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Microbiological risk assessment: a scientific basis for managing drinking water safety from source to tap

Intestinal illness through drinking water in Europe

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Introduction

Ingestion of water has been demonstrated as a vehicle for multiple enteropathogens of bacterial, protozoan and viral origin [Hunter, 1997; Leclerc *et al.*, 2002]. Once ingested, enteropathogens typically cause gastrointestinal symptoms in the host including nausea, vomiting, and diarrhoea. Selective enteropathogens can also give rise to a number of more serious health outcomes including Haemolytic Uraemic Syndrome (HUS), Guillain-Barre syndrome, hepatitis, meningitis, dysentery, and death. Diarrhoeal disease is recognised by the World Health Organisation (WHO) as a major cause of infant mortality in developing countries, comprising around 15% of total child deaths under five [WHO, 2005]. Furthermore, it is estimated that by providing access to in-house regulated piped water and sewerage connection with partial treatment of waste waters, an average global reduction of 69% could be achieved in the number of episodes of diarrhoea [Hutton and Haller, 2004].
Yet the burden of waterborne disease is not restricted to low-middle income countries. Waterborne diseases still present a challenge to the more affluent nations. Immunocompromised individuals, the elderly, pregnant women and the very young are at greater risk of serious illness and mortality from water and foodborne enteric microorganisms as a much smaller infective dose can cause illness [Gerba *et al.*, 1996]. The ageing population and increased use of immunosuppressive drugs in industrialised nations could lead to a greater number of individuals at increased risk of disease.
Our heavy dependence on drinking water and the severe socioeconomic burden associated with waterborne disease emphasise the need to further our understanding of this topic. In light of this, the purpose of this chapter is to depict the scale of waterborne disease through analysis of endemic disease, outbreaks, and public health surveillance strategies.

Endemic waterborne disease

A number of epidemiological tools have been used to investigate possible associations between drinking water and disease. Of these, randomised controlled trials (RCTs) represent the most robust methodological approach. Typically, households are randomly assigned to different water treatment groups.
Two studies conducted in Canada have looked prospectively at the incidence of gastrointestinal illness due to the consumption of drinking water from sewage contaminated surface waters meeting current (as defined at the time of study) water quality criteria [Payment *et al*., 1991, 1997]. In the first of these studies, people in households randomised to receive domestic reverse osmosis (RO) water filters were found to have a lower annual incidence of gastrointestinal illness (0.50 per person/year) in comparison to tap water drinkers (0.76, $p<0.01$); estimating that 35% of the gastrointestinal illness reported by tap water drinkers was water-related. In a successive, larger trial, it was estimated that tap water was accountable for between 14-40% of gastrointestinal illness.
Although both Canadian studies used randomisation, participants were not blinded to the type of water treatment received which can improve the validity of results. Hellard

et al. [2001] conducted a double-blinded RCT in Melbourne, Australia. The drinking water in the study area was reported to be of high quality, derived from a highly protected source treated with chlorination only. Six hundred households received either real or sham RO water treatment units (WTUs). Over a period of 68 weeks participants completed a health diary reporting gastrointestinal illness symptoms. The study found 0.80 highly credible gastroenteritis (HCG) cases per person/year and the ratio of HCG episode rates for families with real vs sham WTUs was 0.99 (95% CI: 0.85, 1.15, p=0.85), indicating that the RO-filters did not significantly reduce the HCGI incidence.

In the US, Colford *et al*. [2005] conducted a triple blinded RCT cross-over intervention study. The drinking water in this study area was derived from a challenged source treated with conventional chlorination and filtration methods to conform to all current US regulatory standards. Participants received either a sham or real treatment device for six months before switching to the opposite device for a further six months. The active device contained a 1 µm absolute ceramic filter and used UV-light. A total of 2366 HCG episodes were recorded for the 1296 participants over a period of 12 months (1.83 cases/person/year). The relative rate estimate of HCG (sham vs real device) was 0.98 (95% CI: 0.86, 1.10), no reduction in gastrointestinal illness was detected following use of the real treatment device.

Further studies from the Americas have shown an association between sporadic cases of illness and use of unfiltered municipal or non-municipal water [Birkhead and Vogt, 1989] and variation in drinking water turbidity [Morris *et al*. [1996], Schwartz *et al*. [2000]).

There have been no randomised controlled trials in Europe and few other studies of endemic waterborne disease. In France, Zmirou and colleagues reported two of the first prospective studies of endemic waterborne disease. In the first study [Zmirou *et al*. 1987] they demonstrated that the risk of childhood gastroenteritis was greater in alpine villages where the water did not satisfy drinking water standards (RR=1.68 95% CI 1.50-1.88). In a follow-up study they went on to show that an excess risk persisted in poor faecally contaminated sources even after chlorination [Zmirou *et al*. 1995]. Also from France, Beaudeau *et al*. [1999] demonstrated a correlation between drinking water turbidity and sales of anti-diarrhoeal medication in Le Havre.

In the UK, an association between self-reported diarrhoea and pressure loss (Adjusted OR 12.5, 95% CI 3.5-44.7) has been demonstrated [Hunter *et al*., 2005]. Whilst in Sweden, Nygard *et al*. [2004] showed a correlation between risk of campylobacteriosis and length of pipe run from the treatment works to the home.

Nevertheless, the level of endemic disease due to public drinking water systems remains difficult to quantify. The latter two studies suggest that there may be a risk of illness due to contamination of water in distribution. For further information we need look to outbreaks of waterborne disease.

Public supply outbreaks in the EU

Introduction

Sporadic cases purportedly represent a greater proportion of waterborne disease than cases related to outbreaks [Nichols, 2003]. In addition, outbreaks are notoriously difficult to detect [Hunter *et al*., 2001]. Despite such paucity, much of what we know about the burden of disease in affluent nations has been generated through outbreak documentation.

What is evident from outbreaks implicating public supplies is that harmful pathogens have the potential to reach a large body of consumers resulting in substantial economic and health-related costs, which is shown by the April 1993 *Cryptosporidium* outbreak in Milwaukee [Mackenzie *et al.* ,1994]. As a result of a filtration failure at a public water supply it was estimated that around 403,000 people suffered illness, 4,400 people were hospitalised and 100 people died, though these figures have been disputed by others [Hunter and Syed 2001]. The total cost of outbreak-associated illness in the Milwaukee outbreak was estimated to be US$96.2 million [Corso *et al.*, 2003]. Furthermore, in a review of 25 studies on the economic burden associated with common water-related diseases [Bartram *et al*., 2002: 78], the cost of an outbreak reflected as a proportion of gross domestic product per person for 7 enteric outbreaks of waterborne disease ranged from 0.002 to 0.230. Whilst costs such as health care expenses, direct and indirect productivity loss, and bottled water purchase are incorporated into these estimates, the absence of macroeconomic costs (for example, reduced consumer confidence and tourism decline) means that the financial burden is underestimated.

Reviews have further discussed the characteristics of waterborne outbreaks inclusive of private supplies [Said *et al*., 2003], recreational water and non-enteric disease in Europe [WHO, 1999] and much investigation has already been accomplished on affluent nations [Hrudey, 2004] including Canada [Schuster *et al*., 2005] and the US [Craun *et al.*, 2002, Blackburn *et al*., 2004, Lee *et al*., 2002]. This section reviews outbreaks featuring enteric waterborne pathogens (*E.coli*, *Campylobacter*, *Cryptosporidium*, *Giardia*, *Shigella*, *Salmonella*, *Norovirus* and gastroenteritis of unknown aetiology) related to drinking water derived from public supplies in the European Union (EU); thus distinguishing them from non-enteric disease and recreational and private water source outbreaks.

Documented Public Water Supply Outbreaks

Electronic searching of databases (such as, Medline and Embase), and personal communication with members of Enter-net (an international surveillance network), led to the detection of outbreaks from scientific literature, outbreak reports, and other published materials.

