Journal of Water and Health | 05.Suppl 1 | 2007

Fault tree analysis of the causes of waterborne outbreaks

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ABSTRACT

Prevention and containment of outbreaks requires examination of the contribution and interrelation of outbreak causative events. An outbreak fault tree was developed and applied to 61 enteric outbreaks related to public drinking water supplies in the EU. A mean of 3.25 causative events per outbreak were identified; each event was assigned a score based on percentage contribution per outbreak. Source and treatment system causative events often occurred concurrently (in 34 outbreaks). Distribution system causative events occurred less frequently (19 outbreaks) but were often solitary events contributing heavily towards the outbreak (a mean % score of 87.42). Livestock and rainfall in the catchment with no/inadequate filtration of water sources contributed concurrently to 11 of 31 *Cryptosporidium* outbreaks. Of the 23 protozoan outbreaks experiencing at least one treatment causative event, 90% of these events were filtration deficiencies; by contrast, for bacterial, viral, gastroenteritis and mixed pathogen outbreaks, 75% of treatment events were disinfection deficiencies. Roughly equal numbers of groundwater and surface water outbreaks experienced at least one treatment causative event (18 and 17 outbreaks, respectively). Retrospective analysis of multiple outbreaks of enteric disease can be used to inform outbreak investigations, facilitate corrective measures, and further develop multi-barrier approaches.

Key words | disease outbreaks, drinking water, pathogens, risk management

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INTRODUCTION

Outbreaks of infectious intestinal disease (IID) caused by contamination of drinking water supplies have resulted in substantial human and economic cost (Laursen *et al.* 1994; Andersson *et al.* 1997; Corso *et al.* 2003). In order to minimise these costs, it is essential to promptly identify and rectify the cause of an outbreak, or better still, to prevent the onset of an outbreak altogether. By identifying the key and potential threats to water quality, it is possible to formulate an effective outbreak or contamination event prevention strategy such as the multi-barrier approach. Multi-barrier approaches to safe drinking water have been adopted in recognition that failures can occur across different stages of the drinking water system between source and tap. Key elements of the multi-barrier approach include: source water, treatment, distribution, management, and response (Hrudey & Hrudey 2004, p 398).

Hrudey *et al.* (2003) examined five elements of the multi-barrier approach in relation to 15 published waterborne disease outbreaks. Most outbreaks had problems with the source water (13 outbreaks), closely followed by treatment

doi: 10.2166/wh.2007.136

(12), then distribution (5), response (3) and monitoring (2). Schuster *et al.* (2005) recently conducted an extensive review of 288 waterborne disease outbreaks associated with public, semi-public and private water supplies in Canada. Approximately 23 outbreak causative factors were grouped into 10 categories including weather events, animals, agriculture, human factors and water treatment issues. Factors relating to treatment and wildlife were cited the most often as contributing towards the outbreaks reviewed. The evidence cited thus far demonstrates a large number of source water and treatment failures. However, these findings were not emulated in a review of outbreaks and deficiencies in US public water systems from 1991–1998 where distribution system deficiencies were identified as the most frequent cause (Craun *et al.* 2003). Such diversity is likely to reflect water industry-, environmental- and country-specific differences in the pool of outbreaks studied by these authors yet the frequency of such causal events still merits further exploration.

Multiple events can concurrently contribute towards outbreaks of waterborne disease and the multi-barrier approach provides multiple levels of protection which together attempt to reduce the risk of outbreaks or events. For the majority of outbreaks reviewed by Schuster *et al.* (2005), a single causative factor was involved, yet in 9 outbreaks, more than 3 factors contributed to the outbreak. Furthermore, Deere *et al.*(2001) list a variety of scenarios consisting of multiple events affecting drinking water systems implicated in disease outbreaks in the UK (McCann 1999) and US (Davison *et al.* 1999). However, to date, few attempts have been made to study causal factors associated with multiple outbreaks in more detail, to discuss the interrelation of such causal factors or to assess their weighted contribution. Therefore, it is the purpose of this paper to further examine the causal factors involved in enteric disease outbreaks related to public drinking water supplies in the EU.

METHOD

We searched for outbreaks of enteric waterborne disease associated with EU public drinking water supplies using electronic databases (including Medline, Embase and Cinahl) and full reference list searches. Eighty-six outbreaks were identified between the years 1990–2005. Full data extraction was performed for each outbreak using a *pro forma* which was designed to gather information such as primary and secondary reference sources, year and month of outbreak onset, country of outbreak, descriptive and analytical epidemiology, environmental investigations, details of water source and causal factors. Individuals fluent in the language performed data extraction for articles not published in the English language. Authors or experts with knowledge about the outbreaks were contacted and invited to provide crucial information which was not available from published sources or to provide outbreak control team reports which were not widely distributed beyond the local level.

The fault tree approach has been discussed in relation to water quality and identified as an approach which embraces the concept that events need to be considered together as scenarios (Stevens *et al.* 1995; Deere *et al.* 2001). Fault tree analysis (FTA) was therefore adopted as a tool for further investigating the relevance of specific outbreak causal factors. A fault tree is a graphic model of various sequential and parallel combinations of faults (or events) that will result in the occurrence of the predefined undesired event (Haimes 2004, pp 528–529). In this context, at the top of the tree is the outbreak (the undesirable event); all preconditions for the outbreak are determined until the primary causes are identified (base events). All events are joined by a series of gates and branches; an AND gate requires all input events to occur and an inclusive OR gate requires one or more input events to occur. The main assumption is that faults, such as outbreaks, occur when multiple events take place.

A generic outbreak fault tree was developed using the key elements of the multi-barrier approach (source, treatment, distribution, monitoring and response) to fit all outbreaks of enteric disease related to drinking water. Base events emerged from appraisal of the outbreaks identified through the reviewing process. A scoring system was developed to encapsulate the severity and likelihood components of the risk matrix. If a base event is reported to have occurred, this base event is given a proportional score between 1 and 100 according to the magnitude of its contribution towards the outbreak. The cumulative score of all base events contributing towards the occurrence of a single outbreak is 100.

