beginning of 2008. Suppliers to CFA members have been required for some time to develop HACCP. In contrast to a high care food factory, the reality of crop production means that it is not possible in many instances to eliminate risk at a critical control point, only to minimise it (Monaghan, 2006).

A feature of the UK guidance is that it tends to be expressed in terms of high level objectives. An example of this is the guidance that "Measures should be put in place to limit the possibility for waterborne contamination and to ensure that water quality is appropriate for its intended use". Little if any supporting guidance is given in many instances and in assessing risk, growers are expected to interpret and assign values to "appropriate" and "contaminated" and to other words which appear in guidance, such as "regular" and "acceptably low".

6.2.1 Crop risk

Crops have different physical and cultural characteristics, and are consumed in different ways. These can impact on their potential to pose a hazard, and some guidance, including that from AP, deals with this by placing crops into different risk categories. This allows the crop risk to be factored into the overall risk assessment and to be used to guide irrigation practice on different crops.

Risk categories are based on various criteria, principally whether the crop is eaten raw or cooked, but also including its physical characteristics and the risk and history of

contamination. Some guidance goes further in categorizing risk, which may help risk management to be more tightly targeted on crops where risk is felt to be greatest.

AP divides crops into three categories, with the overriding proviso that the actual classification should be based on how the crop is used. For example, vegetables that are "always sold to be cooked" would be in the 'low risk' category 3, whereas if they are not, then they will be in one of the other two categories, both of which deal with RTE crops. Most salad crops are placed in 'high risk' category 1, together with raspberries, strawberries and vegetables that can be eaten raw such as cabbage and carrot. Other fruits are generally included in the 'medium risk' category 2 where the criterion of growing clear of the ground is included in the risk profile.

The M&S 'Field to Fork' code of practice includes crops such as carrot, cabbage and broccoli in its second risk category (Monaghan, 2006). These are crops which may be, but which are not always eaten raw. The CFA takes the approach of categorising crops by end-use (raw RTE, cooked or heat processed) and in the case of RTE crops by their crop form (whether baby leaf, (included as an example of highest relative risk), other leaf, stem or root).

6.2.2 Water
The guidance also includes a range of other points for growers to implement or consider regarding water quality, examples of which follow.

Risk assessment for irrigation water is included in some guidance. In the case of AP, a risk assessment to include the quality of water resources is a CFP requiring compliance for new sites. An annual risk assessment on which to base analysis of sources of water and which considers potential microbial contamination is also included as a 'should' question to be aimed for as Good Agricultural Practice. In the case of EUREPGAP, an annual risk assessment for potential microbial pollution of all sources of irrigation water ranks as a 'minor must' for compliance.

The AP and CFA guidance includes examples of the relative risks of various water sources, but being examples, do not necessarily cover the range of risks which may occur within a particular source type. For example, groundwater from deep boreholes is normally higher quality than that from shallow ones. Different types of surface water may also have different risk profiles.

Growers are to implement measures to prevent or minimise contamination, AP and CFA for example citing as sources livestock, other animals, run-off from heavy rain and excess irrigation.

Some guidance draws attention to the risks to the safety of produce from "contaminated water" and to ensuring that water quality is appropriate for its intended use. However, most of the guidance does not contain measurable parameters and standards, and does not inform the grower as to what constitutes "contaminated water", or give guidance as to what is appropriate. So while water testing as a means of assessing water quality is widely recommended, growers may not know how to interpret the results if relying on that guidance alone. AP, for example, refers to levels of faecal coliforms being "acceptable" and "agreed" with customers, while the Defra guide refers to ensuring irrigation water has an "acceptably low" level of microbial contaminants before use.

EUREPGAP and at least one retailer's technical guidance refers to the WHO standard for faecal coliforms of <1,000 cfu/100 ml. Some guidance (e.g. AP and CFA) recommends testing for *E. coli* as an indicator organism in the first instance with additional microorganisms being tested if there is a potential or suspected hazard. No acceptable level is given for *E. coli,* although the CFA recommends that when *E. coli* is regularly detected, a risk assessment should take place. Also, that, where practicable, this water should be applied to lower risk crops, and where not practicable, the risk of contamination of produce should be assessed. The CFA guidance also recommends that trend data should be kept for aerobic colony count (ACC) and significant rises in levels investigated.

It is an absolute requirement for compliance with the AP and EUREPGAP crop assurance schemes that untreated sewage water must not be used. EUREPGAP accepts the use of treated sewage effluent as compliant provided the WHO standard for treated wastewater is met. The EUREPGAP protocol also addresses situations where surface water is polluted by upstream sources, requiring (as a 'major must') that water should comply with the WHO 1989 guidelines for treated wastewater.

Frequency of testing is widely recommended to be based on risk assessment, and constitutes a 'minor must' compliance item in the case of EUREPGAP. The AP Protocol includes a minimum of one sample per year as a 'should' good practice point, and the Guidance Notes go further and suggest minimum frequencies for different source types.

