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A role for human reliability analysis (HRA) in preventing drinking water incidents and securing safe drinking water[1]

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Abstract

The prevalence of water quality incidents and disease outbreaks suggests an imperative to analyse and understand the roles of operators and organisations in the water supply system. One means considered in this paper is through human reliability analysis (HRA). We classify the human errors contributing to 62 drinking water accidents occurring in affluent

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countries from 1974 to 2001; define the lifecycle of these incidents; and adapt Reason's 'Swiss cheese' model for drinking water safety. We discuss the role of HRA in human error reduction and drinking water safety and propose a future research agenda for human error reduction in the water sector.

Keywords: human reliability analysis, human error, Swiss cheese model, drinking water safety, risk, analysis, management

1. Introduction

Preventative risk management has 're-emerged' as a central tenet of drinking water provision following publication of the revised WHO drinking water guidelines (WHO, 2006) and various investigations of disease outbreaks (Hrudey and Hrudey, 2004; Smeets et al. 2008). Risk analysis tools may provide valuable support to process design and optimisation (Pollard et al. 2004), but in isolation, and without being embedded an organisational culture of risk management, are limited in their ability to prevent incidents (Choudhrya et al. 2007). The authors of this paper have a long standing research interest in implementing preventative risk management among water suppliers, and in the role that recent initiatives play in raising the profile of preventative risk management (AWWA et al. 2001). Our studies have progressed beyond an inventory of risk analysis tools (MacGillivray et al. 2007a; 2007b), through an analysis of water quality incidents (Hrudey and Hrudey, 2004) and the benchmarking of water supplier competencies (MacGillivray and Pollard, 2008), to an exploration of the organisational relationships within water suppliers and between suppliers and health agencies (Pollard et al., 2009). Human actions and factors play an important role in water quality incidents (Pollard, 2008) to an extent that we believe a formal analysis of human reliability would be beneficial in preventing disease outbreaks. Here, we present a secondary analysis of Hrudey and Hrudey's (2004) case studies in water disease outbreaks and adopt Reason's (1990) 'Swiss cheese' model of organisational incidents in re-categorising the causal factors that influence disease outbreaks. Reason's model has wide application within the water sector and obvious parallels with the multi-barrier approach that includes several layers of defence to prevent water from contaminantion. Such defences include source water assessment and protection, the identification and correction of system defects, proper maintenance of the well and distribution system, the appropriate use of disinfection where necessary, and monitoring. We are interested in how we might extend Reason's analogy to improve human reliability in water supply operations, with the assistance of HRA (Kirwan, 1996; Kirwan et al. 1997; Kirwan, 1997).

Research attention in the reliability and maintenance community has conventionally been centred on physical and software systems. Industrial accidents were historically characterised in terms of technological malfunctions, and the human element in the cause of the accident tended to be overlooked (Gordon, 1998). A new subject, HRA, has attracted researchers' attention since the 1980s, since post-mortem analyses of fatal accidents have shown that accidents are strongly associated with human error. It is suggested that the cause of about 80% of all accidents can be attributed to human error (Whittingham, 2003). The term 'human reliability' is usually defined as the probability that a person will correctly perform some system-required activity during a given time period, without performing any extraneous activity that might degrade the system. HRA arose from the need to describe incorrect human actions in the context of probabilistic risk assessment (PRA) or probabilistic safety analyses (PSA) Hollnagel, 2000).

As with all risk analysis techniques, advocates and adversaries have emerged for HRA. However, a number of sectors (e.g. nuclear, transport, offshore oil and gas) have enthusiastically embraced HRA as one means of addressing their human factor and safety problems. Alternatively, these sectors have been required to apply them through public or government pressure. The nuclear industry was the first to develop and apply HRA (Kirwan, 1994), in part driven by public and regulatory fears of nuclear accidents and by the risks incurred by investing operational responsibility in the hands of a single control room operator. Other industries including aviation and aerospace, rail, air traffic control, automobile, offshore oil and gas, chemical, and all parts of the military have also applied HRA (Kletz, 1994; Lyons, et al. 2004). A comprehensive review of the distribution of the HRA literature (1981-2003) is provided by Dhillon and Liu (2006), together with a distribution of applied research in various sectors (Figure 1). Their analysis offers little information on the application of HRA to drinking water safety. How then might HRA help the sector?

<<Figure 1: Publication distribution of HRA by industrial sector (adapted from Dhillon and Liu, 2006)>>

Hrudey & Hrudey (2004) studies cases of disease outbreaks in 15 affluent nations over the past 30 years, which provides a detailed retrospective analysis of those water incidents. Below, we reappraise 62 cases of drinking water accidents (Hrudey and Hrudey, 2004), and classify human errors that directly or indirectly cause these accidents, analysing the development process of accidents. We argue that the Reason Swiss cheese model requires modification for drinking water safety, and we offer a revised model.

2 Error and human reliability analysis

HRA applies relevant information about human characteristics and behaviour to the design of objects, facilities, processes and environments that people use (Grandjean, 1980). HRA techniques may be used retrospectively, in the analysis of incidents (though this occurs infrequently), or prospectively to examine a system and its vulnerabilities during the design phase. Most approaches are grounded in a systemic approach, which sees the human contribution in the context of the wider technical and organisational context (Embrey, 2000). The purpose of HRA is to examine any human-involved systems or processes where weaknesses may lie or create a vulnerability to errors, rather than to find faults or apportion blame.