Reported outbreaks were omitted if the water source (public or private), year, or country of the outbreak was not reported, or if published material documenting the outbreak was not available. These factors were considered important for the purpose of differentiating between outbreaks to avoid duplication. For example, 30 additional Swedish outbreaks were identified via personal communication with Torbjorn Lindberg. Twenty-five of these outbreaks implicated groundwater supplies and five surface water supplies. In these outbreaks, the aetiological agent involved was often unknown (77%), in 20% of the outbreaks a viral agent was implicated, and in 3% *Campylobacter* was isolated from patients. Approximately 5,097 people suffered illness and over 44,575 were potentially exposed to the implicated supply. However, the data from these outbreaks was not incorporated as it was not possible to differentiate between small supplies which are part of a commercial/public activity and public drinking water supplies. Similarly, Bartram *et al*. [2002: 113] document that 55 of 154 European outbreaks were associated with networked public supplies

between the years 1986 to 1996; these outbreaks were omitted here as they were not differentiable.
A total of 86 enteric disease outbreaks associated with EU public drinking water supplies for the years 1990 to 2004 were detected. Outbreaks were identified in 10 of the 25 countries of the EU. To facilitate synopsis of these outbreaks, extensive data extraction was performed of population, environmental, epidemiological, microbiological, and water supply characteristics. When interpreting the aggregated data it is important to be cautionary and to consider that there are many differences between countries (including drinking water source, water treatment processes, and surveillance practice) which may influence the characteristics shown.

Month and Year of Outbreak Onset

Figure 1 illustrates the number of outbreaks and cases by month of onset for the years 1990 to 2004. For 19% of outbreaks the month of onset was April. This seasonal trend is consistent with evidence of human, cattle and sheep incidents of cryptosporidiosis [Nichols, 2003] and could therefore be due to contaminated surface water ingress following heavy rainfall. Case numbers reflect the maximum number of cases of illness deemed attributable to the outbreak as calculated by the authors. Case numbers tend to follow the seasonal trend for outbreaks, however, for 15% of cases the month of outbreak onset was January. This figure is due to one gastroenteritis outbreak in which it was estimated that 30% of the population were affected [Chover *et al.*, 1995].

Figure 1: Number of Outbreaks and Cases by Month of the Year (n=84)

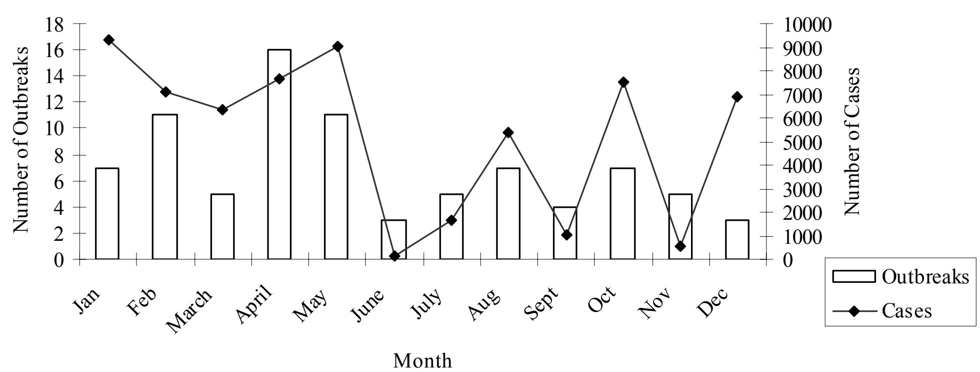
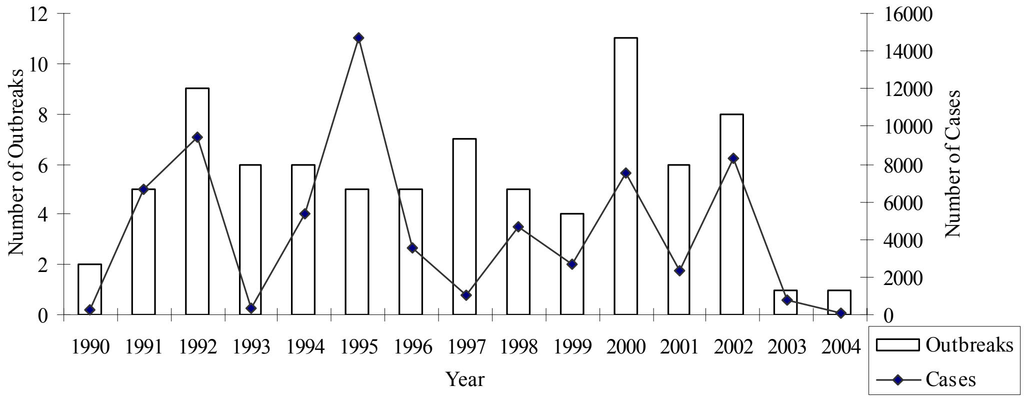


Figure 0.2 depicts the number of outbreaks and cases by year of outbreak onset. Five outbreaks were not included in this graph because they occurred in either the year 1998 or 1999 and one outbreak was not included because it did not report case numbers. The greatest number of outbreaks occurred in the year 2000 (13%) and the least in 2003 and 2004; the decline possibly attributable to the time lag incurred through publication. The small number of cases attributed to the years 1993 and 1997 is due to the reporting of just laboratory positive cases (no population estimates or study cases) in 100% and 57% of the outbreaks respectively.

Figure 0.2: Number of Outbreaks and Cases by Year (outbreaks n=81; cases n=80)



Population, Pathogens and Water Supply

As can be seen from Table 1, it is possible for a large number of people (up to 1.5 million) to be in receipt of a supply implicated in a contamination event which results in high health costs.

Table 1: Number Receiving Supply, Hospitalisations, Fatalities and Cases Reported.

	Population Supplied (n=55)	Hospitalisations (n=32)	Fatalities (n=12)	Cases* (n=85)
Total	7,751,889	341	1	72546
Minimum	95	0	0	3
Maximum	1,500,000	91	1	10000
Mean	140,943	11	-	853
Std deviation	320353	18	-	1857
Median	7,500	5	-	150

Where n=the number of outbreaks reporting this factor.
* The maximum number of cases estimated by authors to be associated with the outbreak.

The number of outbreaks and cases associated with implicated pathogen and source of supply, for each of the ten EU countries in which outbreaks were detected can be found in Table 2. Most of the outbreaks were identified in England (34%), followed by Finland (14%), France (8%) and Sweden (8%). The most predominant agent isolated in the outbreaks was *Cryptosporidium* (32%) and the majority of these *Cryptosporidium* outbreaks occurred in England (61%). The bulk of the *Campylobacter* and *Norovirus* outbreaks (82%) were identified in the Nordic countries, Finland and Sweden. No pathogen was isolated in 12 outbreaks and in five outbreaks a number of pathogens were involved. A further 4 outbreaks involved more than one pathogen; however, these additional outbreaks were classified elsewhere. In two of these four outbreaks, 40% or more of the cases were attributable to just one pathogen and were therefore classified under the predominant pathogens (*Cryptosporidium* and *Giardia*). Two of the 4 outbreaks were classified as 'gastroenteritis'; the number of confirmed cases from one outbreak involving multiple enteropathogens was not differentiable between pathogens and in one large outbreak (~9000 cases) only bacterial analysis was performed yielding relatively few positive results (~5 laboratory confirmed).

Although the greatest number of outbreaks implicated *Cryptosporidium*, most cases were associated with outbreaks of undetermined aetiology (gastroenteritis). In fact *Giardia* and *Cryptosporidium* had the lowest mean number of cases per outbreak (116 (std dev: 153) and 177 (std dev: 133) respectively). Viral outbreaks and *Campylobacter* had the highest mean number of cases per outbreak (1545 (std dev: 1623) and 1802 (std dev: 2140) respectively).