Some guidance reminds growers that testing only reflects water quality at the time of sampling, but the issue of timing of sampling is not widely addressed. The Defra Irrigation Guide draws attention to the fluctuating bacterial loading over time in the case of surface water. AP suggests timing linked to stages in crop growth and flow: at planting (high flow), peak use (low flow) and harvest. These flows may not necessarily correspond with these crop stages.

6.2.3 Irrigation method

The combination of crop type and quality of water source are indicative of the potential risk from growing a crop in a particular location. The choice of irrigation method may influence the risk arising from the crop type in combination with the quality of water being used. Some guidance (AP and CFA) addresses this by providing examples of the relative risk of the different irrigation methods. Guidance also links irrigation method with other risk factors, for example by including statements that the potential for contaminated water to come into contact with the edible portion of the crop should be minimised by good practice such as drip, furrow or underground irrigation. It also explains that water quality may need to be greater for overhead irrigation than drip for high risk crops, or the harvest interval increased.

The use of a decision support tool in these kinds of situations such as is provided in some overseas guidance e.g. Australia (Department for Agriculture Fisheries and Forestry, 2004), could have merit in promoting risk reduction and help avoid the risk of different interpretations amongst growers.

6.2.4 Amount of water applied

Some guidance draws attention to contamination which may arise from "excess irrigation" over and above the crop requirement. The AP protocol strongly recommends that crop irrigation is based on identified need and that scientifically recognized methods of predicting irrigation requirements are used.

6.2.5 Harvest Interval

The results of risk modelling techniques being developed for this review indicate that harvest interval is potentially one of the most important factors in pathogen loading on produce at harvest. Harvest interval is addressed in some guidance by stating that the time gap between irrigation and crop harvesting should be "maximized".

Harvest intervals vary between crops, and whether the maximum interval will be adequate in safety terms may be influenced by the quality of the water and whether it

comes into contact with the edible portion of the crop (i.e. the irrigation method). Leafy salad crops, for example, tend to have shorter harvest intervals than other crops, particularly during dry periods when crops may require misting to hydrate prior to harvest. The AP guidance refers to increasing the harvest interval as a measure to manage the situation where there may be an issue of water quality.

Information as to what would be an adequate harvest interval in food safety terms for any particular set of circumstances (crop, water quality, irrigation method etc) would help in using harvest interval as a means of controlling risk, but at present, this information does not appear to exist.

6.3 Conclusions

UK growers for the most part are dependent on industry-led guidance, largely through membership of a farm assurance scheme or through trading arrangements with their customers. The largest scheme for horticultural produce, AP, and the major retailers are in powerful positions to communicate with the industry, to drive change and to secure grower 'buy in'.

Guidance generally tends to be expressed in terms of high level objectives, often leaving growers to make their own interpretation of what is required in practice. Relatively little information is provided on how they should carry out a risk assessment and the factors to take into account, or measurable parameters and standards, to aid with water monitoring and interpretation of test results.

References

ADAS (2003). "Irrigation Best Practice. Water Management of Soil and Substrate-Grown Crops. A Guide for Top and Soft Fruit Growers." Department for Environment, Food and Rural Affairs, London.

ADAS (2003). "Water Management for Field Vegetable Crops. A Guide for Vegetable Growers." Department for Environment, Food and Rural Affairs. London.

ADAS, CREH and IGER (2005). A desk study assessment of the contribution of agriculture to bathing water failures under the Bathing Water Directive: Phase II. Defra Research Project ESO140.

ADAS (2005). "Irrigation Best Practice. Water Management for Potatoes. A Guide for Growers." Department for Environment, Food and Rural Affairs. London.

Aitken, M., D.W. Merrilees, A. Jones, A.J.A. Vinten and A. Duncan (2004). "Livestock Farming in Bathing Water River Catchments: Risk Identification and Mitigation." Proceedings of SAC and SEPA biennial conference Edinburgh 2004. http://www.sac.ac.uk/mainrep/pdfs/sacsepaproceedings2004.pdf

Anon (1990). "The Food Safety Act." The Stationary Office Limited. London.

Anon (2003). "Water Act, 2003." http://www.opsi.gov.uk/ACTS/acts2003/20030037.htm.

Anon (2007). "Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens." http://www.unitedfresh.org/assets/files/LLG.GAP.Metrics.2007.04.20.pdf.

Assured Produce (2006). "Generic Crop Protocol Standards 2007." http://www.assuredproduce.co.uk/resources/000/245/443/APGenericProtocolstandards2007final27 11 06.pdf.

Assured Produce (2006). "Generic Protocol Guidance Notes 2007." http://www.assuredproduce.co.uk/resources/000/245/444/AP Generic Protocol Guidance Notes 2007.pdf.