2.1 Error classification

Error classification describes the types of errors that humans make. A number of taxonomies exist (Meister, 1971; Swain and Guttman, 1983; Reason 1990). The most commonly used system, proposed by Reason (1990), is to classify human errors into slips, lapses, mistakes, and violations. Two theoretical perspectives on human error in complex, sociotechnical systems are the ‘person’ approach and the ‘systems’ perspective. Person approach (Reason, 2000) errors arise from aberrant mental processes such as forgetfulness, inattention, poor motivation, carelessness, negligence, and recklessness. Here, human error is treated as the cause of most accidents, and the systems in which people work are assumed to be safe. The systems perspective (Reason, 2000) treats error as a systems rather than an individual’s failure, and considers the combined role of latent conditions (e.g. inadequate equipment, poor design, inadequate supervision, manufacturing defects, maintenance failures, inadequate training, clumsy automation, inappropriate or ill-defined procedures) and human errors (also known as active errors or failures) in accident causation and propagation. Human error is no longer treated as the primary cause of accidents; rather as a consequence of latent conditions residing within the system.

Reason (1990) describes four levels of human failure, each influencing the next (Figure 2). In his Swiss cheese model, Reason hypothesises that most accidents can be traced to one or more of four levels of failure: organizational influences, unsafe supervision, preconditions for unsafe acts, and the unsafe acts themselves. An organization's defences against failure are modelled as a series of barriers, represented as the slices of a Swiss cheese. The ‘holes’ in the cheese slices represent individual weaknesses in individual parts of the system, and are dynamically varying in size and position across all slices. Unsafe acts can be seen as active failures, whereas the remaining three slices in Figure 2 are latent failures. The main distinction between active and latent failures lies in:

- Active errors. The consequences of active errors may become apparent within a very short time; such errors can be an omission or using the wrong rule. They are most likely to be caused by front-line operators;
- Latent errors. The consequences of latent errors may only become apparent after a period of time, or when combined with other errors, or particular operational conditions.

Figure 2 The Swiss cheese model (redrawn from Reason 1990)

A brief description of each of the levels and their associated taxonomies is given below.

- Unsafe acts are largely due to operators. These are caused by an operator’s lack of knowledge or poor choices; for example, in an incorrect response to an emergency, or poor decision, etc;

- Preconditions for unsafe acts exist because of adverse mental states that affect performance; for example, loss of situational awareness, and inattention or distraction, or a failure to communicate or coordinate.
- Unsafe supervision occurs through inadequate guidance or oversight, or a failure to provide adequate training.
- Organisational influences such as process or managerial errors result from inadequate or misinterpreted corporate decisions, for example, a failure to provide adequate guidance or inadequate documentation, or the attitudes and behaviours of employees and contractors, etc.

2.2 Error reduction and management

Error management programmes use formal methods to develop a deeper understanding of the nature of, and factors surrounding, error in a particular system. The goal of error management is the eradication, reduction, management and mitigation of errors and their consequences. Reason again (1997) cites a wide range of error management techniques, including selection, training, licensing and certification and skill checks. The techniques of human error prediction are particularly useful. A typical HRA modelling process includes three stages: (1) the identification of human errors, (2) the prediction of their likelihood, and (3) the reduction of their likelihood, if required.

HRA techniques are commonly categorized into two generations. The first-generation were developed for the probabilistic safety assessment of plant risk whereas the second generation applied cognition analysis. First generation tools include the tools THERP (Swain and Guttmann, 1983), HEART (Williams, 1986), SLIM (Embrey, 1984), ASEP (Swain 1987), TESEO (Bello and Colombari, 1980) and HCR (Hannaman, 1984). The second generation tools include ATHEANA (Cooper et.al. 1996), CREAM (Hollnagel, 1998), or MERMOS (Bieder, 1998). By illustration, in the HEART methodology, the failure rate is estimated using an empirical expression of the form:

$$\lambda = \lambda_b \left\{ \prod_{1=1}^{M} \left(EPC_i - 1\right). Ap_i + 1 \right\}$$
$$HEP = HEP_b \left\{ \prod_{1=1}^{M} \left(EPC_i - 1\right). Ap_i + 1 \right\} \qquad (1)$$

where HEP is the human error probability, HEP_b is the nominal human error probability , λ is the overall human error rate , λ_b is nominal human error rate, EPC_i is the ith error promoting condition and Ap_i is a proportion assessment factor for the ith EPC. Here, the error promoting condition can be unfamiliarity, time shortage, noisy or confused signals/communications, poor man machine interface, misperception of risk, poor feedback, inexperience, poor instructions, etc. For example, a given task has the proposed nominal human unreliability value of 0.002, and the factors shown in Table 1.

Table 1: Estimating human error probability.

The final calculation for the human error probability can therefore be given by:

$$HEP=0.002 \times 1.5 \times 3.4 \times 2.2 \times 1.25 \times 1.4 = 0.04$$

3 Applying HRA in the water utility sector

From a physical asset perspective, a drinking water distribution system is an interconnected collection of sources, pipes, and hydraulic control elements (pumps, valves, regulators, and tanks), delivering safe drinking water to consumers in prescribed quantities and at desired pressures. It can be composed of water sources, raw water transmission pipes, unit water treatment processes combined together in treatment plants, and water distribution networks. Unlike conventional HRA applications that involve smaller, highly contained systems (e.g. nuclear plants, aeroplanes), water distribution systems are widely distributed. To illustrate application of Reason's model, we select 62 drinking water incidents from Hrudey and Hrudey (2004) and categorise the human errors in these cases (Table 7). A distribution of the main errors is shown in Table 2 and Figure 3, suggesting that 38% of direct and/or indirect causes can be due to active errors, 36% in the class of latent errors and 3% attributed to consumers and/or regulators. Table 3 lists some failures due to physical or environmental problems. Our definitions are presented in Tables 4-6. One may argue that the errors in Table 4 can be classified as latent and attributable to multiple actors. From Table 2, we note that among the 65 active errors, 16 are attributable to a "mistaken belief in the security of a water system", 11 are attributable to a failure "to recognise warnings" and 19 to a failure "to take adequate measures on warning". All of the three types of errors can traced to organisation structures.