Overall, an equal number of surface water and groundwater supplies were implicated in the outbreaks. Sixteen outbreaks did not report the source of the water supply and 6 outbreaks had a mixed surface water and groundwater supply. The majority of groundwater outbreaks occurred in Finland (31%) and the majority of surface water outbreaks occurred in England (44%). All outbreaks in Scotland and Northern Ireland involved surface water supplies, the majority of outbreaks in Finland (83%) and France (71%) involved groundwater supplies, and a large number of outbreaks in England involved surface water supplies (48%). Groundwater supply outbreaks reported a greater number of cases of illness (60%) than surface water supplies (32%). The country-specific trends for England, France, and Finland reported here tend to reflect the predominant source of supply utilised for drinking water (as reported by Bartram *et al.,* 2002: 87).

Table 2: Number of Outbreaks by Country, Pathogen and Water Supply, and Maximum Cases by Pathogen and Water Supply.

Country	No. Outbreaks	Pathogen Isolated in Cases								Water Supply			
		Bacterial		**Protozoal**		**Viral**							
		Campylobacter	*Shigella*	*Cryptosporidium*	*Giardia*	*Norovirus*	Viral (undete-rmined)	Mixed Pathogen	Gastroenteritis	Ground-water	Surface Water	Mixed	Not Reported
Finland	12	4	-	-	-	6	1	-	1	10	2	-	-
France	7	-	-	2	-	-	-	3	2	5	-	-	2
Germany	2	-	-	-	1	1	-	-	-	1	-	-	1
Greece	3	-	2	-	1	-	-	-	-	2	1	-	-
Italy	1	-	-	-	-	-	-	-	1	-	-	-	1
Netherlands	1	-	-	-	-	-	-	-	1	1	-	-	-
Rep. Ireland	2	-	-	1	-	-	-	-	1	1	1	-	-
Spain	6	1	1	1	-	-	-	-	3	1	-	1	4
Sweden	7	3	-	-	-	1	-	1	2	3	3	-	1
UK (England)	29	-	-	28	-	-	-	-	1	5	14	4	6
UK (N.Ireland)	3	-	-	3	-	-	-	-	-	-	3	-	-
UK (Scotland)	6	-	-	5	-	-	-	1	-	-	6	-	-
UK (Wales)	1	1	-	-	-	-	-	-	-	-	-	-	1
UK (unspecified)	6	-	-	6	-	-	-	-	-	3	2	1	-
No. Outbreaks	86	9	3	46	2	8	1	5	12	32	32	6	16
Cases	72546	16222	531	7772	232	11408	2500	2511	31370*	43571	23047*	906	5022

* One outbreak did not report case numbers.

Of the 54 outbreaks where a pathogen could be isolated from cases and the source of the supply was known, 89% of surface water outbreaks were of protozoan origin compared to 46% of groundwater outbreaks (Table 3).

Table 3: Outbreaks by Pathogen Group and Source of Supply

Pathogen	Water Source		Total
	Groundwater Outbreaks	Surface Water Outbreaks	
Bacteria	7	2	9
Protozoa	12	25	37
Virus	7	1	8
Total	26	28	

Environmental and Epidemiological Investigation

Some form of descriptive or analytical epidemiological investigation of cases was reported in 80% of outbreaks. Seven outbreaks reported investigation of animal samples. The speciation of *Cryptosporidium* (into *C. parvum* and *C. hominis*) was well documented in reported outbreaks yet there have been no reports of the use of subtyping for *Cryptosporidium*. A total of seven outbreaks implicating Campylocater and *Norovirus* used subtyping in an attempt to match human with environmental isolates. Of these 7, only 4 outbreaks (2 implicating *Campylobacter* and 2 *Norovirus*) yielded a match between human and water isolates. Where human and environmental strains match this supports the drinking water hypothesis but the value of the negative result is unclear.
Water quality testing was reported in 88% of outbreaks. Of 62 outbreaks reporting whether or not a pathogen was present in the drinking water, 45% found a positive result (Table 4).
The robustness of epidemiological and environmental investigations will determine the strength of association with water [Tillet *et al*., 1998]. An outbreak is often recognised following the emergence of cases within the community, consequently environmental and epidemiological sampling is initiated after the contamination event has taken place. Hence, the associative link between cases and water can be missed.

Table 4: Percentage of Outbreaks with a Positive Water Quality Result

Drinking Water		Raw Water	
Pathogen (n=62)	Indicator Organism (n=32)	Pathogen (n=34)	Indicator Organism (n=24)
45%	53%	53%	71%

Where n=the number of outbreaks reporting this factor.

Discussion

The outbreaks listed above by no means constitute a definitive list of outbreaks in the EU. As previously noted, outbreak reports were required to meet criteria to avoid inclusion of duplicates, to be referable to the published literature and to allow data

analysis, which will undoubtedly have led to an underestimation of the number of outbreaks identified.
The decline in outbreaks reported in more recent years may in part reflect the time delay between the outbreak occurring and finally being reported in the scientific press. However, a major part of the decline has been due to the significant drop in identified outbreaks in England, possibly secondary to changes in legislation. The recent *Cryptosporidium* outbreak in North Wales has been reported in the media [BBC News, 2005] but has not been included here. It is likely to be some time before full epidemiological findings are reported in the scientific press as the investigative process can be lengthy.
Publication bias can affect the number of outbreaks or the incidence of disease documented. 'Hot topic bias', whereby articles are accepted for publication only if the subject matter conforms to current trends, could, for example, disproportionately promote a particular pathogen or specific country. In the same way, caution should be exercised when comparing outbreaks across different European countries and pathogens as different member states have very different surveillance systems. The detection and reporting of waterborne disease is a product of the adopted public health surveillance strategy. As surveillance strategies vary between countries, it is likely that outbreaks and sporadic cases of disease identified in one country would be missed in another.
No pathogen was isolated from cases in 14% of the outbreaks reviewed. Identification of pathogens in waterborne outbreaks is difficult. In an analysis of public supply outbreaks in the USA, a viral, bacterial or protozoal pathogen was identified in 41%, in 18% a chemical agent was identified, and in the remainder an aetiological agent was not determined [Craun *et al*., 2002]. A thorough and timely water sampling regime following the emergence of cases of illness within the community has the potential to make a link with water but not a definitive refutation of such a claim. Among many other factors, the sensitivity and specificity of laboratory tests must be considered.
To further understand the patterns of and interrelation between seasonality, case numbers, pathogens, countries, and water sources, it is necessary to look at the causes of these outbreaks.