Assured Produce (2007). "Assured Produce Newsletter. Spring 2007." http://www.assuredproduce.co.uk/resources/000/237/477/ap news spring2007.pdf.

Assured Produce (2007). "Assured Produce Newsletter. Autumn 2007." http://www.assuredproduce.co.uk/resources/000/248/745/Produce077.pdf

Assured Produce (undated). Crop specific protocols for 50 fruit and vegetable crops 2007. http://www.assuredproduce.co.uk/ap/scheme/standards.aspx

Bidwells (undated). Water Framework Directive and Cross Compliance. Efficient use of water in the farming and food industry, East of England Development Agency.

Campden and Chorleywood Food Research Association (2000). "HACCP in agriculture and horticulture (second edition)." http://www.campden.co.uk/publ/pubfiles/g10 2ed.htm.

CEC (1976). "Council Directive of 8 December 1975 concerning the Quality of Bathing Water (76/160/EEC)." Official Journal of the European Communities L 31, 5.2.1976.

CEC (1979). "Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds." Official Journal of the European Communities L 103, 25/04/1979: 0001- 0018.

CEC (1991). "Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC)." Official Journal of the European Communities **http://ec.europa.eu/environment/water/water-nitrates/directiv.html.**

CEC (1991). "Directive concerning urban waste water treatment, 91/271/ EEC." Official Journal of the European Communities. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX: 31991 L027 1 :EN:NOT

CEC (1992). "Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora." Official Journal of the European Communities **L 206, 22/07/1992:** 0007-0050.

CEC (1996). "COUNCIL DIRECTIVE 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control" http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX: 31 996L0061 :EN:NOT

CEC (1998). "COUNCIL DIRECTIVE 98/83/EC of 3 November 1998 on the quality of water intended for human consumption." Official Journal of the European Communities **L330/32.**

CEC (2000). "Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy." Official Journal of the European Communities **http://eur-lex.europa.eu/LexUriServ/site/en/oj/2000/l 327/l 32720001222en00010072.pdf.**

CEC (2002). "Regulation (EC) No 178/2002 of the European parliament and of the council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety authority and laying down procedures in matters of food safety." Official Journal of the European Communities. **http://eur-lex.europa.eu/pri/en/oj/dat/2002/l 031/l 03120020201en00010024.pdf.**

CEC (2004). "REGULATION (EC) No 852/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004 on the hygiene of foodstuffs." Official Journal of the European Union, **L139 of 30 April 2004.**

CFSAN (2001). Analysis and Evaluation of Preventive Control Measures for the Control and Reduction/Elimination of Microbial Hazards on Fresh and Fresh-Cut Produce. http://www.cfsan.fda.gov/~comm/ift3-toc.html

Chilled Food Association (2002). "Microbiological Guidance for Produce Suppliers to Chilled Food Manufacturers. Kettering." 43 pp. http://shop.chilledfood.org/acatalog/Microbiology.html

Defra (undated). Basic Horticultural Statistics 2006. Fruit details. http://statistics.defra.gov.uk/esg/publications/bhs/2006/fruit%20details.pdf

Defra (undated). Basic Horticultural Statistics 2006. Vegetable details.

http://statistics.defra.gov.uk/esg/publications/bhs/2006/vegetable%20details.pdf

Defra (2002). Directing the Flow. London, Defra. http://www.defra.gov.uk/environment/water/strategy/directflow.htm

accessed 24 April 2007.

Defra (2005). "Livestock distributions in the UK census araes for 2nd June 2003." http://www.defra.gov.uk/animalh/diseases/vetsurveillance/reports/pdf/rp6051.pdf

Defra (2005). "Single Payment Scheme. Cross Compliance Handbook for England. 2006 edition." Ref. PB 11305. London.

Defra (2006). "Single Payment Scheme. Cross Compliance Handbook for England. 2006 edition supplement." Ref. PB 11917. London.

Defra (2007). Water resources and abstraction. Restoring Sustainable Abstraction Programme. London, Defra.
http://www.defra.gov.uk/environment/water/resources/abstraction/index.htm

Defra (2007). The protection of Waters Against Pollution from Agriculture. Cinsulttaion on diffuse sources in England. London. Defra.
http://www.defra.gov.uk/corporate/consult/waterpollution-diffuse/index.htm

Department for Agriculture Fisheries and Forestry (2004). "Guidelines for On-Farm Food Safety for Fresh Produce."
http://www.horticulture.com.au/docs/publications/Guidelines for On Farm Food Sa fety for Fresh Produce Second Edition.pdf.

Department of Health (2007). 5 A DAY introduction.
http://www.dh.gov.uk/en/Publichealth/Healthimprovement/FiveADay/FiveADaygenerali nformation/DH_4069924

DETR (1999). Taking water responsibly. London, Department of the Environment, Transport and the Regions.
http://www.defra.gov.uk/environment/water/resources/abstreview/index.htm

Environment Agency (2001). Managing Water Abstraction. Environment Agency.
http://www.environmentagency.net/commondata/acrobat/mwa english.pdf

Environment Agency (2001). "Running water, whatever the weather." Environment Action June 2001.