Table 2. Human error distribution in the 62 cases.

Figure 3 Human error distribution.

The literature review indicates that, in comparison to other domains in which HRA has been identified as a major problem, the construct has received relatively little attention within the water sector. This is surprising given the apparently significant role of human error reported by Hrudey and Hrudey (2004; Table 2). Latent errors contribute significantly to the human errors in the 62 cases (Table 2) suggesting organisational reliability is a critical factor contributing to drinking water incidents.

3.1 The gestation of drinking water incidents

Unlike accidents in other industries, many drinking water incidents last for extended periods from the initial period of contamination to the restoration of safe drinking water quality. The immediate outbreaks in Milwaukee (case 38; Table 7) and in Walkerton (case 57; Table 7), lasted more than one month with subsequent consequences lasting for many months and years thereafter. Another example of the extended duration of drinking water incidents is the accidental contamination of drinking water supplies in north Cornwall that occurred in July 1988, the long term health impacts of which has been reviewed on a number of occasions, most recently in 2005 (DoH, 2005). Whilst there is no opportunity for recall once drinking water has been supplied, responsive action by water suppliers and health agencies may still reduce impacts on consumers. The gestation of a typical drinking water incident might be represented by Figure 4.

1) Contamination phase. This period is the time starting from the occurrence of a triggering cause capable of contaminating the drinking water until the time that the drinking water is actually contaminated. The contaminating period can be hard to estimate exactly. The cause can be due to extreme weather (e.g. the heavy rainfall in case 57), or unsafe maintenance work (e.g. a sewerage system maintenance exposing water distribution to risk in case 30), or wastes from infected wildlife (e.g. infected beavers in case 7). Numerous human errors may occur in this period, such as maintenance errors (e.g. case 30), design errors (e.g. case 57), unsafe acts (e.g. case 16).
2) Sensing phase. Abnormalities associated with the contaminated water can be sensed by either consumers or quality monitoring systems. Human errors that might occur include: failure to perform routine monitoring (e.g. case 17, 57); design errors in the monitoring system (e.g. case 23); failure to interpret monitoring results correctly (e.g. case 59); failure to respond to consumer complaints (e.g. case 38).
3) Alarm phase. This is the time between abnormalities being sensed and warning(s) being signalled. After consumers or monitoring systems have sensed any abnormalities about water, alarms should be raised to engender a response. A

common human error in this period is that no warning signals are raised or warnings are inadequate. For example, infected consumers were not recognized to signal warnings (e.g. case 43) or did not signal warnings in a timely manner (e.g. case 59).

4) Recognition period. Although warnings about abnormalities have been signalled, they have ignored or not been paid enough attention. Human errors in this period can be: failure to respond to warnings (e.g. cases 2, 13, 20, 22, 35, 37, 54, 57, 61), inadequate response to warnings (e.g. cases 9, 10), etc. It should be noticed that raising warnings or issuing a boil water advisory might be a difficult measure for a water company to take on its own but such decisions should ideally be coordinated with public health authorities. Frequent warnings or issuing boil water advisories can damage a company's reputation, but failure to provide warnings when they are required will certainly attract liability.
5) Investigation and recovery phase. The previous four phases might not all exist for accidents occurring in other industries, for example, the crash of an aeroplane or the explosion of a chemical plant. However, common to all accidents is the need for an investigation and recovery period after an accident occurs. In both literature and post-mortem analysis reports, no discussion on human error occurring in this period has been found. However, an obvious human error that is likely to be all too common would be denial, leading to an inadequate investigation.

It should be noted that drinking water incidents do not necessarily go through all of the above periods. They may have only some of the periods as shown in Figure 4.

Figure 4 A typical gestation for a drinking water incident.

3.2 A modified Swiss cheese model

The Reason Swiss cheese model has two limitations restricting its application, unmodified, to drinking water accidents. Firstly, an accident is defined as a one-off event lasting for a very short time, which is the case for aeroplane crashes, or explosions at chemical plant. However, drinking water incidents are seldom one-off events; they usually develop with time and often last for several days. The gestation (or lifecycle) of a typical drinking water incident is presented in Figure 4. Secondly, the organisational boundary for drinking water incidents extends well beyond the corporate structure to include other stakeholders. From the 61 case studies, we notice that water consumers and regulators can play important roles in preventing more serious outcomes during these events. Their involvement can be to sense abnormalities, to report abnormalities, and to comply with measures their drinking water supplier has taken:

- To sense abnormalities. This is often the first critical step in drinking water incidents. For example, in case 34, a consumer had sensed a foul smell but didn't report the abnormality, this also happened in case 54.
- To report abnormalities. Early warning signals are critical. Since a drinking water system is commonly a widely distributed system, it can be hard for the water supplier to sense every abnormality the whole time. It is vitally important that consumers report any abnormalities about their drinking water and systems to their supplier. Hrudey and Hrudey (2004) comment:

> The observation that the earliest signs of this outbreak were signalled by consumer complaints about excess turbidity provides an important message to drinking water providers about the attention that should be paid to consumer complaints about water quality (page 177, Hrudey and Hrudey, 2004)

> This case study provides another example where consumers noticed the water was *"off"*. This observation might have provided an opportunity for earlier intervention if the first mention of a consumer noticing something wrong had been reported and acted upon (page 220, Hrudey and Hrudey, 2004).