Outbreak causal factors

Introduction

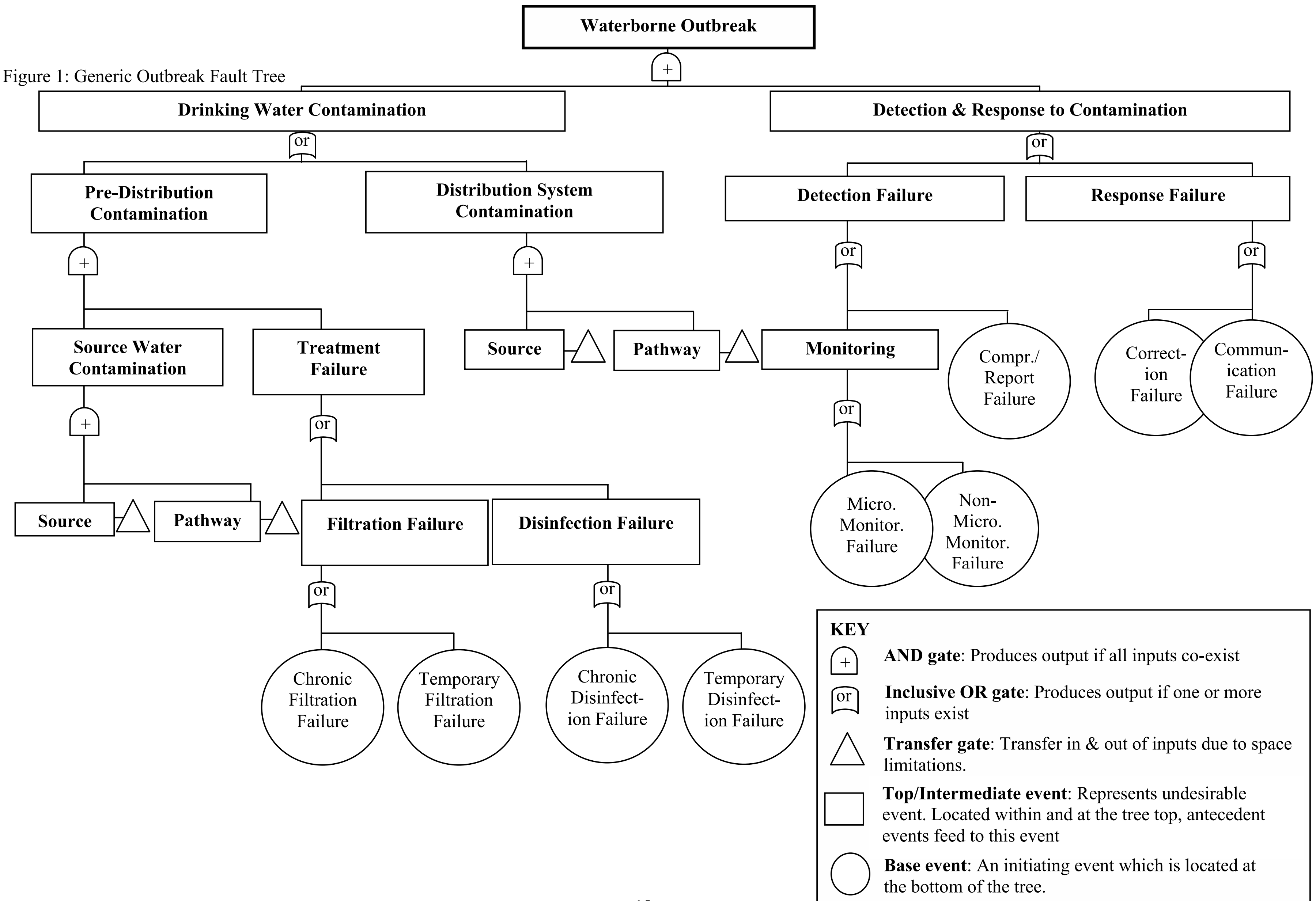
Aside from lessons for disease ecology and socioeconomic burden, outbreaks implicating public supplies also present the unique opportunity to gain a credible, realistic understanding of the contamination pathway; the large volume of consumers and the legislative and regulatory position behind public supplies can stimulate robust environmental and epidemiological investigation.
The Canadian Council of Ministers of the Environment (CCME) multi-barrier approach to safe drinking water identifies three key elements (source water, drinking water treatment plant, and distribution system) to be managed in an integrated manner using tools such as water quality management and monitoring, legislation, and guidelines [Federal-Provincial-Territorial Committee on Drinking Water, 2002]. The IWA Bonn Charter for safe drinking water [2004] also illustrates the necessity for

clear roles and responsibilities and knowledge sharing between stakeholders in achieving safe drinking water that has the trust of consumers. The flow of information between stakeholders and provision of multiple barriers is necessary to reduce the risk of contamination as outbreaks can involve failures across elements of the drinking water system. The *E.coli 0157H7* and *Campylobacter* outbreak of May 2000 in Walkerton, Ontario, occurred as a result of multiple failings including: poor operative training, inadequate monitoring, falsification of records and shortcomings in inspection programs. The contamination event culminated in more than 2,300 people suffering illness, 65 hospitalisations and 7 fatalities [O'Connor, 2002]. Among several important lessons, this outbreak highlights the need to rapidly link an outbreak to its cause to ensure implementation of confinement and correction measures (for example, a boil water advisory or flushing of the system) to reduce attack rates.
Analysis of the multi-factorial nature of outbreaks is therefore fundamental to achieving the goal of safe drinking water. This section aims to take a retrospective look at the causal pathways involved in past outbreaks to identify commonalities thus helping to direct investigations and resources to provide an effective event detection and prevention strategy.

Fault Tree

Sixty-one of the 86 outbreaks previously identified had sufficient information available regarding contributory failures to be utilised in the development of a generic outbreak fault tree (see Figure 1).
Fault tree analysis is a diagrammatical risk assessment technique to describe the sequence and interrelation of possible events leading to an undesirable outcome (in this case, an outbreak). Using a top-down approach, preconditions for the undesirable outcome (top event) are determined until the basic causes (base events) are identified. All events are joined by a series of branches and gates. An AND gate requires all input events to occur, an OR gate requires one or more input events to occur. Typically the likelihood of each event is determined and probabilities are assigned.
A fault tree for waterborne outbreaks was designed using the key elements identified by the CCME multi-barrier and IWA Bonn Charter approach to safe drinking water. Each failure considered to contribute to an outbreak was classified according to one of 32 pre-defined base events grouped under four main intermediary events (source, treatment, distribution and detection). Each base event was assigned a percentage score according to the extent of its contribution towards the outbreak. Each outbreak had a total score of 100; thus multiple failures within an outbreak would have a cumulative score of 100. The classification and scoring was performed by seven individuals from five EU countries with expertise in the field of water and health. Further details of the fault tree diagram, methodology and results are currently being prepared for publication.

Figure 1: Generic Outbreak Fault Tree



Fault Tree Analysis

A total of 198 events were scored across 30 of the 32 available base events. Table 1 illustrates the number of outbreaks with at least one base event failure within each of the four intermediary events and the mean % score attributed by intermediary event (mean contributory scores). The results are also broken down into water source (groundwater and surface water supplies).
Failures occurring at the 'source' of the supply and during 'treatment' occurred with similar frequency and mean contributory scores. 'Distribution' system failures occurred less often but with higher mean contributory scores. Failures associated with the 'detection' of, and response to, microbial and non-microbial pathogens occurred the least often and had the lowest mean contributory score. The pattern for groundwater and surface water outbreaks remained similar with the exception that groundwater outbreaks had a higher 'source' mean contributory score and surface water outbreaks had a higher 'treatment' mean contributory score.

Base Events

As the number of base event failures associated with each intermediary event varies it is not useful to directly compare base events across intermediary events. Base events will therefore be considered within each intermediary event.
Looking in more detail at 'source' water failures, both 'livestock activity' and 'rainfall' base events often featured in outbreaks (41% and 44% of outbreaks respectively) which is consistent with the identified seasonality of month of outbreak onset. 'Sewage discharge into the water' or 'onto surrounding land' had higher mean contributory scores (18.4 and 21.8 respectively) than 'rainfall' (17.9) and 'livestock' (14.9), but relatively low frequency of below 10%. The low mean contributory scores for rainfall and livestock are likely due to the existence of further barriers (such as treatment and detection) between source water contaminated with surface water run-off and the consumer. Direct sewage contamination of the surrounding land or water may be intense thus compromising effectiveness of further barriers such as treatment.
With regard to 'treatment' base events, 'chronic filtration failures' were the most frequently documented (38% of outbreaks), yet, 'temporary filtration failures' attained the highest mean contributory score of 58.8. Long-standing inadequate treatment of a supply occurred as a result of multiple failures (such as, poor water quality monitoring) whereas a temporary interruption to filtration was more likely to occur as a solitary event. When segregated into groundwater and surface water supplies, both types of supply suffered most often from 'chronic filtration failures' (18% and 16% of outbreaks respectively). 'Chronic disinfection failures' were deemed to have the greatest contribution to groundwater supply outbreaks (mean contributory score of 36.3) and 'temporary filtration failures' to surface water supply outbreaks (36). Some of the reports documenting groundwater supply related outbreaks noted that groundwater was considered by treatment facilities to represent a purer source than surface water. This assumption led them to apply less stringent treatment regimes resulting in chronically inadequate treatment.
For 'distribution' system base events, 'backflow/cross-connection' caused by a water company employee received a high mean contributory score (95) yet this was associated with just one outbreak. 'Backflow/cross-connection' caused by individuals outside of the water company (such as, an irrigation user) had a comparatively high

frequency (15%) and high mean contributory score (85.4). This pattern remained true when separated into groundwater and surface water outbreaks, which is likely as the distribution failures are expected to be independent of the type of source water.
Concerning 'detection' base events, 'comprehension' of the significance of existing or historical microbial or non-microbial results was the most frequently identified event (18% of outbreaks) and also marginally received the highest mean contributory score (16.7). This event occurred most frequently in outbreaks related to surface water supplies (10% of outbreaks) yet it was deemed more influential in groundwater supply-related outbreaks (mean score of 14.5). A lack of knowledge and experience concerning the significance of poor raw and treated water quality results, particularly with regard to turbidity fluctuations, contributed to this result. This finding highlights a potential knowledge gap to be addressed through additional education and training of water utility staff.