Environment Agency (2007). Identifying areas of water stress. Bristol, Environment Agency.

Environment Agency (2007). "Waterwise on the Farm." http://www.environment-agency.gov.uk/commondata/acrobat/geho0307blvhepweb 432285 .pdf.

Environment Agency (2007). Environmental facts and figures. Water Pollution incidents. Bristol. Environment Agency.

EUREPGAP (2007). "IFA - Fruit and Vegetables Modules."
http://www.eurepgap.org/fruit/Languages/English/documents.html.

EUREPGAP (2007). "IFA –All Farm Module (Crops) (FV)."
http://www.eurepgap.org/fruit/Languages/English/documents.html.

EUREPGAP (2007). "IFA –Crops Base Module (FV)."
http://www.eurepgap.org/fruit/Languages/English/documents.html.

Food Safety Authority of Ireland (2001). "Code of Practice For Food Safety in the Fresh Produce Supply Chain in Ireland."

http://www.fsai.ie/publications/codes/cop4.pdf.

Food Standards Agency (2005). "Food and feed hygiene for farmers and growers." Food Standards Agency, London.

Food Standards Agency (December 2005). "FSA Guidance on the Requirements of Food Hygiene Legislation."
http://www.food.gov.uk/multimedia/pdfs/fsaguidefoodhygleg.pdf.

Fresh Produce Consortium (1998). "The Control of Microbial Hazards. A Produce Industry Guide." 38pp. London.

Groves, S., N. Davies and M. Aitken (2002). "A review of the use of water in UK agriculture and the potential risks to food safety." A report to the Food Standards Agency.: 133pp.

Havelaar, A. H., M. van Olphen and J. F. Schijven (1985). "Removal and inactivation of viruses by drinking water treatment processes under full scale conditions." Water Science and Technology **31**(5/6): 55-62.

Horticultural Development Council (2005). "Keeping It Clean." East Malling. http://www.hdc.org.uk.

House of Commons (2006). Select Committee on Science and Technology. Eighth Report. London, House of Commons.

Ioris, A.A.R. (2004). "Allocation and abstraction of water in rural Scotland". Proceedings of SAC and SEPA biennial conference Edinburgh 2004. http://www.sac.ac.uk/mainrep/pdfs/sacsepaproceedings2004.pdf

Johnson, G. (2006). "What's the forecast?" Farmers Weekly. 1 December 2006: 35. Jolly,

T. (2007). "Effects of restrictions." Farmers Guardian. 2 February 2007.

Knox, J. W. (2005). "Onus on water users to improve their efficiency." Farmers Weekly May 6-12, 2005: 50-5 1.

Knox, J. W., J. A. Rodriguez-Diaz, E. K. Weatherhead and K. Khan (2006). Climate change impacts on water for irrigated horticulture in the Vale of Evesham. Environment Agency.

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

MAFF (1996). Winter Storage Reservoirs. Ref PB 2512. London. MAFF

(1998). Air Code. Ref. PB 0618. London: 80pp. MAFF (1998).

Soil Code. Ref PB 0617. London: 66pp. MAFF (1998). Water Code.

Ref PB 0616. London.

Monaghan, J. M. (2006). "United Kingdom and European Approach to Fresh Produce Food Safety and Security." HortTechnology **16(4):** 9-12.

National Farmers Union (2005). Agriculture and Climate Change. http://www.nfuonline.com/documents/Policy%20Services/Environment/Climate%20 Change/NFU%20Climate%20Change.pdf, accessed 16/3/07.

Rees, B., F. Cessford, R. Connelly, J. Cowan, R. Bowell, E. K. Weatherhead, J. W. Know, C. L. Twite and J. Morris (2003). Optimum use of water for industry and agriculture: Phase 3. Environment Agency R & D Report W6-056/TR2. Bristol,

Environment Agency. http://publications.environment-agency.gov.uk/epages/eapublications.storefront/469f1ca4023b1e9a273fc0a802960680 /Product/View/SW6&2D056&2DTR2&2DE&2DE#

Risk Policy Analysts (2000). Economic Instruments in Relation to Water Abstraction. London, Department for Environment, Food & Rural Affairs.