An outbreak fault tree validation meeting was held with seven participants from five EU countries with expertise in the field of water and health and working in industry, epidemiology, academia, microbiology and public health. During this meeting participants reviewed 50 outbreaks of waterborne disease and came to a collective decision on scores for base events. Information about each outbreak was often gathered from a number of sources; the data extraction forms organised and gathered this information into one place. Therefore, to ensure that all relevant information was easily accessible, participants were given the completed data extraction forms and the full text of all information gathered concerning each outbreak. A copy of the generic fault tree also accompanied this information.

Following the validation meeting a number of revisions were made to the fault tree to further characterise the route cause and effect of some outbreak scenarios. Figure 1 represents the final version of the generic outbreak fault tree. Table 1 further defines the base and intermediary events. Scoring was subsequently re-applied to 61 outbreaks which contained sufficient detail on the cause(s) of the outbreak. A minimum of three people have agreed scores for each of the 61 outbreaks (the outcome of which is documented in the fault tree analysis section of the results). To inform readers of the information resources utilised and the nature of outbreaks included in the fault tree analysis, brief descriptive characteristics of the 61 included outbreaks are provided as an introduction to the results section. A list of the primary references used for each of the 61 outbreaks can be found in the appendix.

RESULTS AND DISCUSSION

Outbreak characteristics

The strength of association (SOA) with water (as defined by Tillet *et al.* (1998)) was already classified by the authors of the paper in 44% of outbreaks (for the remainder, 38% were classified by 1 reviewer and 18% by 2 reviewers). Fifty six

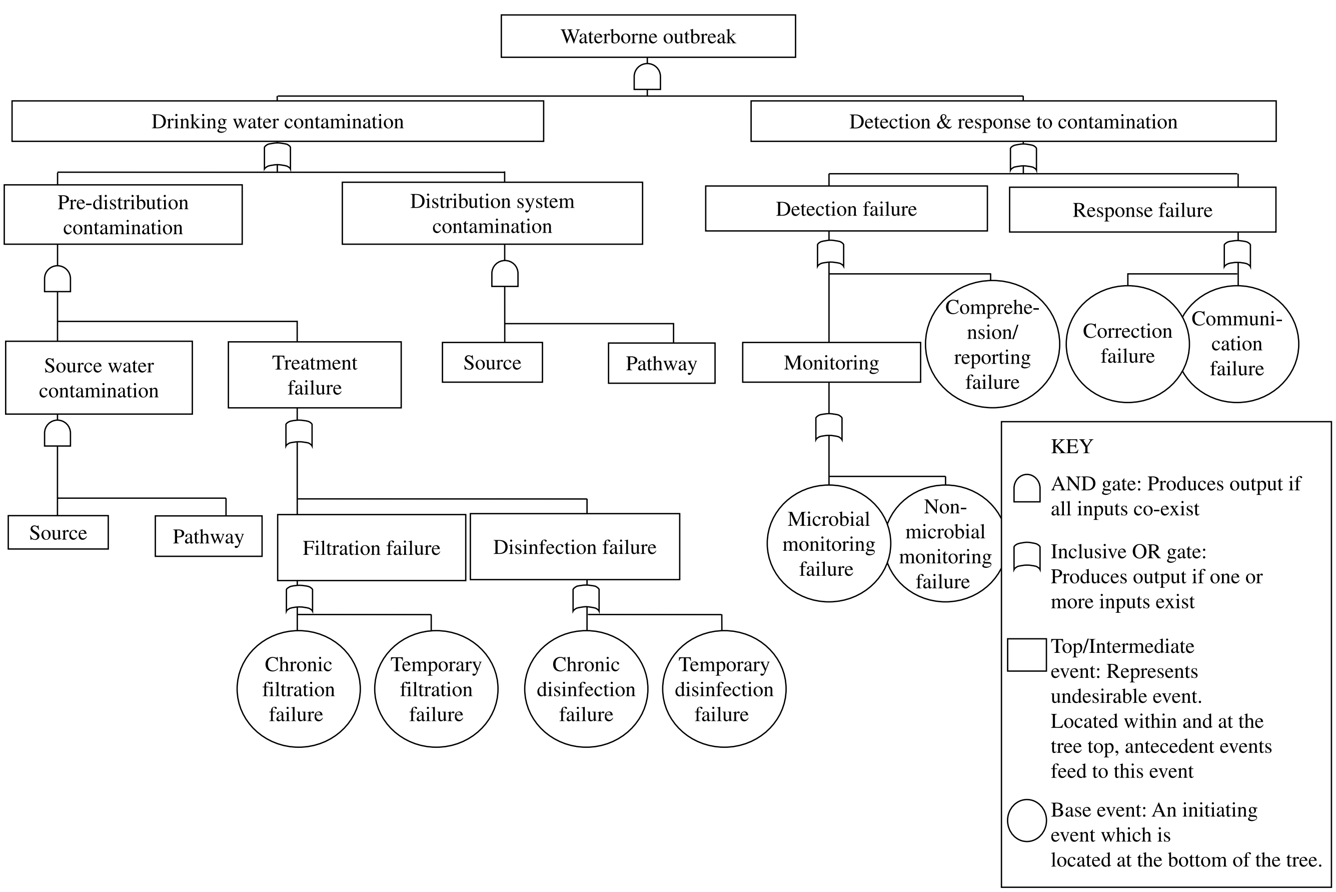

Figure 1 | Fault tree for waterborne outbreaks.