For example, in case 38, it is the drinking water supplier who failed to recognize warning signals from consumer complaints.

To comply with measures their drinking water company has taken. During disease outbreaks compliance with boil water notices (advisories) can be vital to preventing propagation of disease. Although it has been reported that the effectiveness of boil water advisories is questionable given the evidence that compliance is far from universal and reduces with time(O'Donnell, Platt and Alston, 2000; Willcocks et al, 2000; Karagianmis, Schimmer and de Rouda Husman, 2008), collaborations from water consumers are still important. Again, as Hrudey and Hrudey (2004) indicated:

> This finding raises concern about the level of understanding that may exist in a community during the boil water advisory and raises the need for an explanatory literature to be provided to any population at risk immediately after a boil water advisory is issued (page 287, Hrudey and Hrudey 2004).

Equally, regulators play an important role in preventing drinking water accidents. For example, in case 7, one of the causes was that regulators failed to appreciate the vulnerability of surface water, and in case 57, regulators failed to implement policy requiring continuous chlorine residual monitors on vulnerable shallow wells. Viewing Table 7, the main contributions of error involved the following:

- customers sensed abnormalities, but failed to report to their water supplier;
- customers sensed abnormalities, reported to their water suppliers, but the supplier then failed to respond to the reports;
- customer sensed abnormalities and reported to their water suppliers which responded to the reports, and accidents were successfully prevented. These may have happened in many cases but have not been reported.

The Swiss cheese model does not consider the role of third parties beyond the scope of an individual company or organisation. From this analysis however, it is suggested that third parties (regulators and the drinking water consumers), be considered in the HRA of drinking water incidents. We therefore propose another ‘slice’ of cheese to represent the consumer and third parties (Figure 5). It is conceptually presented with more holes, suggesting that this slice might arguably be the weakest barrier of a system. However, a forward-looking water utility can strengthen the protection offered by this slice by engaging their public health agency in constructive dialogue and informing consumers about their reasonable expectations for water quality and how they should respond when those expectations are not being met.

It can be surmised that the systems perspective approach to human error has greater potential in analysing the safety of a drinking water system than the person approach as the former considers not only the errors made by individual operators within the system, but also the role of various latent conditions that reside within the system. From the above analysis, monitoring, assuring and improving the safety of drinking water systems requires various levels of stakeholder participation and responsibilities. In their analysis of two water incidents (Case 47 and Case 59 in Table 7), Woo and Vicente (2003a) conclude that effective risk management should consider various actors at each level including government, regulators/associations, company, management, staff and work. These levels constitute a complex sociotechnical system of risk management (Rasmussen, 1997). Research on the impact on drinking water safety can also be found in Vicente and Christoffersen (2006), Hrudey and Hrudey (2003), Woo and Vicente (2003b), and Vicente and Christoffersen (2006).

The Swiss cheese model can be developed along with a consideration of approaches used in risk management for dynamic sociotechnical systems. The Swiss cheese model does not mention that the number of holes and the locations and sizes of holes in a slice can dynamically change but this is self evident. The dynamic forces that lead to accidents have often been in place for some time, yet the feedback to reveal the safety implications of these forces is often largely unavailable to the actors observing these systems (Vicente and Christoffersen, 2006)

Figure 5 A Swiss cheese model for drinking water safety.

4 Concluding remarks

Major accidents are almost always the result of multiple errors, or combinations of single errors with pre-existing vulnerable conditions (Wagenaar et al., 1990). The incidents in the water sector are combinations of many errors. Not all HRA techniques are suitable for application in the water utility sector. However, drinking water incidents can be caused by a lack of sufficient vigilance regarding warning signals (that might lead to such incidents), poor system design, poor installation; and poor maintenance. All of these can be regarded as involving human error to a certain degree. Most of the current HRA approaches have been developed for a single organisation, but safe drinking water is widely understood as a collective responsibility (IWA, 2004). Therefore, the Swiss cheese model requires amendment for the context of drinking water systems. Here we have defined the gestation and lifecycle of drinking water incidents and investigated human errors in each period of the lifecycle; and developed an extended Swiss cheese model that depicts barriers existing in drinking water safety. Through a re-analysis of case studies, we have reconfirmed the long delay time of drinking water incidents and reported the active role of latent errors, and third parties. Critically, we reassert the necessity of proactive, preventative risk management in identifying and remedying latent conditions. Pertinent areas for future research include:

- The development of human error databases. Research into how to collect and analyse human error data and the application of error management approaches within water utilities is required.

- Investigation of the lifecycle of drinking water accidents. Understanding the distribution of human errors across the lifecycle of drinking water incidents might help reduce errors and allow targeted action
- Development of human error management tools. We suggest error management, warning handling and error prediction tools are required for the drinking water sector. An on-line tool may be useful for this purpose.
- Development of effective warning systems. For the new slice in Figure 5, emergency population warning (EPW) systems, for example, have been used for tornadoes, hurricanes, and ice storms; geological incidents such as earthquakes, landslides, volcanic eruptions, and tsunamis. It is a method whereby local, regional, or national authorities can contact members of the public en masse to warn them of an impending emergency. Might such a method help contain drinking water outbreaks?
- Addressing overconfidence arising from the infrequent occurrence of drinking water outbreaks in developed countries making the maintenance of informed vigilance a management challenge.