Standing Committee on the Food Chain and Animal Health (2005). Annotated EC Guidance on the implementation of Articles 11, 12, 16, 17, 18, 19 and 20 of

Regulation (EC) No 178/2002 on General Food Law.
http://www.food.gov.uk/multimedia/pdfs/gflreu1782002.pdf

Stuart, D. (2006). Reconciling Food Safety and Environmental Protection: A Literature Review. Salinas, CA. USA, Resource Conservation District of Monterey County.
http://caff.org/policy/documents/ReviewofFoodSafetyLiterature.pdf

Taylor, H.D., J.L. Wallis, J.E. Ebdon and J.L. Caplin. (2004). "Faecal Source Tracking as a Tool for Agricultural Pollution Management". Proceedings of SAC and SEPA biennial conference Edinburgh 2004.
http://www.sac.ac.uk/mainrep/pdfs/sacsepaproceedings2004.pdf

Tyrrel, S.F. (2005). "Water Quality - an issue for irrigators?". UK Irrigation 33: 31 - 32

Tyrrel, S. F., J. W. Knox and E. K. Weatherhead (2006). "Microbiological water quality requirements for salad irrigation in the United Kingdom." J Food Prot 69(8): 2029-35.

van Breemen, L. W. C. A., H. A. M. Ketelaars, W. Hoogenboezem and G. Medema (1998). "Storage reservoirs - a first barrier for pathogenic microorganmisms in the Netherlands." Water Science and Technology 37(2): 253-260.

Weatherhead, E. K. and K. Danert (2002). Survey of irrigation of outdoor crops in 2001 - England. Cranfield University, Silsoe.

Weatherhead, E. K., K. J.W., d. V. T.T., R. S., G. J., A. N.W., O. N., H. K., S. C., S. A., C. D., W. C., B. S., H. J. and C. B. (2006). Sustainable water resources: A framework for assessing adaptation options in the rural sector. Tyndall Centre Technical Report 44. Norwich, Tyndall Centre for Climate Change Research, UEA.

Weatherhead, E.K. and M. Rivas-Casado (2006). Survey of irrigation of outdoor crops in 2005 - England. Cranfield University, UK.

WHO (1989). Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture. Geneva, World Health Organization: 74.

Appendix 1.
Areas irrigated and volumes abstracted and applied

The principal source of data on irrigation is contained in the Defra "Survey of irrigation of outdoor crops" (the Irrigation Survey). Data from the 1995 survey were used in the previous study of agricultural water use and food safety (Groves, Davies and Aitken 2002), but since then, results from two further surveys in 2001 and 2005 have become available (the latter in draft and subject to revision). Both these were carried out for the government by Cranfield University (Weatherhead and Danert 2002 and Weatherhead and Rivas-Casado 2006).

Prior to 1995, the data in this survey had been presented for both England and Wales but from 1995 onwards the data are for England only. In practice this is not a significant factor as irrigation in Wales would account for around 1% or less of the earlier data (Weatherhead and Rivas-Casado 2006). A further break from previous surveys is that the sample size for the 2005 survey was considerably smaller. This was due to it being based on the returns from Defra's June Agricultural Survey rather than on a full June Agricultural Census Holdings, and because it also excluded holdings irrigating less than 1 hectare (ha) for the first time. Questionnaires were sent to growers who indicated in their response to Defra's June 2005 Agricultural Survey that they had irrigated 1 ha or more in that year.

The 2005 data has been analysed for the first time on a Catchment Abstraction Management Strategy (CAMS) basis rather than by county as was the case prior to the introduction of CAMS in 2001 (see Appendix 4 for details of CAMS catchment units). In principle this should give a finer breakdown than was the case at county level, but Defra rules on disclosure of information when this has been obtained from less than 5 responses prevent the release of such data. This has meant that at the CAMS level, the data for the large majority of cells in the spreadsheet have been withheld. One factor contributing to this will be the trend in concentration of production, particularly in specialised sectors. The reduction in the sample size for the 2005 survey will also have been a factor.

Areas irrigated and volumes applied
The use of irrigation, both in terms of the crop areas irrigated and the volumes of water applied, varies significantly year to year. This is largely a reflection of the level of rainfall. In irrigation terms, 1987, 1992, 2001 and 2005 were wet years, 1990 and 1995 were dry, and 1982 and 1984 were average (Weatherhead and Rivas-Casado 2006). These

variations mean that the data should be interpreted with care. Some clear trends do nevertheless emerge from the Defra Irrigation Survey regarding irrigation of different outdoor crops.

Table 1 below illustrates that the areas irrigated of relatively low value crops such grass, sugar beet and cereals is tending to decline, while that for vegetables has risen markedly since the 1995 survey despite 2001 and 2005 being wet years and 1995 a dry year. Potatoes are the principal crop irrigated. These comprised 43% of the irrigated area and received 56% of water applied in 2005, compared with vegetables in second place, comprising 28% of the irrigated area and receiving 27% of water (Tables 1 and 2).

Table 3 gives a broad indication of the distribution of irrigated crops within England. Irrigation is concentrated in the Environment Agency's (EA) Anglian Region with almost three fifths of the crops irrigated, reflecting the high proportion of the English potato and vegetable crops being grown there. A further fifth of irrigated crops are grown in the EA Midlands Region.