Table 1 | Description of intermediary and base events

Source water	**An event affecting the quality of the source water**
Livestock/Agri	Livestock, animal or agricultural activity in the catchment area.
ST/DT (land)	The presence of leaking septic tanks (ST) or dry toilets (DT) in the catchment area.
Sew. Dis. (land)	Treated or untreated sewage discharge on land within the catchment area, e.g. a broken sewer pipe.
Sew. Dis. (water)	Treated or untreated sewage discharge in the water (other than chronic discharge from overflow pipe), e.g. accidental discharge from sewage treatment works.
Sew. Out. (water)	Direct, chronic discharge of sewage from a sewage outflow pipe leading into the source water.
GW: Abs. /Des. /Barr.	Groundwater abstraction location, design or barrier failure influencing source water quality, e.g. a broken well head.
SW: Abs. /Des. /Barr.	Surface water abstraction location, design or barrier failure influencing source water quality, e.g. inadequate fencing surrounding source water.
Rain/Clim.	A rainfall or climate event influencing or potentially influencing source water quality, e.g. record flood levels following heavy rainfall.
Other Source	Other source water failure not accounted for in the above definitions.
Treatment	**A factor preventing or adversely affecting the adequate treatment (in terms of disinfection or filtration) of water for the removal of harmful enteropathogens.**
F: Chronic	Filtration which is chronically inadequate, e.g. inadequate or no filtration for effective removal of oocysts.
F: Temp	Filtration which has been interrupted on a temporary basis, e.g. the result of human error or mechanical failure.
D: Chronic	A chronic disinfection problem adversely affecting treatment, e.g. a long-standing lack of adequate residual chlorine.
D: Temp	A temporary disinfection problem adversely affecting treatment, e.g. a mechanical failure.
Other Tmt	Other treatment failure not accounted for in the above definitions.
Distribution	**An event occurring within the distribution system network adversely affecting the quality of the drinking water.**
Const./Repair	Construction on, or repair of, the distribution system.
Flush./Cleaning	Flushing or cleaning of the distribution system.
Ext. Back./X-conn	Backflow or cross-connection contaminating drinking water as a result of an external user, e.g. a farmer uses an illegal cross-connection for crop irrigation.
Int. Back./X-con	Backflow or cross-connection contaminating drinking water as a result of an internal user, e.g. an employee of the water company forgets to close a valve.
Low Pressure	Low pressure in the distribution system.

Table 1 | (*continued*)

Stag. Water	Stagnant water in the distribution system.
Dmgd/Old Main	Damaged/old main or conduit causing ingress of contaminated water into the distribution system.
Rsrvr/Stor. Cont	Contamination of a reservoir or storage tank in the distribution system.
Regrowth (biofilms)	Regrowth of biofilms in the distribution system.
Other Dbn	Other distribution system failure not accounted for in the above definitions.
Detection	**No/inadequate detection of poor drinking water quality.**
Microbial	No/inadequate monitoring of the microbial (bacterial/faecal/pathogen) indicator standard of the drinking water, e.g. no *Cryptosporidium* monitoring in place following risk assessment highlighting requirement to do so.
Non-Microbial	No/inadequate monitoring of the non-microbial (e.g. turbidity/taste/odour/colour) indicator standard of the drinking water.
Unk.Micro/N-Micro	No/inadequate monitoring of the drinking water quality; whether or not this is a microbial or non-microbial monitoring deficiency is unreported.
Comp.Exist/Prev.Res.	No/inadequate comprehension or action upon existing or previous water quality monitoring results.
Lab. Report.	Adverse water quality monitoring results not effectively communicated to relevant management for action.
Other Detection	Other detection failure not accounted for in the above definitions.
Response	**No/inadequate correction or response to an alerted event which may put the public at risk.**
Correction	No/inadequate/delayed correction of a failure to prevent an outbreak.
Communication	No/inadequate/delayed communication to the population at risk to prevent the outbreak, e.g. timely and effective issue of boiling water notice.
Other Response	Other response failure not accounted for in the above definitions.

percent of outbreaks were deemed to have a strong SOA with water. Sixty-six percent of outbreaks were derived from a report from the Outbreak Control Team (OCT) or journal article(s) (solely dedicated to analysis of the outbreak) and had a strong or probable SOA.

The number of outbreaks associated with each country can be found in Figure 2. Data for the UK is provided for its constituent countries to enhance detail; the exact location of the outbreak was not reported for 6 outbreaks, which are classified in Figure 2 under ‘UK (undefined)’. Most outbreaks occurred in the year 2000 (10 outbreaks) and the predominant months of outbreak onset were February and April (each experiencing 9 outbreaks).

The number of outbreaks associated with each pathogen group (isolated from human cases) is illustrated in Figure 3. Over half of the outbreaks were associated with protozoan

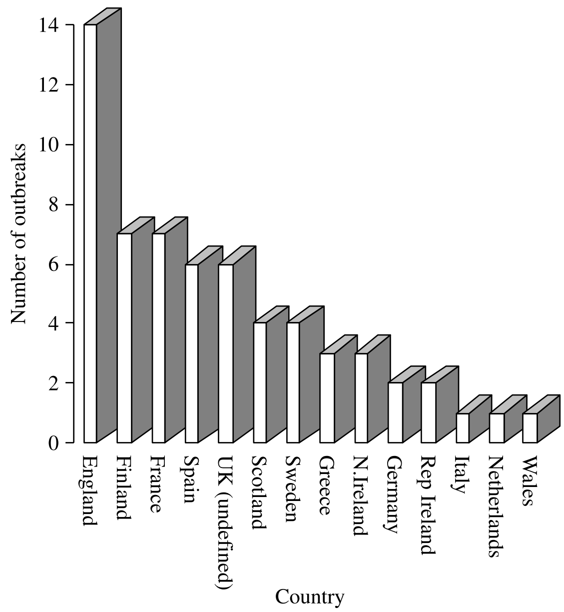

Figure 2 | Country of FTA outbreak origin.

parasites (29 *Cryptosporidium* and 2 *Giardia* outbreaks). Bacterial outbreaks consisted of 5 *Campylobacter* and 3 *Shigella* outbreaks. The viral outbreaks consisted of 4 *Norovirus* outbreaks and 1 undetermined viral outbreak. Five outbreaks were caused by a number of pathogens (classified as 'mixed') and in 12 outbreaks the implicated enteropathogen was either not isolated or not reported (classified as 'gastroenteritis').

Of the 42 outbreaks reporting the number of people on the distribution networks of the implicated supplies, an aggregated total of approximately 3.5 million people were served. Forty-five outbreaks lasted for an aggregated period of 1793 days and, of the 25 outbreaks reporting outcomes, there were 326 hospitalisations and one fatality. When looking at the authors' maximum estimates of the number of cases attributed to each outbreak, the total number of cases reported to have suffered illness was 53 290 (of 60 outbreaks reporting figures). However, a total of only 3472 cases were confirmed by laboratory diagnosis (of 47 outbreaks). Eighty-three percent of outbreaks reported details of descriptive or analytical epidemiological investigation of cases.