To pursue the above mentioned research, we shall develop a software prototype that is composed of the following subsystems: a database containing drinking water incidents, a modelling sub-system that can learn from the incidents and build incident prediction models for the purpose of preventing latter incidents, and a management sub-system that can help in EPW.

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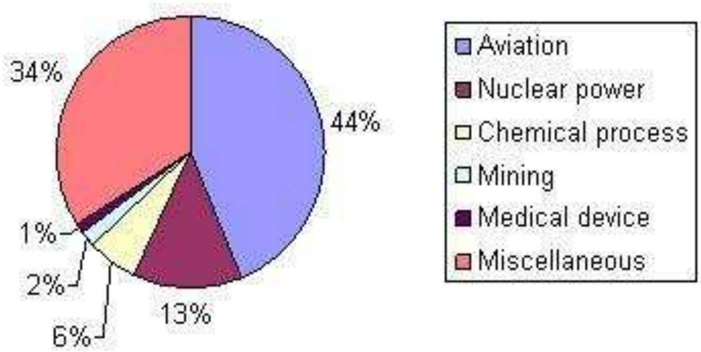

Figure 1: Publication distribution of HRA (adapted from Dhillon and Liu, 2006).

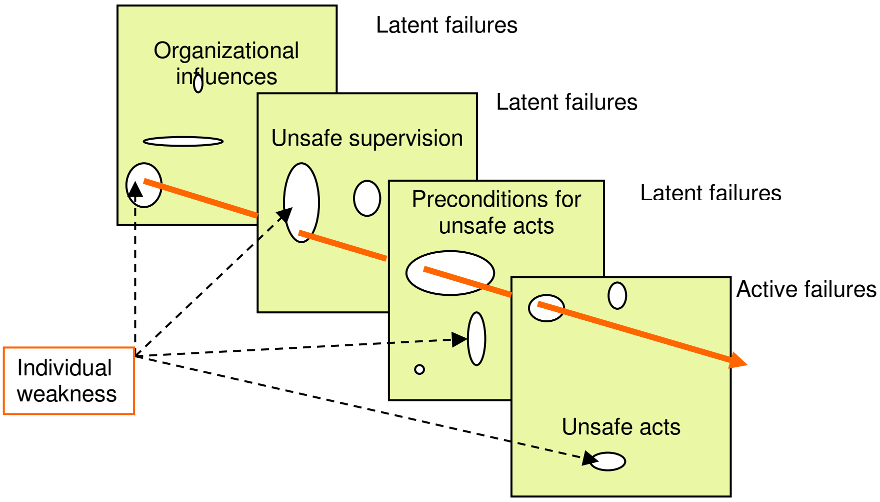

Figure 2 The Swiss cheese model (redrawn from Reason1990).

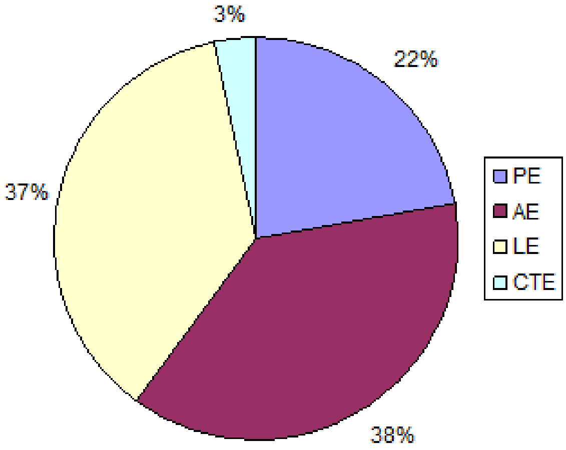

Figure 3 Human error distribution.

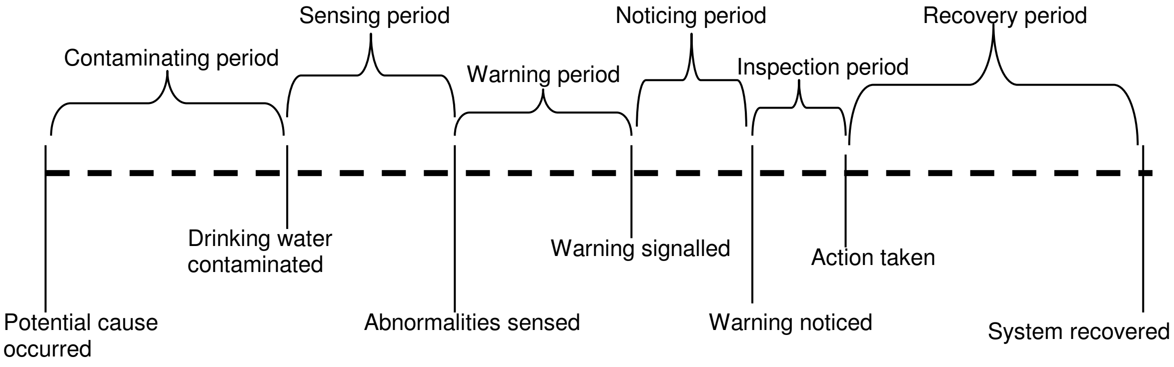

Figure 4 A typical gestation for a drinking water incident.