Table 1 Irrigated areas (ha) by crop category 1982-2005

Crop category	1982	1984	1987	1990	1992	1995	2001	2005	2005 (%)
Early potatoes	8050	7720	5360	8510	8180	8730	7300	6415	5.5
Main crop potatoes	22810	34610	29520	43490	45290	53390	69820	43140	37.1
Sugar beet	15770	25500	10100	27710	10520	26820	9760	8487	7.3
Orchard fruit	3100	3250	1330	3320	2280	2910	1580	1468	1.3
Small fruit	3610	3560	2230	3470	2750	3250	3770	2631	2.3
Vegetables	14810	17460	11040	25250	20200	27300	39180	32202	27.7
Grass	16440	18940	6970	15970	7240	10690	3970	3671	3.2
Cereals	14800	24700	7510	28100	7160	13440	4620	10979	9.4
Other	4100	4890	2440	8650	4320	9120	7280	7280	6.3
Total	103490	140630	76500	164470	107940	155650	147270	116272	100.1

Table 2 Volumes of water applied ('000m3) by crop category 1982-2005

Crop category	1982	1984	1987	1990	1992	1995	2001	2005	2005 (%)
Early potatoes	4680	4920	2350	6770	5590	9345	5710	6433	6.9
Main crop potatoes	15280	32730	14700	51170	38520	74460	69940	45637	49.1
Sugar beet	8260	17370	3430	20320	4860	21295	4630	3776	4.1
Orchard fruit	2180	2430	550	2930	1220	2445	900	731	0.8
Small fruit	1890	2660	970	3180	2000	4320	3370	2434	2.6
Vegetables	6830	11390	4640	18450	12180	25500	34120	24740	26.6
Grass	10030	13550	3550	13100	4280	9920	2320	1982	2.1
Cereals	5040	8300	2160	11830	2260	5625	1470	2394	2.6
Other	1020	4030	1270	6040	4160	11160	8840	4757	5.1
Total	55210	97380	33620	133790	75070	164070	131300	92883	99.9

Source of both tables: Defra Survey of Irrigation of Outdoor Crops 2005 (Weatherhead and RivasCasado 2006). Summing errors due to rounding. Data up to 1992 for England and Wales, data for 1995, 2001 and 2005 for England only.

Table 3 Irrigated areas by crop types and EA region 2005

EA Region	Total Area (ha)	%	Vegetables Area (ha)	%	Small fruit Area (ha)	%	Orchard fruit Area (ha)	%	Potatoes Area (ha)	%
Northeast	8293	7	468	1	w	w	w	w	6340	13
Anglian	67001	58	18803	58	1082	41	195	13	29085	59
Midlands	22950	20	5043	16	474	18	w	w	8468	17
Thames	2161	2	w	w	w	w	w	w	304*	<1*
Southern	10773	9	6760	21	618	23	892	61	1549*	3*
Southwest	1916	2	126	<1	346	13	w	w	399*	<1*
EA Wales **	1605	1	w	w	w	w	w	w	1228*	2*
Northwest	1573	1	w	w	w	w	w	w	837*	2*
Area	116272		31200		2521		1087		48210	
Total area	116272		32202		2631		1468		49555	
% disclosed	100%		97%		96%		74%		97%	

Source: data from Defra Survey of Irrigation of Outdoor Crops (Weatherhead and Rivas-Casado 2006). *Maincrop potatoes only, earlies not disclosed **England part of EA Wales region only. w = withheld for confidentiality reasons. Totals include withheld data.

The Anglian Region is a large one and comprises 14 CAMS units (numbers 13 -26) (Table 4). Irrigation is widespread in the region with only three units not identified in the 2005 survey as having irrigated crops. CAMS unit 24, the Cam and Ely Ouse including South Level, is one of largest units and is by far the most important in terms of irrigated area and volume of water applied. This single CAMS unit contained around 30,000 ha of irrigated crops in the 2005 survey, more than 25% of the irrigated area for England. Its share of irrigated vegetable production (8028 ha, or 25%) was similar. In all, 6 of the 14 Anglian catchments account for approaching 90% of the irrigated area in the Anglian Region.

Irrigation is far less widespread in the Midlands Region with only 7 of the 16 CAMS units (numbers 27- 42) identified in the 2005 survey. Around two thirds of the irrigated area is concentrated in three units, but the areas involved are for the most part relatively low compared with the areas in the Anglian CAMS units.

The Environment Agency (EA) maintains a database of abstraction licences which includes information from the annual returns of surface water and groundwater abstractions of spray irrigators in England and Wales. The returns do not include trickle irrigation because this use is not currently subject to licensing.

The NFU conducts a "Waterwise" Survey, which includes questions on irrigation. The results of the 2006 survey had not been published as at the time of writing.