Events by Pathogen Group

Table 2 lists the number of outbreaks in which at least one base event failure occurred within each of the intermediary events (source, treatment, distribution and detection) and the mean contributory scores for each intermediary event by pathogen group. All pathogen groups attained the highest mean contributory score for 'distribution' system failures. Despite bacterial, protozoal, and viral outbreaks having a high mean contributory score for 'distribution' failures, this type of failure is relatively infrequent; this is in contrast to gastroenteritis outbreaks which have more 'distribution' than 'source' or 'treatment' failures, and mixed pathogen outbreaks which have the same number of 'treatment' and 'distribution' failures. 'Livestock' was more often associated with protozoal outbreaks than any other pathogen group; livestock are known risk factors of such parasites [Hunter *et al.*, 2004; Robertson *et al.*, 2002; Roy *et al.*, 2004].

Table 1: Intermediary Event Fault Tree Analysis Results by Water Source

Intermediary Event	**No. of Outbreaks**	**Mean % Score (std. dev)**	***Water Source****			
			Groundwater		**Surface Water**	
	n=61		No. of Outbreaks n=24	Mean % Score (std dev)	No. of Outbreaks n=22	Mean % Score (std dev)
Source	41	50.5 (26.6)	19	60.3 (23.2)	17	39 (26.3)
Treatment	41	49.0 (25.6)	18	35.6 (22.3)	17	59 (23.2)
Distribution	19	87.4 (22.0)	6	84.5 (24.9)	5	80.8 (26.5)
Detection	16	22.6 (16.0)	6	17.8 (08.3)	7	18.6 (18.3)

* Fifteen outbreaks either did not report the source of the outbreak or the source constituted a mixed supply.

Table 2: Intermediary Event Fault Tree Analysis Results by Pathogen Group

Intermediary Event	**Pathogen**									
	Bacterial		***Protozoal***		***Viral***		***Gastroenteritis***		***Mixed***	
	No. of Outbreaks (%) n=8	Mean % (std dev)	No. of Outbreaks (%) n=31	Mean % (std dev)	No. of Outbreaks (%) n=5	Mean % (std dev)	No. of Outbreaks (%) n=12	Mean % (std dev)	No. of outbreaks (%) n=5	Mean % (std dev)
Source	5 (62.5)	57.0 (22.4)	26 (83.9)	45.3 (28.2)	3 (60)	63.7 (11.1)	5 (41.7)	61.8 (23.2)	2 (40)	53.5 (44.6)
Treatment	5 (62.5)	43.2 (16.4)	23 (74.2)	53.9 (25.8)	4 (80)	46.5 (35.8)	6 (50.0)	38.8 (9.5)	3 (60)	43.0 (49.4)
Distribution	3 (37.5)	81.0 (32.9)	5 (16.1)	86.8 (26.8)	1 (20)	100.0 (-)	7 (58.3)	88.6 (20.4)	3 (60)	88.0 (20.8)
Detection	3 (37.5)	18.7 (10.3)	10 (32.3)	25.0 (18.8)	2 (40)	11.5 (5.0)	1 (8.3)	32.0 (-)	0 (-)	-

Additional Swedish Outbreaks

A singular causal event was documented for each of the 30 additional Swedish outbreaks which were omitted from the review of outbreaks. Fifty seven percent were caused by faecally contaminated raw water passing through the waterworks, 37% were caused by faecally contaminated water entering the distribution system (after the waterworks), and in 7% of outbreaks the cause was unknown.

Discussion

Presenting the major causal factors involved in waterborne outbreaks of disease using the novel diagrammatic approach of fault tree analysis highlights the issues relevant to public water suppliers, consumers, and catchment users.

Results have implications for the treatment of groundwater and surface water supplies and the monitoring of metrological, microbial, and non-microbial data. Although distribution system failures were considered to have the greatest contribution to surface water outbreaks, surface water supplies suffered most often from treatment failures. Of the treatment failures, chronic filtration failures occurred most often and temporary interruption to filtration was the most influential in causing such outbreaks. This is consistent with the finding that 89% of surface water outbreaks were associated with protozoa.

Establishing and maintaining effective collaborative links with factories, farmers, and other users of the network, could help to prevent contamination of the distribution system where fewer barriers to the consumer exist. Such collaboration should also be present with catchment users. Increasing awareness about the effects of agricultural practice and sewage contamination, and communicating the importance of early warning, can help to protect the quality of source water and ensure optimal treatment.

The enteropathogenic waterborne disease outbreaks reviewed here provide valuable information concerning where and how failures can occur. It is hoped that in applying this fault tree methodology a greater understanding of the likelihood and severity of events and the complex interactions between them can be gained. This may have important policy implications for water companies in terms of targeted resource management and outbreak prevention strategies. Catchment, source water and distribution network protection, communication with stakeholders, and review of treatment and monitoring procedures have been highlighted. These are primary components of the Water Safety Plan and thus formulate the basis for hazard identification. Water Safety Plans should be developed for all water supply chains and tailored to each system. Further validation and use of this fault tree can be demonstrated through application to additional outbreaks. Fault trees could be adapted to reflect individual systems, for example, to look in more detail at the probability of human and technological failure of individual treatment processes.

Waterborne disease in non-community supplies

Introduction

The regulation, legislation and outbreak documentation for public drinking water delivery system is more vigilant compared with smaller non-community supplies (private water supplies) due to the larger number of people affected by any microbiological failure. Despite non-public or private water supplies (PWS) serving just 1% of the English population [Clapham, 1993], the public health risk is high as studies have demonstrated a high level of microbiological failure [DWI, 1996] and low-level compliance with water regulations [Rutter *et al*., 2000]. The situation is much the same across rural areas of Eastern and Western Europe, with private/small community supplies receiving little or no treatment, with inadequate monitoring [DWI, 1999]. In England, the Private Water Supplies Regulations [1991] is the current legislation specifying the responsibilities of the Local Authorities over the quality of PWS drinking water. Since inception, the Water Supply (Water Quality) Regulations in England have been updated in accordance with the European Council Directive 98/83/EC [E.U., 1998], with a slant towards risk assessment. Regulatory revisions are ongoing and therefore a thorough understanding of the risk of contamination and the effect upon the health of PWS consumers is paramount.

Outbreaks Associated with Private Supplies

Waterborne outbreak data from England and Wales (1971 – 2005) were reviewed [Galbraith *et al*., 1987; Said *et al*., 2003]. All documented PWS associated waterborne outbreaks were summarised according to aetiological agent.