The predominant source of supply implicated in these outbreaks was groundwater (39%), followed closely by surface water (36%). Eighteen percent of outbreaks did not report the implicated source of supply and in 8% of outbreaks the implicated supply was from a mixture of groundwater and surface water sources. Sixteen of the 26 outbreaks caused by protozoan parasites implicated surface water supplies. Seventy-seven percent of outbreaks reported the outcome of drinking water quality testing.

Fault tree analysis

Using the information gathered for the 61 outbreaks, a total of 198 events were recorded and scored across 30 of the 33 predefined base event categories. The mean number of base events contributing to an outbreak was 3.25 (std. dev. 1.97; range 1–10). From Figure 4, it can be seen that only 13 of the 61 outbreaks had just one base event scored; the remaining outbreaks involved more than one base event.

In the following results, base events are grouped under four main intermediary events: Source Water, Treatment, Distribution and Detection. No 'Response' events were identified in any of the 61 outbreaks analysed; this finding is likely to

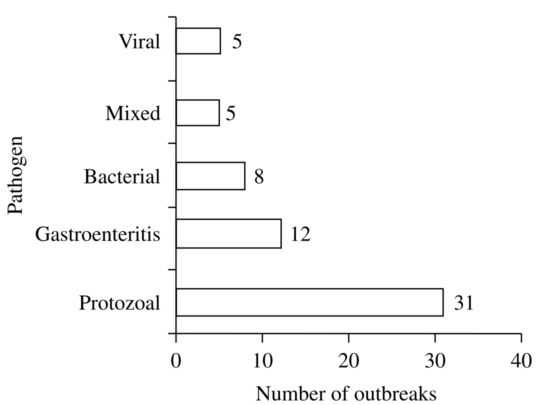

Figure 3 | Pathogen group implicated in FTA outbreaks.

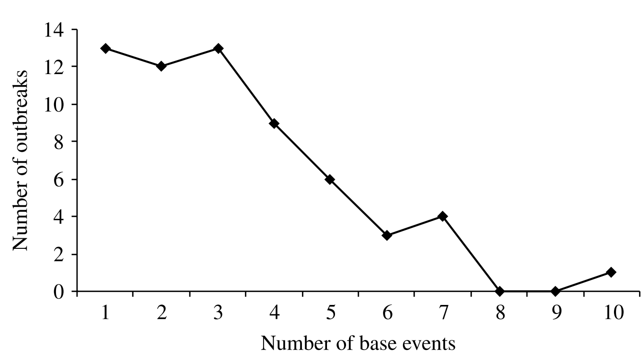

Figure 4 | The number of base events contributing towards outbreaks.

reflect the type of information included in published sources and expectations about how outbreaks can be prevented.

The mean number of base events scored per outbreak according to each intermediary event is given in Table 2. Table 3 is a cross-tabulation demonstrating the number of outbreaks in which intermediary events occurred concurrently. Tables 4–11 demonstrate summary statistics for the contributory scores attributed to base events for each of the 61 outbreaks. Results have also been analysed separately according to implicated water source (groundwater and surface water) and the primary pathogen with which the outbreak is associated (bacterial, protozoal, viral, gastroenteritis and mixed pathogen). Outbreaks associated with a mixed groundwater/surface water supply or those with an unreported source of supply are excluded from the analysis by water source. Intermediary events will be discussed comparatively using results from Tables 2 and 3; these results are followed by a discussion of base events grouped under intermediary event headings.

Intermediary events

Table 4 displays the number of outbreaks with at least one base event scored within the respective intermediary event (Source Water, Treatment, Distribution and Detection) and the respective mean and median contributory scores for each intermediary event. When grouped by intermediary event, the results follow a similar pattern to those reported by Hrudey *et al.* (2003) and Schuster *et al.* (2005); failures relating to source and treatment occurred with similar frequency to one another and more often than other types of failure. As shown in the fault tree diagram (Figure 1), contamination of the source water should take place alongside a treatment event in order for an outbreak to occur. When looking at all outbreaks in Table 4, it can be seen that 'Source Water' and 'Treatment' events were each documented in 41 outbreaks. 'Source Water' and 'Treatment' events occurred concurrently in 56% of all outbreaks (Table 3). In 79% of outbreaks at least one 'Source Water' or 'Treatment' causative event was documented.

For the 19 outbreaks with at least one 'Distribution' system base event scored, the mean number of base events attributed to such outbreaks was less than that for other intermediary events (Table 2). Only a small number of 'Distribution' system events occurred concurrently with other intermediary events (Table 3). As 'Distribution' system events were frequently solitary events they achieved the highest mean contributory score of all intermediary events of 87.42 (Table 4). Indeed, 18 of the 27 'Distribution' system events ranked as a primary

Table 2 | Mean number of base events per outbreak by intermediary event. *n* represents the number of outbreaks with at least one base event scored within the intermediary event

	Intermediary event			
	Source water (*n* =41)	Treatment (*n* =41)	Distribution (*n* =19)	Detection (*n* =16)
Mean no. of base events per outbreak (std. dev.)	4.07 (1.85)	4.00 (1.92)	2.11 (1.49)	5.09 (2.10)

Table 3 | Cross-tabulation of intermediary events which occurred concurrently

	Intermediary event					
	Source water		Treatment		Distribution	
Intermediary event	No. of outbreaks*	% of outbreaks*	No. of outbreaks*	% of outbreaks*	No. of outbreaks*	% of outbreaks*
Treatment	34	56	–	–	–	–
Distribution	4	7	5	8	–	–
Detection	14	23	14	23	1	2

*In which intermediary events occurred concurrently.