In Scotland there are no regular irrigation surveys. A survey was carried out in 2001 by the Scottish Agricultural College (SAC) which indicated maincrop potatoes were the most extensively irrigated crop, accounting for 328 1ha. (45%) of the total irrigated area of 7309ha. Other important crops in terms of volumes of water applied were calabrese, carrots, cauliflowers, Brussels sprouts, lettuce and soft fruit. Most irrigation occurs along the East Coast and around Ayrshire (Ioris, 2004).

Table 4 Areas (ha) of irrigated crops by CAMS unit 2005 (Weatherhead and Rivas-Casado, 2006)

CAMS Unit	Earlies	Main crop	Sugar beet	Orchards	Small fruit	Veget ables	Grass	Cereals	Other	Total
7	w	2054	w	w	w	w	w	w	w	2545
8	w	824	w	w	w	w	w	w	w	1116
9	w	w	w	w	w	w	w	w	w	2670
10	w	867	w	w	w	w	w	w	w	1239
13	w	912	w	w	w	w	w	w	w	1300
15	436	2244	221	w	w	1439	w	w	362	4918
16	w	910	w	w	w	w	w	w	w	1126
19	w	1269	w	w	w	404	w	w	w	1909
20	242	3810	w	w	w	3795	w	w	w	8381
21	1110	1673	471	w	183	2183	w	w	w	6368
22	511	1949	619	w	188	1173	w	w	275	5602
23	w	1223	w	w	w	w	w	w	w	2113
24	906	8033	2459	w	w	8028	608	w	2370	30127
25	w	3303	w	w	w	w	w	w	w	3712
26	w	w	w	w	w	640	w	w	w	1786
28	w	1374	w	w	w	1575	w	w	w	4133
29	w	1961	822	w	w	1685	w	w	w	6033
34	w	w	w	w	w	w	w	w	w	1858
37	278	1710	w	w	w	1114	w	w	w	4090
38	w	1090	w	w	w	w	w	w	w	2910
40	w	w	w	w	w	505	w	w	1424	2669
41	w	w	w	w	w	w	w	w	w	421
58	w	w	w	699	149	2753	w	w	w	3736
59	w	w	w	w	w	w	w	w	w	258
60	w	471	w	w	w	2268	w	w	w	3230
64	w	w	w	w	w	w	w	w	239	1923
85	w	w	w	w	w	w	w	w	w	151
90	w	1238	w	w	w	w	w	w	w	1602
Disclosed	3483	36913	4591	699	520	27560	608	0	4670	107926
% disclose	54%	83%	55%	48%	20%	83%	17%	0%	48%	90%
Total	6415	43140	8487	1468	2631	32202	3671	10979	7280	116272

Source: Survey of Irrigation of Outdoor Crops 2005 (Weatherhead and Rivas-Casado, 2006), w = withheld for confidentiality reasons. Totals include withheld data.

Table 5 Irrigation methods (percent of irrigated area) by CAMS unit 2005 (Weatherhead and Rivas-Casado, 2006)

CAMS Unit	Sprinklers	Reel-gun	Reel-boom	Pivot/linear	Trickle	Other	Drip users
7	w	95%	w	w	w	w	w
8	w	90%	w	w	w	w	w
9	w	100%	w	w	w	w	w
10	w	99%	w	w	w	w	w
13	w	62%	w	w	w	w	w
15	w	69%	18%	w	10%	w	17%
16	w	60%	w	w	w	w	w
19	w	100%	w	w	w	w	w
20	w	84%	16%	w	w	w	w
21	1%	72%	19%	w	3%	1%	36%
22	5%	76%	17%	w	2%	w	35%
23	w	87%	w	w	w	w	w
24	w	57%	25%	w	w	w	w
25	w	62%	37%	w	w	w	w
26	w	77%	w	w	w	w	w
28	3%	69%	w	w	w	w	w
29	w	65%	w	w	w	w	w
34	w	98%	w	w	w	w	w
37	w	71%	19%	w	w	w	w
38	w	57%	w	w	w	w	w
40	21%	25%	w	w	w	w	w
41	w	w	w	w	w	w	w
58	7%	34%	29%	w	30%	w	50%
59	w	w	w	w	85%	w	9%
60	57%	33%	w	w	w	w	w
64	w	w	w	w	w	w	w
85	w	w	w	w	w	w	w
90	w	98%	w	w	w	w	w
Disclosed							148
ALL	5%	67%	19%	4%	5%	0%	426
% disclosed							38%

Source: Defra Survey of Irrigation of Outdoor Crops 2005 (w = withheld for confidentiality reasons. This occurs where there are only a small number of respondents' data in a cell. Growers are informed prior to participation in the survey that only aggregated data, from which their own responses cannot be identified, will be published.)