There have been 29 waterborne outbreaks related to private drinking-water supplies in England since 1971 (Table 1). Most of the PWS outbreaks were reported within 10 years after the introduction of enhanced surveillance in the early 1990s, suggesting that there may have been an under reporting of PWS outbreaks prior to 1990. Investigations into these 29 outbreaks have identified 2751 cases, with more than 4866 people at risk of infections. From the outbreak data, *Campylobacter* was the most commonly identified pathogen (45%), followed by unknown aetiology (17%), *Cryptosporidium* (10%); combination of *Cryptosporidium* and *Campylobacter* (7%), and *Escherichia coli 0157* (7%). *Giardia*, *Salmonella* Paratyphi *B* (PT1), *Streptobacillus moniliformis* (rats found in spring and sewer) and a combination of *Cryptosporidium* and *Escherichia coli 0157* were also identified as the causal pathogen in PWS outbreaks. The strength of association for implicating water as the vehicle or cause of the outbreaks was strong or probable in 76% of the outbreaks. Although the population at risk and the number of cases were relatively low in these outbreaks, the attack rate in each of the outbreaks ranged from 4% to 89% (mean = 42.5%). It is notable that the range of pathogens causing outbreaks associated with private supplies in England and Wales is much broader than those causing outbreaks in public supplies.

Table 1: PWS outbreaks from 1971-2005 (up to June 2005)

Decade	Pathogen	No. outbreaks	Population Supplied	No. cases
1971-1980	S.paratyphi B (PT1)	1	10	7
	Unknown	2	>316	172
1981-1990	*Campylobacter*	3	>767	520
	Streptobacillus moniliformis	1	700	304
	Unknown	1	?	138
1991-2000	*Campylobacter*	9	>1081	195
	Cryptosporidium	3	>664	77
	Cryptosporidium & *Campylobacter*	1	200	43
	E.coli 0157	1	16	14
	Giardia	1	260	31
	Unknown	2	752	83
2001-2005	*Campylobacter*	1	30	4
(June)	*Cryptosporidium* & *Campylobacter*	1	50	2
	Cryptosporidium & *E.coli 0157*	1	16	16
	E.coli 0157	1	4	4

Private Water Supply Microbiological Quality

Drinking water supplied by both public and private water supplies are subjected to the same microbiological standard (i.e. the absence of E.coli and coliforms in 100ml of water sample). The water quality data from public water suppliers are nationally collated and monitored by the Drinking Water Inspectorate. In contrast, water quality data from PWS are monitored by the Local Authorities. In 1996, the Communicable Disease Surveillance Centre (CDSC) created a data collection system to collate microbial water quality results from PWS samples sent to PHLS for analyses with the aim of providing a national picture of the water quality from PWS in England and Wales [Rutter et al 2000].

The results from the first 2 years of data collection (January 1996 to December 1997) were published in Rutter et al 2000. Within this period, there were 6551 samples from 2911 supplies in the Private Water Supply Microbiological Quality Surveillance Database. The key findings from Rutter's paper indicated that over one fifth of the PWS samples failed to comply with the microbiological standards (21% contained *E.coli*, 27% contained coliforms). The quality of water from larger supplies tends to be of better quality compared with those from smaller supplies. The source (where the drinking-water derive from) is also a contributing factor to the water quality, with the gradient of contamination increases from groundwater to spring to surface water; where surface water has the highest level of *E.coli* contamination. Although there was no distinct seasonal sampling pattern during the data collection period; a seasonal trend of *E.coli* contamination was observed with an upward trend from April, culminating in a peak in August and November for both years.

The water quality of PWS can be affected by location and construction of the PWS system. Water derived from surface water and land-drain and shallow groundwater are at higher risk of microbial and chemical contamination compared with water derived from deep boreholes. Contaminated surface water can enter into badly constructed and poorly protected water abstraction systems during rain events. Most of the PWS in England and Wales are in rural settings, delivering water to single dwellings and premises requiring less than $100m^3$ of water per day. There is a comparatively fewer number of large water supplies delivering more than $1,000m^3$ per day. The larger supplies are often maintained and monitored more frequently compared with the smaller supplies due to the public health significance of more people using these supplies. The smaller supplies tend to be of poorer quality and at higher risk of faecal contamination from wildlife and farmed animals and local sanitation systems (e.g. septic tank).

Since Rutter's publication, CDSC continued to collect PWS microbiology quality data until and between 1996 and 2003, there were over 37,000 results from more than 13,000 premises. The majority of the results were from premises where more than 1 sample was taken during the data collection period mainly due to compliance with the sampling regulations. The higher the number people using the PWS, the higher the frequency of water testing. By increasing the proportion of multiple testing per premises may increase in the probability of detecting *E.coli* in the water from larger supplies. Nonetheless, the concentration of *E.coli* detected and number of *E.coli* failure is much higher in the smaller supplies compared with the larger supplies. Further analysis on this dataset is required to assess trends between the different types of water supplies and with other external factors.

Endemic Disease Associated with Private Supplies

The effect of individual exposure to waterborne pathogens can differ depending on their immune status. Although certain subgroups of the population are more vulnerable to infections (e.g. the young and the old and people who are immunocompromised), repeated exposure to contaminated water may not lead to serious illness due to acquired immunity. Hence, visitors using PWS may be at higher risk of gastrointestinal illness than regular PWS owners/users due to their continuous exposure to the water. Nonetheless, the excess risk of illness associated with private water supplies in Europe is unknown. The considerable number of samples from private supplies containing *E. coli* demonstrated both here and elsewhere [the Netherlands, Schets, *et al.*, 2005] indicates that such supplies are at high risk of faecal contamination. The studies by Zmirou *et al*. [1987, 1995] reported above are almost certainly relevant to the issue of PWS. If these studies are applicable, then this would suggest that the risk of gastroenteritis illness in people with PWS, at least those subject to faecal contamination would experience a 40% increase in risk of gastroenteritis. This figure is consistent with a study of private rural systems in Canada [Strauss *et al*. 2001].

People living in rural locations often have PWS that are prone to faecal contamination. It is the possible that PWS are an important contributor to the burden of waterborne disease within Europe, although there is little published evidence for this excess illness. This is an area of water safety that is currently substantially under-researched.

Discussion

Reviewing cumulative water quality results and data from past outbreaks can improve understanding of the indicator organism load in PWS. These vital data can be used to examine trends; establish frequencies and consequences of system failures and identify pathogens that are frequently associated with waterborne outbreaks. The major issue in resolving the water quality problems with PWS is that every system is unique. Thus the problems associated with water quality in PWS can differ substantially from site to site. Although the population using PWS is generally less than those using public water supplies; the microbial quality of water from PWS is poorer and the water is usually consumed untreated. Consequently, the health risk to people using PWS could actually be higher than people using public water supplies.

The enhanced knowledge gained from the surveillance and outbreak data provided a view into the state of the PWS quality and the public health outcome of consuming microbiologically poor quality water. Yet there is little knowledge on the source and route of contaminations and the actual health risks association between people using PWS and the quality of their drinking water. Therefore it is necessary to conduct studies to ascertain where the contamination come from, how much and how often the consumers are exposed to the contamination and to establish the prevalence of disease associated with the consumption of PWS in the community.

Due to the lack of centralised water quality monitoring regulation and surveillance system in England, the enforcement of the PWS regulation currently lies with the Local Authorities who have limited power and resources to act. Thus the owners and users of the PWS are responsible for the quality of their water supply. However, everyone involved in PWS should be made aware of the potential hazards that can enter into their drinking water and the interventions in place to reduce the likelihood and consequence of drinking water contaminations. They should be vigilant in protecting the source water; conducting regular checks on the water supply system and water treatment facilities. Hence conducting regular assessment of the risks to PWS can be beneficial in preventing the water quality non-compliances and waterborne outbreaks.

Public health surveillance of waterborne disease

Introduction

National communicable disease surveillance institutes collate local, national and international intelligence to better inform public health policy. Not all countries conduct communicable disease surveillance and, of the active institutes (see Table 1), not all monitor enteropathogens associated with drinking water. A range of surveillance strategies have been adopted by different national institutes and researchers to monitor the incidence and prevalence of waterborne disease. The structural and organisational integrity of the strategy can not only affect the number of cases detected, but also the strength of an epidemiological association with water. Analysing reported incidence of waterborne disease in conjunction with the characteristics of adopted surveillance strategies can lead to a greater understanding of country-specific trends.