Table 4 | Intermediary Event fault tree analysis results

	All outbreaks (n =61)			Groundwater (n =24)		Surface water (n =22)		Bacterial (n =8)		Protozoal (n =31)		Viral (n =5)		Gastroenteritis (n =12)		Mixed pathogen (n =5)	
Intermediary event	$N^\dagger$	Mean % score (std. dev.)	Median % score (25.75%ile)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)	$N^\dagger$	Mean % score (std. dev.)
Source water	41	50.46 (26.62)	50 (30, 67.5)	19	60.26 (23.22)	17	39 (26.27)	5	57 (22.36)	26	45.27 (28.19)	3	63.67 (11.06)	5	61.80 (23.22)	2	53.5 (44.55)
Treatment	41	49.00 (25.60)	44 (29.5, 70)	18	35.61 (22.31)	17	59 (23.17)	5	43.2 (16.35)	23	53.87 (25.78)	4	46.5 (35.8)	6	38.83 (9.52)	3	43 (49.37)
Distribution	19	87.42 (21.97)	100 (70, 100)	6	84.5 (24.91)	5	80.8 (26.47)	3	81 (32.91)	5	86.8 (26.81)	1	100 (–)	7	88.57 (20.35)	3	88 (20.78)
Detection	16	22.56 (16.04)	17.5 (10, 31.5)	6	17.83 (8.26)	7	18.57 (18.27)	3	18.67 (10.26)	10	25 (18.81)	2	11.5 (4.95)	1	32 (–)	0	–

†Where N (and consequently the mean % score denominator) represents the number of outbreaks with at least one base event scored within the intermediary event

cause of the outbreak. Events occurring in the distribution system are likely to be more catastrophic as there are fewer barriers between the incident and the consumer, leaving less time and opportunity for remediation.

'Detection' events occurred the least often (in 16 outbreaks) and had the lowest mean contributory score of 22.56 (Table 4). Much of the information concerning outbreaks was gathered from medical literature. It is possible that base events noted under the intermediary event 'Detection' were recorded less often because they were not a main focal point in journal articles.

When outbreaks are divided by water source (Table 4), it can be seen that groundwater supply-related outbreaks have a higher mean contributory score for 'Source Water' events than surface water supplies (60.26 and 39, respectively). Conversely, surface water supply-related outbreaks had a higher mean contributory score for 'Treatment' events than groundwater supplies (59 and 35.61, respectively). Looking at the intermediary results by pathogen group (Table 4), it can be seen that all pathogen groups (bacterial, protozoal, viral, gastroenteritis and mixed) attained the highest mean contributory scores for 'Distribution' system events (scoring 81, 86.8, 100, 88.57 and 88, respectively). 'Distribution' system events were the least common type of event for protozoal outbreaks yet they were the most common type of event for gastroenteritis outbreaks (occurring in 16% and 37% of outbreaks, respectively). Trends related to water source and pathogen group are further discussed under the relevant intermediary events.

Source water base events. The number of outbreaks in which a 'Source Water' base event was scored and the mean and median contributory scores for all outbreaks and for outbreaks divided by water source is illustrated in Table 5.

When looking at the results for all outbreaks, it can be seen that, although 'livestock' and 'rainfall' base events were frequently reported (in 25 and 27 outbreaks, respectively, and concurrently reported in 19 outbreaks), their mean contributory scores were relatively low (14.92 and 17.89, respectively). The base event with the highest 'Source Water' mean contributory score of 35.61 was 'groundwater abstraction, design or barrier failure' and 14 of the 18 outbreaks reporting this event were ranked as the primary cause of the outbreak.

Table 5 | Source water base events (all outbreaks and outbreaks by water source)

	All outbreaks (*n* =61)			**Groundwater outbreaks (*n* =24)**		**Surface Water outbreaks (*n* =22)**	
Source water base events	***N*‡**	**Mean % score (std. dev.)**	**Median % score (25.75%ile)**	***N*‡**	**Mean % score (std. dev.)**	***N*‡**	**Mean % score (std. dev.)**
Livestock	25	14.92 (14.72)	10 (4, 20)	11	14.73 (15.01)	10	15.6 (17.02)
ST/DT (land)	3	8.33 (3.06)	9 (5, 11)	2	8 (4.24)	1	9 (–)
Sew. Dis. (land)	6	21.83 (16.17)	21 (6.5, 37.75)	5	19.8 (17.2)	1	32 (–)
Sew. Dis. (water)	5	18.40 (13.07)	21 (5, 30.5)	2	27.5 (19.19)	3	12.33 (12.70)
Sew. Out. (water)	3	6 (2.65)	7 (3,8)	1	7 (–)	1	8 (–)
GW:Abs./Des./Bar.	18	35.61 (12.64)	34 (26.75, 42.5)	16	22 (37.31)	–	–
SW:Abs./Des./Bar.	10	27.5 (14.48)	27 (19.25, 36)	–	–	8	31.13 (13.09)
Rain/Clim.	27	17.89 (19.74)	13 (8, 20)	12	16.5 (11.63)	12	12.67 (10.35)
Other Source	5	6.2 (7.85)	3 (1.5, 12.5)	4	2.75 (1.71)	1	20 (–)

‡ Where *N* represents the number of outbreaks in which the base event was scored.

Table 6 | Source water base events by pathogen group

	Bacterial outbreaks (*n* =8)		Protozoal outbreaks (*n* =31)		Viral outbreaks (*n* =5)		Gastroenteritis outbreaks (*n* =12)		Mixed Pathogen outbreaks (*n* =5)	
Source water base events	***N***	**Mean % score (std. dev)**	***N***	**Mean % score (std. dev)**	***N***	**Mean % score (std. dev)**	***N***	**Mean % score (std. dev)**	***N***	**Mean % score (std. dev)**
Livestock	2	1.5 (0.71)	21	17.14 (15.05)	1	3 (–)	1	7 (–)	0	–
ST/DT (land)	2	8 (4.24)	1	9 (–)	0	–	0	–	0	–
Sew. Dis. (land)	1	32 (–)	1	5 (–)	1	37 (–)	3	19 (18.25)	0	–
Sew. Dis. (water)	0	–	1	5 (–)	2	24 (4.24)	1	5 (–)	1	34 (–)
Sew. Out. (water)	0	–	2	5 (2.83)	0	–	1	8 (–)	0	–
GW:Abs./Des./Bar	4	35.5 (8.85)	7	35.57 (13.78)	2	29 (11.31)	3	46.33 (15.82)	2	26.5 (10.61)
SW:Abs./Des./Bar	1	53 (–)	6	22.5 (9.95)	1	11 (–)	2	38 (9.9)	0	–
Rain/Clim.	3	10.33 (5.51)	20	19.2 (22.76)	2	17 (4.24)	1	17 (–)	1	17 (–)
Other Source	3	2.67 (2.08)	1	20 (–)	0	–	0	–	1	3 (–)