Table 6 Water abstracted for irrigation by CAMS unit and source 2005 (Weatherhead and Rivas-Casado, 2006)

CAMS Unit	Water Source					
	Surface	Ground	Mains	Harvested	Re-use	Other
7	51%	49%	w	w	w	w
8	w	64%	w	w	w	w
9	w	72%	w	w	w	w
10	54%	w	w	w	w	w
13	w	w	w	w	w	w
15	78%	18%	w	w	w	w
16	84%	w	w	w	w	w
19	w	86%	w	w	w	w
20	34%	62%	w	w	w	w
21	46%	54%	w	w	w	w
22	66%	17%	w	5%	w	w
23	35%	66%	w	w	w	w
24	41%	57%	w	w	w	w
25	93%	w	w	w	w	w
26	62%	w	w	w	w	w
28	45%	56%	w	w	w	w
29	54%	43%	w	w	w	w
34	w	w	w	w	w	w
37	60%	37%	w	w	w	w
38	62%	38%	w	w	w	w
40	83%	w	w	w	w	w
41	w	w	w	w	w	w
58	44%	38%	14%	w	w	w
59	w	70%	w	w	w	w
60	69%	w	18%	w	w	w
64	94%	w	w	w	w	w
85	w	w	w	w	w	w
90	93%	w	w	w	w	w
Total	54%	41%	1%	1%	1%	2%

Source: Defra Survey of Irrigation of Outdoor Crops 2005 (w = withheld for confidentiality reasons. This occurs where there are only a small number of respondents' data in a cell. Growers are informed prior to participation in the survey that only aggregated data, from which their own responses cannot be identified, will be published.)

Table 7 Availability and usage of reservoirs from 2005 (Weatherhead and Rivas-Casado, 2006)

CAMS Unit	Reservoirs		
	% growers with	% of water from	% of capacity used
7	w	w	w
8	w	w	w
9	w	w	w
10	w	w	w
13	88%	82%	72%
15	55%	52%	66%
16	w	w	w
19	w	w	w
20	23%	24%	51%
21	33%	23%	114%
22	69%	83%	38%
23	w	w	w
24	24%	19%	54%
25	71%	69%	66%
26	63%	57%	w
28	63%	23%	56%
29	w	w	w
34	w	w	w
37	53%	36%	76%
38	w	w	w
40	60%	32%	66%
41	w	w	w
58	59%	48%	58%
59	w	w	w
60	46%	15%	34%
64	w	w	w
85	w	w	w
90	56%	w	w
Total	42%	30%	50%

Source: Defra Irrigation Survey of Outdoor Crops 2005
(w = withheld for confidentiality reasons. This occurs where there are only a small number of respondents' data in a cell. Growers are informed prior to participation in the survey that only aggregated data, from which their own responses cannot be identified, will be published.)

Appendix 2

CAMS areas for which results are included in the 2005 Defra Survey of Irrigation of Outdoor Crops (Weatherhead and Rivas-Casado 2006) by EA Region

North East
7 Swale, Ure, Nidd and Upper Ouse
8 Derwent
9 Wharfe and Lower Ouse
10 Hull and East Riding

Anglian
13 Grimsby and Ancholme
15 Witham
16 Welland
19 North Norfolk
20 Broadland Rivers
21 East Suffolk
22 North Essex
23 North west Norfolk
24 Cam and Ely Ouse
25 Old Bedford, including Middle Level
26 Upper Ouse and Bedford Ouse

Midlands
28 Lower Trent and Erewash
29 Idle and Torne
34 Tame and Anker
37 Worcestershire Middle Severn
38 Shropshire Middle Severn
40 Warwickshire Avon
41 Severn Vale West

Southern
58 Medway
59 North kent
60 Stour
64 Arun and Western Streams

South West 86 Parrett

EA Wales 90 Wye

North West
No survey results disclosed for individual CAMS units in 2005.

Source: Environment Agency, 2001. Managing Water Abstraction.

Appendix 3

List of Assured Produce Crop Protocols, 2007

Asparagus, Aubergine
Beans - Broad, Fresh
Beans - Broad, Processed
Beans - Green, Fresh
Beans - Green, Processed
Beans - Runner
Beetroot
Blueberries
Broccoli, Brussel Sprouts
Cabbage, Carrots, Cauliflower
Celeriac, Celery
Chicory
Chinese Cabbage, Pak Choi and Choi Sum - protected
Chinese Cabbage, Pak Choi, Choi Sum
Courgettes, Marrows, Squash and Pumpkins
Cress - Salad
Cucumbers
Fennel
Fruit - Bush
Fruit - Cane
Fruit - Stone
Fruit - Top
Garlic
Herbs - Culinary
Hops
Leeks
Lettuce - Field
Lettuce - Protected
Mushroom
Onions - Bulb
Onions - Salad
Parsnips
Peas - Picking, Fresh
Peas - Vining, Processed
Peppers - Chilli
Peppers - Sweet,
Protected Potatoes
Radish
Rhubarb
Spinach
Strawberries
Swede, Turnip and Kohlrabi
Sweetcorn
Tomatoes - Protected
Watercress