Laboratory and Clinician-Based Reporting

Laboratory and clinician-based reporting constitute the main body of surveillance employed by many national institutes. A host of factors can affect the accuracy and efficiency of national surveillance based on this method. The infectious intestinal disease (IID) incidence study, conducted in England between 1993 and 1996, demonstrated that one case was reported to national surveillance for every 1.4 laboratory identifications, 6.2 stools sent for laboratory investigation, 23.2 cases presenting to general practice, and 136 community cases [Food Standards Agency, 2000]. The number of cases present in the community can depend upon dose-response, acquired immunity and pathogenicity. GP utilisation may be affected by accessibility of services, stool sampling upon budgetary constraints, and positive laboratory findings upon the specificity and sensitivity of diagnostic tests and the selection of pathogens to test for.

It is possible that reporting behaviour is affected by country-specific regulatory and policy-based recommendations. A comprehensive account of the statutory position behind laboratory and clinician reporting of waterborne pathogens and diseases in Europe is given by [Poullis *et al.*, 2002]. Table 2 updates this information for seven enteropathogens and the six surveillance systems briefly described in Table 1.

Table 1: National Public Health Surveillance Centres (content derived from official institute websites).

National Public Health Institute (KTL), Finland Established in 1982, KTL has a number of functions including monitoring, education and training, international collaboration, research and dissemination of health information. The Department of Infectious Disease Epidemiology (INFE) at KTL is responsible for the surveillance of infectious disease and provides support to municipal authorities in outbreak/epidemic situations. The department is also the national coordinator for the EU monitoring network of infectious diseases.
The National Institute for Public Health Surveillance (InVS), France Founded in 1998, InVS is a relatively young institution. Reporting to the Ministry of Health InVS is responsible for the surveillance and monitoring of public health fulfilling a number of policy-advisory goals. Sixteen regional epidemiology units (CIRE) relay information to InVS. CIRE conduct field epidemiology, investigate epidemics and carry out quantitative risk assessment. The Department of Infectious Diseases is organised into five thematic units including 'Enteric, Food and Zoonoses Infections' which monitors mandatory notifications and conducts epidemiological investigations. The department also co-ordinates the National Reference Centre (CNR) and offers training in intervention epidemiology. The Water related risks Unit of the Environment and Health department of the InVS contributes to the surveillance and monitoring of waterborne diseases.
The Robert Koch Institute (RKI), Germany The Law for the Prevention of Infection (Infektionsschutzgesetz, IfSG) assigned the task of a federal epidemiological centre for infectious diseases to RKI. In addition to this, the new Protection against Infection Act has ensured national surveillance of a number of infectious diseases; this work is carried out by the Department of Infectious Disease Epidemiology at RKI. Division 32 (Surveillance) and 35 (Gastrointestinal Infections, Zoonoses and Tropical Infections) of this department are responsible for surveillance and the investigation of outbreaks including the development of algorithms for early outbreak recognition. A "rapid task force" is available for the investigation of regional outbreaks or epidemics if requested by federal states. National reference centres and consultant laboratories in infectious disease information are also available for certain diseases.
National Instiute of Publich Health and the Environment (RIVM), The Netherlands RIVM conducts surveillance, risk assessment and research in the areas of health, nutrition and the environment. RIVM offer guidance and support in the event of incidents and for the purpose of health protection. The Centre for Infectious Disease Control at RIVM is responsible for the prevention and control of infectious diseases through effective prevention, surveillance and rapid response. The Centre is comprised of a number of units including the Centre for Infectious Disease Epidemiology (CIE). CIE co-ordinates the Infectious Diseases Surveillance Information System (ISIS); ISIS provides a rapid visual representation of infectious diseases to health professionals. Information from laboratories and the Public Health Services (GGD) is sent electronically to CIE for this purpose. Information is assessed weekly and recent developments are relayed by the 'Reporting and Supporting' group, information is also published monthly and annually. Using mathematical modelling, RIVM provide detailed information on disease patterns and trends to support surveillance initiatives and policy-making.
The Swedish Institute for Infectious Disease Control (SMI), Sweden Of the six departments of SMI, the Department of Epidemiology is responsible for the national communicable disease surveillance. A computerised reporting system 'SmiNet' collects and analyses the surveillance data. Feedback of surveillance data is provided weekly and bimonthly as well as annually. A yearly report provides further insight on the disease patterns observed throughout the year. Sweden has collaborative links with the National Board of Health and Welfare, the National Veterinary Institute, the National Institute of Public Health, the National Food Administration, the Swedish Armed Forces, the Swedish Defence Research Agency, the Swedish Work Environment Authority, the Swedish Federation of County Councils and the Swedish Association of Local Authorities.
The Health Protection Agency (HPA), United Kingdom The HPA provides an advisory and preventative approach to environmental hazards and infectious disease. The infectious disease element of HPA is dealt with by the Centre of Infections which conducts surveillance, provides reference microbiology and advice and performs outbreak co-ordination. Information for surveillance purposes is assembled from a number of sources including the national laboratory reporting scheme, hospital episode statistics and incident and case reports gathered from physicians, laboratories, Environmental Health Officers (EHOs) and Consultants in Communicable Disease Control (CCDC). The Centre of Infections also liaises with the Water and Environmental Reference Unit and the Drinking Water Inspectorate (DWI) for the investigation of waterborne disease.

Table 2: Enteropathogen surveillance and statutory position

Pathogen	Country					
	Finland	France	Germany	Netherlands	Sweden	UK
Campylobacter	●	o	●	o	●	o
Cryptosporidium	●	-	●	o	●	o
E.coli 0157: *H7*	●	o	●	●	●	o
Giardia	●	-	●	o	●	o
Norovirus	●	o	●	o	o	o
Salmonella	●	o	●	o	●	o
Shigella	●	o	●	●	●	o
Acute Gastroenteritis*	●	o	●	●	o	●
Outbreak	●	●	●	●	●	o

Information Source: Finland: KTL [2005] ; France: Vaillant *et al.* [2004]; Germany: IDCA [2001]; Netherlands: IDA [1999], RIVM [2005]; Sweden: CDA [2004], Lindqvist *et al*. [2001], SMI [2005]; UK: HPA [2005a; 2005b].
* Linked to either a food handler or food poisoning.
● Statutorily notifiable.
o Data collected on a voluntary reporting basis.
\- No information on notification procedures were identified.

All statutorily notifiable pathogens listed in Table 2 require notification from the laboratory with the exception of *Shigella* in the Netherlands which is only statutorily notifiable by the attending clinician (where *Shigella* is classified as ‘bacillary dysentery’). In Sweden statutorily notifiable pathogens also require notification from the attending clinician (complementary to laboratory notification).

The coverage and timeliness of surveillance varies between countries and pathogens. In France, data on *Campylobacter*, *Salmonella*, and *Shigella* are collected by National Reference Centres (CNRs). Data on *E.coli*, *Norovirus* and gastroenteritis are based on sentinel or otherwise limited surveillance. Therefore, not all data is suitable for the purposes of rapid outbreak detection. In the Netherlands the Infectious diseases Surveillance Information System (ISIS) is an internet-based reporting system designed to describe the day-to-day changes in the frequency of communicable diseases. Statutorily notifiable diseases have national reporting coverage; voluntary reporting coverage is expected to rise to 35% by the year 2006. Coverage is higher for some pathogens, *Salmonella* coverage is estimated at 64% of the population [Widdowson *et al*., 2003]. Sweden also has a computerised reporting system (SmiNet) with approximately 18 of 21 counties connected [Jansson *et al*., 2005].