'Livestock' and 'rainfall/climate' events featured often in both groundwater (11 and 12 outbreaks, respectively) and surface water supply-related outbreaks (10 and 12 outbreaks, respectively). Heavy rainfall led to run-off from or ingress of surface water contaminated with livestock faecal material; the source water was often compromised by abstraction design or barrier failures. The low contributory scores for rainfall and livestock are likely due to the existence of further barriers (such as treatment and detection) to prevent contaminants reaching the consumer. Thirty-six percent of events relating to sewage discharge were ranked as the primary cause of the outbreak compared to 8% of 'rainfall/climate' and 'livestock'

Table 7 | Treatment base events (all outbreaks and outbreaks by water source)

	All outbreaks (*n* =61)			Groundwater outbreaks (*n* =24)		Surface Water outbreaks (*n* =22)	
Treatment base events	***N***	**Mean % score (std. dev.)**	**Median % score (25.75%ile)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**
F: Chronic	23	39.87 (25.26)	36 (15, 63)	11	28.55 (20.81)	10	54.8 (24.83)
F: Temp	4	58.75 (37.70)	63 (21.25, 92)	0	–	3	75.33 (21.94)
F: Unknown	2	77.50 (3.54)	77.5 (75, 80)	0	–	1	80 (–)
D: Chronic	12	33.75 (24.93)	29.5 (21.25, 43.5)	9	36.33 (26.46)	2	36 (19.8)
D: Temp	5	49.40 (34.94)	33 (22, 85)	0	–	3	25.67 (10.21)
D: Uknown	1	50.00 (–)	50 (–)	0	–	0	–

Table 8 | Treatment base events by pathogen group

	Bacterial outbreaks (n =8)		Protozoal outbreaks (n =31)		Viral outbreaks (n =5)		Gastroenteritis outbreaks (n =12)		Mixed Pathogen outbreaks (n =5)	
Treatment base events	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**
F: Chronic	0	–	18	45.78 (25.02)	1	6 (–)	2	29 (9.9)	2	14.5 (0.71)
F: Temp	0	–	4	58.75 (37.7)	0	–	0	–	0	–
F: Unknown	0	–	2	77.5 (3.55)	0	–	0	–	0	–
D: Chronic	4	36.5 (7.55)	2	5.5 (0.71)	3	49 (44.24)	3	33.67 (14.54)	0	–
D: Temp	1	70 (–)	1	14 (–)	1	33 (–)	1	30 (–)	1	100 (–)
D: Unknown	0	–	0	–	0	–	1	50 (–)	0	–
Other Tmt	0	–	0	–	0	–	0	–	0	–

Table 9 | Distribution base events (all outbreaks and outbreaks by water source)

	All outbreaks (n =61)			Groundwater outbreaks (n =24)		Surface water outbreaks (n =22)	
Distribution base events	***N***	**Mean % score (std. dev.)**	**Median % score (25.75%ile)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**
Const./Repair	4	47.75 (35.50)	33 (25.25, 85)	1	26 (–)	1	25 (–)
Flush./Cleaning	2	22.50 (24.75)	22.50 (5, 40)	0	–	0	–
Ext. Back./X-conn	9	85.44 (20.96)	100 (62, 100)	3	88 (20.78)	2	100 (0)
Int. Back./X-conn	1	95 (–)	95 (–)	1	95 (–)	0	–
Low Pressure	2	12.50 (10.61)	12.50 (5, 20)	1	5 (–)	0	–
Stag. Water	1	45 (–)	45 (–)	0	–	1	45 (–)
Dmgd/Old Main	3	49.33 (41.48)	39 (14, 95)	1	14 (–)	2	67 (39.6)
Rsrvr/Stor. Cont.	1	100 (–)	100 (–)	0	–	0	–
Regrowth (Biofilms)	1	3 (–)	3 (–)	1	3 (–)	0	–
Other Dbn.	3	80 (34.64)	100 (70, 100)	1	100 (–)	0	–

Table 10 | Distribution base events by pathogen group

Distribution base events	Bacterial outbreaks (*n* =8)		Protozoal outbreaks (*n* =31)		Viral outbreaks (*n* =5)		Gastroenteritis outbreaks (*n* =12)		Mixed pathogen outbreaks (*n* =5)	
	N	% score	*N*	Mean % score (std. dev.)	*N*	% score	*N*	Mean % score (std. dev.)	*N*	Mean % score (std. dev.)
Const./Repair	1	26	0	–	1	40	2	62.5 (53.03)	0	–
Flush./Cleaning	1	40	0	–	0	–	0	–	1	5 (–)
Ext. Back./X-conn	0	–	2	100 (0)	1	60	3	83.33 (28.87)	3	86.33 (11.23)
Int. Back./X-conn	0	–	0	–	0	–	1	95 (–)	0	–
Low Pressure	1	20	0	–	0	–	1	5 (–)	0	–
Stag. Water	0	–	0	–	0	–	1	45 (–)	0	–
Dmgd/Old Main	1	14	2	67 (39.6)	0	–	0	–	0	–
Rsrvr/Stor. Cont.	1	100	0	–	0	–	0	–	0	–
Regrowth (Biofilms)	1	3	0	–	0	–	0	–	0	–
Other Dbn.	1	40	1	100 (–)	0	–	1	100 (–)	0	–

events; sewage-related incidents were at times either accidental or intense, thus comprising the effectiveness of treatment barriers.

Table 6 gives the 'Source Water' base event results by pathogen group. Both 'rainfall/climate' and 'livestock' events were more frequently documented in protozoal outbreaks (occurring in 20 and 21 outbreaks, respectively) than in any other pathogen group (occurring in 4 and 7 outbreaks, respectively).

At any one time communities served by large public supplies will be affected by a wide range of enteropathogens. It is therefore unsurprising that a greater proportion of 'Source Water' base events for viral, gastroenteritis and mixed pathogen outbreaks were associated with sewage than was the case for bacterial and protozoal 'Source Water' base events (35% and 7% of events. respectively).