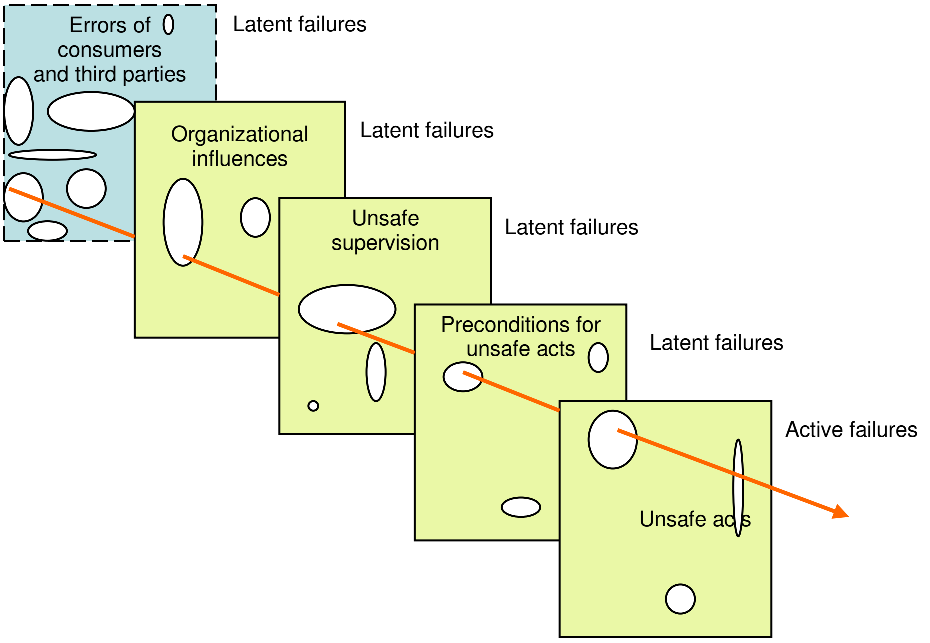

Figure 5 A Swiss cheese model for drinking water *safety*.

Table 1: Estimating human error probability

Factor	Error promoting condition	Proportion assessment factor	Assessed Effect
Inexperience	2	0.5	(2-1) × 0.5 + 1 =1.5
Opposite technique	4	0.8	(4-1) × 0.8 + 1 =3.4
Risk Misperception	3	0.6	(3-1) × 0.6 + 1 =2.2
Conflict of Objectives	1.5	0.5	(1.5-1) × 0.5 + 1 =1.25
Low Morale	2	0.4	(2-1) × 0.4 + 1 =1.4

Table 2: Human error distribution in the 61 cases.

Error classification		Occurrences
Physical system failures and extreme environmental conditions (PE)		39
Active errors (AE)	Mistaken belief of the security of a water system	16
	Failed to recognise warnings	11
	Failed to take adequate measures on warnings	19
	Others	20
	Subtotal of the occurrences of active errors	66
Latent errors (LE)		64
Influences from consumers, third parties (CTE)		6
Total		172

Table 3. Physical system failures and extreme environmental conditions (PE).

- Equipment failure
- Disease-carrying animals
- Animal waste
- Extreme weather

Table 4. Active errors (AE).

- Failed to appreciate the vulnerability of water systems
- Failed to recognise warning signals
- Failed take adequate measures after waning signals were received
- Sanitary violations
- Failed to follow recommendation

Table 5. Latent errors (LE).

- Design errors
    - A lack of sufficient water safety barriers
    - Deficiencies existed in system
    - Raw water not being isolated from animal wastes
- Maintenance errors
- Operation errors
- Insufficiently qualified staff
- Inadequately trained operators
- Communication error

Table 6. Influences from consumers, third parties (CTE).

- Failure to inform new residents and visitors consuming undisinfected surface water
- Failure to report warning signals
- Failure to appreciate of the risk of disease transmission
- A lack of cooperation or interaction among various parties responsible for water safety
- Poor communication among various parties
- Regulator failed to implement policy

Table 7. 61 Drinking water incident cases and their corresponding human errors.