Laboratory and country specific guidelines concerning the routine screening for pathogens should also be considered. It is possible that routine screening policies or the absence of a legal requirement to report protozoal pathogens in the Netherlands contributed to the lack of protozoal outbreaks identified. However, it is also feasible that, as treatment is largely concentrated on coagulation and filtration, activated carbon filtration and ozonation or UV (rather than chlorination) and a larger proportion of drinking water is supplied by groundwater sources in the Netherlands [Bartram *et al*., 2002: 87-93], protozoa have little chance of reaching the consumer.

An awareness of such environmental and epidemiological surroundings should not be underestimated in determining the source of an illness. Many enteropathogens associated with drinking water are also associated with risk factors such as animal contact and food. Detecting an association between drinking water and infectious disease can be extremely difficult. This is especially true in the instance of sporadic illness. Therefore, in order to conduct accurate surveillance of waterborne disease, epidemiological investigation of cases must accompany microbiological detection. Information of this type is unattainable through direct laboratory-based reporting due to the absence of patient contact. Laboratory notifications need to be supplemented with case history gathered through direct patient consultation.

Reported Strengths and Weaknesses

As part of this study we were able to interview key individuals with demonstrated experience and academic record in the field of epidemiology and surveillance in a number of European states (Finland, France, Germany, the Netherlands, Sweden and the UK). Reported strengths and weaknesses of existing national surveillance strategies principally concerned methods of laboratory and clinician-based surveillance and reporting practice.

Strengths of existing waterborne disease surveillance strategies recounted by interviewees included approachability of the national centre and the ability to construct relationships with reporting individuals and institutes. Provision of feedback and accessibility of current local and national disease trend information to clinicians, laboratories, and other reporting bodies was judged to encourage continued involvement in surveillance. Statutory notification of disease with clearly defined regulatory boundaries was seen as a further means of encouraging reporting practice.

A reporting system which promotes the direct provision of information to a centralised national reporting system without delay at the intermediary or regional level of reporting was viewed as a distinct advantage. Technological process capabilities such as electronic notification and internet-based reporting were deemed to facilitate the speed and accuracy of surveillance. Standardisation of laboratory techniques and development of common standards to improve epidemiological case investigation were also identified as means of improving the accuracy of surveillance.

The frequency of patient sampling was thought to be restricted if the financial burden for these samples was taken directly from the clinician's budget, thus limiting the number of pathogens detected and eliminating the necessity to report. In the laboratory setting, infrequent testing for parasites and a lack of detailed patient background information were believed to reduce the effectiveness of surveillance. Another reported weakness of waterborne surveillance was the difficulty encountered in linking cases to water; this was deemed to be hindered by a lack of sporadic case data, local staff lacking experience in outbreak investigation and infrequent notification of pipeline repair.

Additional Components of Surveillance

Alternative methods of surveillance attempt to address some of the shortcomings of national reporting based solely upon patient sampling and testing.

Laboratory sampling can become expensive and 'sentinel' practices and laboratories which have been set up for enhanced surveillance of particular diseases in known problem localities can reduce costs.

Surveillance based upon the incidence of single pathogens may not identify waterborne outbreaks caused by sewage contamination. Monitoring levels of gastrointestinal illness in the community or 'syndromic surveillance' can identify outbreaks caused by multiple enteropathogens. Studies have researched the feasibility of monitoring anti-diarrhoeal drug sales [Beaudeau *et al.*, 1999; Edge *et al.*, 2004; Sacks *et al.*, 1986], telephone help-lines [Rodman *et al*., 1998] and emergency department visits [Heffernan *et al*., 2004] as forms of syndromic surveillance. Guidance has been written on implementation of syndromic surveillance informed by first-hand experience of such systems [Mandi et al., 2004]. In addition to positive laboratory diagnoses, in the Netherlands records are kept of negative results. Such records could be used to inform the efficiency, sensitivity, specificity, and effectiveness of pathogen-specific testing. An increase in sampling requests could also be used to indicate an outbreak of undetermined aetiology or of mixed pathogen source.

Syndromic surveillance may identify a cluster of cases but supplementary information is required to ascertain an epidemiological link between cases and with water. 'Proper officers' such as the Consultants in Communicable Disease Control (CCDCs) in England and Wales, County Medical Officers (CMOs) in Sweden, and epidemiologists from the CIREs in France, investigate epidemiological associations between cases at the local level. Alternative risk factors can be ruled out but the link with water can be compounded by the complexity of the distribution system. Monitoring consumer complaints about the odour, colour, or taste of the drinking water can help to identify clusters and facilitate the epidemiological linkage of cases with water. Monitoring incidents affecting the water supply such as, poor water quality results, treatment deficiencies, and pipeline repair, can also be used to inform this process. Collaborative links with other organisations can promote the exchange of knowledge supplementing information from reporting and improving the accuracy of epidemiological investigation. SMI in Sweden, for example, has established links with environmental, veterinary and food organisations.

International dissemination of surveillance information is necessary to promote the linkage of purportedly sporadic cases of illness. The EU-wide surveillance network for *Salmonella* and *VTEC 0157* infections, Enter-net, is an example of one international surveillance body which is based on a harmonised laboratory system. In using information collected from the microbiologist in charge of the national reference laboratory and the epidemiologist responsible for the national surveillance of these organisms, Enter-net has facilitated case-linkage across national boundaries [Eurosurveillance, 2002].

Discussion

Pathogen isolation from water and patient sampling can be an expensive and lengthy process. This is especially true where there is low reported endemicity and the nature of illness is self-limiting. In instances where testing for *Cryptosporidium* is not feasible, limiting testing to the immumocompromised and children aged fifteen years or younger has been suggested [Crook *et al.,* 2002]. Syndromic surveillance combined with water incident and consumer complaints data can provide more timely information. Although this data is less accurate, once a possible trend has been identified active surveillance using laboratory testing can be pursued [Thompson, 2003].

It is likely that national surveillance institutes employing a combination of surveillance methods coupled with a collaborative approach promoting inter-organisational information integration will generate a more accurate depiction of the burden of waterborne disease. It is important that such systems evolve continuously to embrace changing population dynamics and to incorporate technological development. Electronic reporting of notifiable diseases has been found to more than double the total number of laboratory based reports received [Effler *et al.*, 1999]. The degree and speed of notification has been noted to increase with laboratory as opposed to clinician based reporting [Rietveld *et al.*, 2005]. The feasibility of using algorithms for rapid outbreak detection has also been discussed [Buckeridge *et al.*, 2005].

In summary, reducing heterogeneity between EU surveillance systems and laboratory methods, using a combination of surveillance practices described and improving the methodological robustness of outbreak investigation should increase detection rates; making incidence patterns more representative and less a reflection of a country's surveillance system.

Conclusion

Levels of endemic waterborne disease are probably low in most member states. However, public supplies serve very many consumers and as such contamination, even if causing illness in a small proportion of consumers, can pose a significant threat to public health. This is most clearly seen during outbreaks of illness associated with public water supplies. Although private water supplies serve a smaller population, they are frequently prone to faecal contamination and probably pose a greater risk to people reliant on them for their primary drinking water source.

Review of outbreak data can lead to a greater understanding of the epidemiological, ecological, and environmental factors contributing to the causes of waterborne disease. Heavy rainfall and livestock activity are frequent contributory factors involved in the occurrence of outbreaks. Although the probability of occurrence is less, the magnitude of effect is greater for distribution system incidents. Increased awareness of the public health hazard associated with illegal cross-connections and source water contamination could ameliorate these issues. Production of standardised guidelines and training may improve comprehension of existing or previous microbial and non-microbial results leading to a reduction in repetitive incidents.

The detection and investigation of outbreaks is important for the protection of public health, yet detection and reporting varies from one European member state to another making comparison across Europe difficult. A number of specialist tools and methods of surveillance have been generated from existing national surveillance systems. Studying their diversity can promote the exchange of ideas between countries and help to inform incidence data. Increased collaboration between a number of industries including water, food, veterinary, and health, can improve detection and epidemiological association. Advances in technological processes, data handling, and information integration can also improve the speed and accuracy of surveillance.

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