Treatment base events. 'Treatment' base event results are displayed in Table 7. In three outbreaks the type of treatment event (disinfection or filtration) was documented but it was not known if this was a result of a temporary or chronic event ('filtration unknown' and 'disinfection unknown').

When results are grouped together, events relating to 'filtration' occurred more often (29 failures) and received higher mean contributory scores than 'disinfection' events (18 failures). 'Temporary' events had higher mean contributory scores than 'chronic' events often because chronic deficiencies in treatment were coupled with other causal factors. 'Chronic filtration' events were the most frequently documented base event (occurring in 23 outbreaks), yet 'temporary filtration' attained the highest mean contributory score of 58.75 (excluding 'filtration unknown'). These results are due to the volume of events relating to protozoal outbreaks. Unsurprisingly, as chlorination cannot remove this pathogen from the water supply, and as filtration is an effective barrier against *Cryptosporidium*, the majority of protozoal outbreak 'Treatment' events were the result of 'chronic filtration' (Table 8). Indeed, livestock and rainfall in the catchment area along with no/inadequate filtration of water sources contributed concurrently to 11 of the 31 *Cryptosporidium* outbreaks.

Table 11 | Detection base events (all outbreaks, outbreaks by water source and by pathogen group)

	All outbreaks (n=61)			Groundwater outbreaks (n=24)		Surface water outbreaks (n=22)		Bacterial outbreaks (n=8)		Protozoal outbreaks (n=31)		Viral outbreaks (n=5)		Gast. outb. (n=12)		Mixed pathogen outbreaks (n=5)
Detection base events	***N***	**Mean % score (std. dev.)**	**Median % (25.75%ile)**	***N***	**Mean % score (std. dev.)**	***N***	**Mean % score (std. dev.)**	***N***	**% score**	***N***	**Mean % score (std. dev.)**	***N***	**% score**	***N***	**% score**	***N***
Microbial		16.50	16.50(10, 23)	0	–	1	23(–)	0	–	2	16.5(9.19)	0	–	0	–	0
	2	(9.19)					14.67				13.75					
Non–Micro.		16.67	16(8.25, 24.75)	1	9(–)	3	(8.5)	1	30	4		1	15	0		0
	6	(8.87)						1			(7.72)					
Unk.Micro./N.Micro		14.67			14.67											
	3	(6.11)	16(8, 20)	3	(6.11)	0	–	1	16	1	20(–)	1	8	0	–	0
Comp. EXist./Prev.Res.		16.73									15.78					
	11	(14.84)	10(3, 28)	3	18(14.53)	6	10(9.33)	1	10	9	(15.47)	0	–	1	32(–)	0
Lab Report	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Three-quarters of viral and gastroenteritis 'Treatment' events and all bacterial 'Treatment 'events were related to 'disinfection' as this is a key mode of pathogen removal (Table 8). The highest mean contributory score for surface water supply-related outbreaks was for 'temporary filtration' (excluding 'filtration unknown') and the highest mean contributory score for groundwater supply-related outbreaks was for 'chronic disinfection'.

Eighteen of 24 groundwater outbreaks had treatment deficiencies (Table 4); all of these deficiencies were chronic (Table 7). The majority of surface water outbreak treatment deficiencies were related to chronic filtration (53%), yet the remaining causative events were more evenly distributed through chronic and temporary deficiencies (Table 7). These findings highlight the need for continual assessment of groundwater sources and treatment regimes.

Distribution base events. Table 9 displays the results for 10 'Distribution' system base event categories. 'Backflow/cross-connection' caused by a user external to the water supplier (such as an irrigation user) had both a high frequency (occurring in 9 outbreaks) and a high mean contributory score of 85.44; indeed, in all 9 outbreaks this event ranked as the primary cause. The 'external backflow/cross-connection' mean contributory score remained high for both groundwater and surface water supply-related outbreaks. These findings emphasise the need for effective communication and monitoring strategies in relation to stakeholders, landowners and vulnerable areas of the distribution system. 'Construction/repair' and 'damaged/old main/conduit' events were reported less often but warrant similar internal communication, monitoring and alert strategies.

Table 10 displays summary results for the 'Distribution' base events by pathogen group. Distribution system base events were fairly evenly dispersed across pathogen groups. Nine 'distribution system' events were scored in 7 of the 12 gastroenteritis outbreaks; these events were distributed across 6 base event categories. The 9 outbreaks with 'external backflow/cross-connection' events were distributed across 4 of the pathogen groups.

Detection base events. 'Detection' base events, organised by water source and pathogen group, are depicted in Table 11. In three outbreaks it was unclear whether the 'inadequate monitoring' reported by authors was related to microbial or non-microbial parameters. Mean contributory scores for the four scoring base events were low (ranging from 14.67 to 16.73); indeed, there were no documented laboratory reporting events and no 'Detection' base events related to mixed pathogen outbreaks. However, this may only reflect institutionalised expectations about the relevance and role of water analyses and reporting in outbreak prevention.

'Comprehension of existing or previous results' was the most frequently identified base event occurring in 11 outbreaks, 9 of which were protozoal outbreaks. This event occurred most frequently in outbreaks related to surface water supplies (6 outbreaks), and yet it was deemed more influential in groundwater supply-related outbreaks (mean contributory score of 18). Turbidity fluctuations and groundwater supplies under the influence of surface water were events documented by outbreak investigators; although these events were sometimes evident from data available to water suppliers, the evidence was either not fully explored or understood. The underlying message here is that many of the failures leading to outbreaks are repeat incidents which could be avoided with appropriate staff training and reappraisal of historical records. As solitary events do not always lead directly to outbreaks, familiarity with these incidents on a day-to-day basis is likely to reduce the perception of their relevance.

CONCLUSION

Analysis of a wide range of outbreaks associated with public drinking water supplies has enabled the identification of key causative factors involved in enteric disease outbreaks. Most notably, distribution system failures were highlighted as causative factors which often occur as a solitary events contributing considerably towards the occurrence of individual outbreaks (mean contributory score of 87.42). Improving collaborative links with potential distribution system users and increased monitoring in vulnerable areas of the distribution system network may reduce the risk of a cross-connection incident.