No	Place, time	Possible causes
1	Richmond Heights, Florida, USA., January-Mar 1974	• Failure in a physical system (PE) • Mistaken belief in the security of the groundwater supply (AE) • Poor operating practices (LE) • Failed to take adequate action to protect consumers after the fault was recognised (AE)
2	Rome, New York, USA., Nov 1974-Jun 1975	• Failed to recognize that the level of chloramination was too low (AE) • A lack of water filtration (LE) • Warnings being unheeded (AE)
3	Crater Lake, Oregon, USA., Jun-Jul 1975	• Extreme weather caused water contamination (PE)
4	Camas, Washington, USA, Apr-May 1976	• Errors in design of the water system (LE) • Poor operating practice (LE) • Infected animal (PE) • Physical system failure (PE)
5	Berlin, New Hampshire, USA, Mar-May 1977	• Physical system failure (PE) • Serious deficiencies in the rebuilt filters (LE) • Violations of regulations found (AE)
6	Bennington, Vermont, USA, May 1978	• Inadequate response to the conditions that triggered outbreak warnings (AE)
7	Bradford, Pennsylvania, USA, Jul-Dec 1979	• Operators failed to appreciate the vulnerability of surface water sources (AE) • Regulators failed to appreciate the vulnerability of surface water sources (CTE) • Infected animals (PE) • Extreme weather (PE) • Failed to equip with sufficient barriers (LE) • Inadequate operating practice (LE)
8	Georgetown, Texas, USA, Jun 1980	• Failed to understand the vulnerability of groundwater (AE) • Failed to recognize signals from the first outbreak (AE) • Failed to equip the water system (LE) • Extreme weather (PE)
9	Red Lodge, Montana, USA, Jun-Aug 1980	• Failed to appreciate the vulnerability of the surface water supply (AE) • Insufficient water treatment (LE) • Failed to effectively respond to warning signals (AE)
10	Bramham, Yorkshire, England, July 1980	• Staff intentionally kept chlorine levels low (AE) • Failed to effectively respond to warning signals (AE) • Physical system failure (PE)
11	Rome, Georgia, USA, August 1980	• Poor isolation of the textile plant distribution system from the drinking water system (LE) • Failed to protect the water supply system (AE)
12	Grums and Valberg, Varmland, Sweden, Oct 1980	• Failed to isolate the water supply system from the river water irrigation systems (LE)
13	Eagle-Vail, Colorado, USA, Mar 1981	• Inadequate operation (LE) • Failed to investigate an alarm (AE) • Failed to equip with effective barriers (LE)
14	Mjovik, Blekinge, Sweden, Oct 1992	• Failure of a sewer system (PE) • Failed to provide disinfection in the water system (LE) • Failed to know the system thoroughly (AE)
15	Drumheller, Alberta, Canada, Feb 1983	• Failure in a physical system (PE) • Extreme weather (PE) • A lack of cooperation or interaction among various parties (CTE) • Failed to issue a boil water advisory earlier (AE) • Failed to recognise vulnerable situation of sewage pump station (AE) • Operating winter treatment without coagulation made system vulnerable (LE)

16	Greenville, Florida, USA, May 1983	• Bird droppings (PE) • Poor design of the treatment system (LE) • Unsafe acts by operators (AE) • Staffing an unlicensed operator (LE)
17	Braun Station, Texas, USA, May-Jul 1984	• Failed to monitor raw well water (AE) • Flawed design in the system (LE)
18	Alsvag, Norway, June-Jul 1984	• Animal waste (PE) • Failed to provide treatment for the surface water supply (LE)
19	Orangeville, Ontario, Canada, Apr 1985	• A lack of chlorination (LE) • Animal waste (PE)
20	Pittsfield, Massachusetts, USA, Nov 1985-Jan 1986	• Malfunction in the chlorination equipment (PE) • Failed to provide sufficient barriers or treatment (LE) • Failed to respond to warning signals (AE) • Failed to recognise that an outbreak was in progress (AE) • Poor operating practice (LE)
21	Penticton, B.C., Canada, Jun and Nov 1986	• Inadequate water treatment (LE) • Extreme weather (PE) • Animal waste (PE)
22	Salen, Dalarna, Sweden, Dec 1986-Jan 1987	• Failure in the sewer system (PE) • Failed to respond to warning signals (AE) • Poor design in backflow prevention (LE)
23	Carrollton, Georgia, USA, Jan 1987	• Inadequate operation: they did not follow proper filtration protocols (AE) • Poor design in the monitoring system (LE)
24	Sunbury, Diggers Rest and Bulla, Victoira, Australisa, Oct 1987	• Incorrect judgement that unprotected surface water can be supplied to consumers without any treatment barriers (AE) • No effective barriers (LE)
25	Boden, Sweden, March-Apr 1988	• Physical system failure (PE) • Extreme weather (PE) • Failed to provide sufficient water treatment (LE)
26	Saltcoats/Stevenston, Ayrshire, Scotland, Mar-Apr 1988	• Inadequate construction and repair (LE) • Failed to recognize livestock wastes as a major source of human pathogens (AE) • Failed to meet regulations (LE)
27	Skjervoy, Norway, July-Aug 1988	• Absence of disinfection (LE) • Failed to signal warnings (AE)
28	Swindon, Oxfordshire and Wiltshire, England, Dec 1988-Apr 1989	• Inadequately treating recycling filter backwash water (AE) • Poor operating practice (LE)
29	Oakcreek Canyon, Sedona, Arizona, USA, Apr 1989	• Failed to confirm and verify the security (AE) • Unforeseen contamination scenario (AE) • A lack of any disinfection barrier (LE)
30	Cabool, Missouri, USA, Dec 1989-Jan 1990	• Risks associated with water main break repair during extreme weather not recognized (AE) • Poor sewerage systems maintenance exposing water distribution to risk (LE) • No treatment barrier in place (LE)
31	Moama, New South Wales, Australia, Dec 1989-Jan 1990	• Failed to recognise or understand the risks of drinking non-potable water (AE) • Maintenance error: broken sewer system (LE)
32	Creston/Erickson, Canada, Jan-Apr 1990	• Infected animal (PE)
34	Naas, Count Kildare, Ireland, Oct 1991	• Failurein the physical system (PE) • Consumers failed to report warnings (CTE)
35	Uggelose, Denmark, Dec 1991-Jan 1992	• Extreme weather (PE) • Failure of a physical system (PE) • Failed to respond to queries about the potential dangers posed by a connection (LE) • Failed to signal sufficient warnings despite a risk having been raised (AE)

36	Jackson County, Oregon, USA, Jan-Jun 1992	• Animal waste (PE) • Extreme weather (PE) • Failed to provide sufficient barriers (LE) • Poor treatment performance (AE)
37	Warrington, Cheshire, England, Nov 1992-Feb 1993	• Extreme weather (PE) • Failed to investigate the warning signals even when abnormal turbidity reading presented (AE) • Failed to conduct routine monitoring (LE)
38	Milwaukee, Wisconsin, USA, Mar–Apr 1993	• Risks associated with sewage contamination of water intake not recognized (AE) • Apparently not aware of Cryptosporidium risk (AE) • Failed to maintain optimum filtration performance (LE) • Failed to recognize signal from consumer complaints (AE)
39	Gideon, Missouri, USA, Nov–Dec, 1993	• Poor maintenance of water storage allowed faecal contamination (LE) • Animal waste (PE) • Extreme weather (PE) • Water quality management not based on good knowledge of system (AE) • No treatment barrier in place (LE)
40	Noormarkku, Finland, Apr 1994	• Failed to protect the water supply by disinfection (AE) • Failed to recognize the dangers posed by flooding conditions (AE) • Failed to take appropriate sanitary measures (AE)
41	Temagami, Ontario, Canada, Feb-May 1994	• Infected animal (PE) • Extreme weather (PE) • Poor performance and inadequate design of the water system (LE,AE) • Poor operation of the package water-treatment plants (AE)
42	Victoria, B.C., Canada, Oct 1994-May 1995	• Infected animal (PE) • A lack of an effective and robust treatment barrier (LE)
43	Village in Fife, Scotland, Mar 1995	• Failure of a physical system (PE) • Failed to signal warnings promptly (AE)
44	South Devon, England, Aug-Sep 1995	• Failure of a physical system (PE) • Deficiencies in the operation (LE) • Failed to pay adequate attention to recommendations (AE)
45	Klarup, North Jutland, Denmark, Dec 1995-Mar 1996	• Failed to follow up unusual events (AE) • A lack of an adequate treatment system (LE)
46	Cranbrook, B.C.,Canada, May-Jun 1996	• Animal waste (PE) • Raw water not being isolated from livestock (LE)
47	Ogose Town, Saitama Prefecture, Japan, Jun 1996	• Failure of a physical system (PE) • Failed to recognise a major disease risk (AE)
48	Stromsund, Jamtland, Sweden, Aug-Sep 1996	• Animal waste (PE) • Failed to isolate the water system from animal wastes (LE)
49	NW London and W Hertfordshire, England, Feb 1997	• Extreme weather (PE) • Failed to follow the recommendations of the reports on preventing Crytosporidium contamination (AE,LE)
50	Resort Hotel, Bermuda, Feb 1998	• Failure in physical systems (PE) • No awareness of the system vulnerability (AE) • Sanitary deficiencies in the unchlorinated water system (LE) • Poor maintenance of the water system (LE)
51	Heinavesi, Finland, Mar 1998	• Failed to understand the mixing behaviour of sewage effluents (AE) • Poor knowledge about water treatment (AE)
52	Alpine, Wyoming, USA, Jun-Jul 1998	• Failed to protect and treat water systems (LE)
53	Brushy Creek, Williamson County, Texas, USA, Jul 1998	• Wrong assumption on the safety of groundwater (AE)
54	La Neuveville, Bern Canton, Switzerland,	• Frequent false alarms on failures, but paid attention to(AE) • Failure of a physical system (PE)

	Aug 1998	• Consumers failed to report abnormalities (CTE)
55	Washington County Fair New York USA, Sept 1999	• Not aware of risk from septic seepage field (AE) • Allowed use of unchlorinated water from a shallow well (LE) • Failed to consider that extreme drought of previous summer might affect water supply safety (AE)
56	Clitheroe, Lancashire, England, Mar 2000	• Deficiencies in the security being found (LE) • Failed to follow up or act on the deficiencies that an effective risk assessment should reveal (AE)
57	Walkerton Ontario Canada, May 2000	• Ignored warnings about vulnerability of shallow well when first installed in 1978 (AE) • Failed to adopt source protection recommendations at installation (LE) • Regulator failed to implement policy requiring continuous chlorine residual monitors on vulnerable shallow wells (CTE) • Operators inadequately trained with no knowledge that contaminated water could kill consumers (AE) • Failed to recognize that extreme weather could cause water contamination (AE) • Failed to maintain chlorine residuals (LE) • Failed to monitor chlorine residuals as required (AE)
58	Resort, Gulf of Taranto, Italy, Jul 2000	• Resort water supply placed at risk by poor design and unsanitary practices (LE) • Consumers failed to be aware of the risk of disease transmission (CTE)
59	North Battleford, Canada, Mar-Apr 2001	• Failed to fix a long-standing vulnerability of water intake downstream of sewage discharge (LE) • Failure to recognise risk from Cryptosporidium if fine particle removal not optimal (LE) • Poorly timed and inadequately performed maintenance on water treatment plant (AE) • Slow recognition of pattern of illness as an indication of a waterborne outbreak. (LE)
60	Asikkala, Finland, Aug 2000, Aug 2001 and Oct, Nov 2001	• Failed to provide disinfection for insecure water (LE)
61	Boarding School, Hawke’s Bay, New Zealand, May 2001	• Failed to protect the water source from grazing cattle (LE) • Failed to maintain the UV treatment system (LE)
62	Camp/Conference Centre, Stockholm County, Sweden, May-Jun 2001	• Failed to investigate warning alarms and take further action to prevent the system from contamination (LE) • Failed to provide barriers in place to protect consumers from contaminated water (LE) • Failed to maintain aged sewers (LE)