The results demonstrated that numerous causative events are associated with such outbreaks (a mean of 3.25 events per outbreak). Source water contamination and treatment system failures occurred frequently (each in 41 outbreaks) and concurrently (together in 34 outbreaks). In 19 outbreaks, the presence of livestock in the catchment area coupled with rainfall led to surface water run-off and ingress contaminating the groundwater or surface water sources. Reflecting the key modes of pathogen removal, 90% of treatment events for protozoal outbreaks were related to filtration yet 75% of treatment events for bacterial, viral, gastroenteritis and mixed pathogen outbreaks were related to disinfection deficiencies. No/inadequate comprehension or no action upon existing/previous water quality monitoring results was recorded in 11 outbreaks. For some outbreaks it was noted by investigative teams that chronic, long-term treatment deficiencies were the result of poor understanding of or action upon microbial and non-microbial results. Communicating with potential water supply and catchment area users, and both monitoring and acting upon fluctuations in rainfall and microbial and non-microbial parameters, were areas highlighted for improvement by outbreak investigation teams.

Of source water base events, 'groundwater abstraction/design/barrier failure' received the highest mean contributory score of 35.61 and all of the treatment base events for groundwater outbreaks were chronic in nature (20 events). Although groundwater is often considered to be of better quality than surface water, this assumption can evoke a false sense of security. Groundwater abstraction locations require continual assessment to ensure that they are not damaged and/or under the influence of surface water. Surface water sources also require frequent assessment and inspection; the majority of surface water outbreak treatment events were the result of chronic filtration deficiencies (53%).

Inadequate correction and/or response to an alerted event which may put the public at risk was not reported in any of the 61 outbreaks examined. A failure to respond or communicate risk to the public is suggestive of negligence on the part of, for example, a water provider, treatment operatives, the local council or the government; discussion of these factors may not be a focal point in medical literature – the scope may require expansion. Furthermore, many borderline issues relating to prolonged negligence on the part of water providers are likely to be classified under detection failures (for example, inadequate action based upon historical water quality results).

Many of the outbreaks identified and included in this article were UK *Cryptosporidium* outbreaks. Different approaches to waterborne disease surveillance can lead to variation in the effectiveness and nature of outbreak detection and reporting across member states (Risebro & Hunter 2007). Not all outbreaks will be detected nor reported let alone published. Information about outbreaks in the UK was likely to be more complete as authors had greater access to further information concerning these outbreaks. Splitting the data by pathogen group attempts to make the analysis more informative.

Only 61 of the 86 outbreaks identified had information on the cause of the outbreak and so were included in the fault tree analysis. The volume and nature of outbreaks and information identified from literature sources and reported in articles is subject to publication bias, hot-topic bias and outcome reporting bias. O' Brien *et al.* (2006) calculated various Publication Bias Indices (PBI) in a comparison of information about foodborne outbreaks from national surveillance data and peer-reviewed literature sources. When categorised into type of causative fault (e.g. cross-contamination or inadequate heat treatment) most faults were over-represented in the literature outbreaks compared to outbreaks from the surveillance dataset. When categorised by pathogen/toxin, outbreaks of *Campylobacteriosis* and *Escherichia coli* O157 were reported more often by literature outbreaks than by surveillance dataset outbreaks (PBI of 4.3 and 5.0 ($p<0.001$), respectively). Although the study by O'Brien and colleagues relates to foodborne rather than waterborne infections, it nonetheless demonstrates that information gathered from literature-based sources can provide a distorted viewpoint which does not necessarily reflect reality. The level of detail provided in literature sources used in this review of outbreaks related to public water supplies varied substantially, as did the documented accuracy and completeness of epidemiological investigation. It was difficult to determine if certain investigations had been overlooked or if they were simply not reported (outcome reporting bias). As a result, not all causative factors may have been included in the fault tree analysis. Although 13 outbreaks involved just one causal event, unreported and undetected causal events may have contributed. Accurately recording and reporting events and investigative findings from outbreaks generates an opportunity for others to learn from hindsight; it may prove beneficial to develop guidelines to standardise the reporting of outbreaks in the literature.

In addition to unreported factors, legislation and guidelines for water quality and public health policy governing EU member states were not examined. It is likely that such legislation and guidelines influenced the likelihood of certain causal events at different historical time points. Equally so, over the years scientific knowledge and expertise has advanced; problems relating to the absence of certain treatment practices and catchment protection programmes occurring in the early 1990s may not be seen in the early part of the 21st century.

Here the fault tree has been designed to be applicable to multiple outbreaks of enteric disease related to public drinking water supplies. However, the fault tree could be tailored to suit different drinking water systems, pathways and causative factors including human factors, mechanical failures, and additional point and non-point contaminant sources. In-depth analysis of further drinking water outbreaks involving different etiologic agents and drinking water supplies is required. Individual water companies could use such information to prioritise areas of concern and aid distribution of resources for outbreak prevention strategies.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the European Commission for funding the work presented in this paper (contract no. EVK1-CT-2002-00123). MD was also supported by the Gulbenkian Foundation and the British Council. The authors would like to thank the many professionals who provided further information and documentation on individual outbreaks, including: Volker Gornik and Thomas Kisteman (Institute of Hygiene and Public Health, University of Bonn, Germany); Henriette de Valk and Pascal Beaudeau (Institute de Veille Sanitaire (InVS), France); Jennifer Clay (North Cumbria Public Health, UK); Richard Elson, Gordon Nichols, Bengu Said and Bryan Smith (HPA, UK); Jean-Francois Loret (Suez Environment, France); and Torbjörn Lindberg (National Food Administration, Sweden).

This paper was presented in part at the International Water Association (IWA) 13th International Symposium on Health Related Water Microbiology (Watermicro), 4–9 September 2005, Swansea, Wales. This article also forms a more detailed expansion to work summarised elsewhere (Risebro *et al.* 2006).

DISCLAIMER

This paper was prepared while Miguel Doria was at the Centre for Environmental Risk, University of East Anglia, UK. The opinions and assertions contained in this paper should not be considered as reflecting the views or carrying the endorsement of the United Nations Educational, Scientific and Cultural Organization.

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APPENDIX: PRIMARY REFERENCES OF FTA OUTBREAKS

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