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The Walkerton *E. coli* outbreak: a test of Rasmussen's framework for risk management in a dynamic society

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In May 2000, the water transportation system in Walkerton, Ontario (a small town with 4800 residents) became contaminated with *E. coli* bacteria, eventually causing seven people to die and 2300 to become sick. The 700-page report from a comprehensive public inquiry into this tragedy provided a rich source of data about the outbreak itself and the factors leading up to it. That report was used to test the explanatory adequacy of Rasmussen's framework for risk management in a dynamic society. Close agreement was observed between the predictions of the framework and the causes contributing to the Walkerton outbreak. The sequence of events reveals a complex interaction between all of the levels in a complex sociotechnical system spanning strictly physical factors, the unsafe practices of individual workers, inadequate oversight and enforcement by local government and a provincial regulatory agency and budget reductions imposed by the provincial government. Furthermore, the dynamic forces that led to the accident had been in place for some time—some going back 20 years—yet the feedback to reveal the safety implications of these forces was largely unavailable to the various actors in the system. Rasmussen's framework provides a theoretical basis for abstracting from the details of this particular incident, thereby highlighting generalizable lessons that might be used to ensure the safety of other complex sociotechnical systems.

Keywords: Risk management; Safety; Public health; Water quality

1. Introduction

> We need more studies of the vertical interaction among levels of socio-technical systems with reference to the nature of the technological hazard they are assumed to control (Rasmussen 1997, p. 187).

> I was born and raised in Walkerton and have lots of memories of this town ... but now ... When I think of Walkerton I think of *E. coli* and the death of my mother. I find it difficult to be in Walkerton. I don't enjoy it like I once did .... This tragedy has affected me every day (Terry Trushinski, cited in O'Connor 2002a, pp. 46–47).

In May 2000, the water supply system in Walkerton, Ontario became contaminated with deadly *E. coli* bacteria. In a town of 4800 residents, seven people died and an

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estimated 2300 became sick. Some people, especially children, are expected to experience lasting health effects. The total economic cost of the tragedy was estimated to be over $64.5 million CAD.

In the aftermath of the deaths and illnesses, citizens were terrified of using tap water to satisfy basic human needs. Those who were infected or lost loved ones suffered tremendous psychological trauma, their neighbours, friends and families were terrorized by anxiety and many across the province of Ontario and the rest of Canada worried about how the fatal event could happen and whether it could possibly occur again in their town or city. Attention-grabbing headline news stories continued unabated for months in newspapers, on radio and on television. Eventually, the provincial government appointed an independent commission to conduct a public inquiry into the causes of the disaster and to make recommendations for change. Over the course of 9 months, the commission held publicly-televised hearings, culminating in the politically-devastating interrogation of the Premier of Ontario (the leader of the provincial government) himself. On 14 January 2002, the Walkerton Inquiry Commission delivered Part I of its report to the Attorney General of the Province of Ontario (O'Connor 2002a).

The purpose of this article is to use the Walkerton *E. coli* outbreak as a case study to evaluate the ability of Rasmussen's (1997) risk management framework to explain how and why large-scale industrial accidents occur in a dynamic society. While there are many reports, articles or books in the literature analysing well-known accidents (e.g. Oversight Hearings 1979, Vaughan 1996, Commission of Inquiry on the Blood System in Canada 1997), there appear to be far fewer articles that use an accident as a case study to test the explanatory adequacy of an existing theoretical framework. Given the comparatively meagre number of such studies, it would be premature to conduct a comparative test of various competing frameworks unless one can first establish that a particular framework has some success in accommodating a body of evidence. For this reason, only one framework was chosen for analysis here. Rasmussen's work was chosen for two reasons: (a) it represents the culmination of almost 40 years of systematic research on risk management in complex systems (see Rasmussen *et al.* 1994, Vicente 1999, 2001 for reviews); and (b) the research programme on which it is based has influenced the work and thinking of other prominent researchers in the cognitive engineering and safety science communities (Moray 1988, Reason 1990, Norman 1993, Amalberti 2001).

The results presented in this article make a contribution both to scholarly research and to public policy. From a research perspective, this work appears to be the first comprehensive and independent test of Rasmussen's (1997) framework (for accident analyses based on comparable frameworks, see Tanabe (2000) and Hopkins (2000)). The Walkerton Inquiry Commission was not aware of and, thus, did not adopt this framework when it conducted its analysis. Furthermore, although the authors have collaborated with Rasmussen on other research topics (e.g. Vicente and Rasmussen 1992), they were not involved in the development of this particular framework in any way. Thus, this work complements the non-independent tests of the same framework conducted by Svedung and Rasmussen (2002) and Rasmussen and Svedung (2000). From a public policy perspective, a theoretically-motivated analysis allows one to abstract from the idiosyncratic details of this particular accident and thereby develop potentially generalizable lessons. To paraphrase the Commission report, knowing what happened in Walkerton from a theoretical perspective can assist in a general sense in ensuring the future safety of other complex sociotechnical systems. This practical contribution will become increasingly important as contemporary society tries to safeguard the public interest in the face of growing trends toward more stringent financial pressures and market competitiveness.

2. Risk management in a dynamic society

Rasmussen's (1997) framework—which has its basis in systems thinking (e.g. Buckley 1968)—is motivated by the observation that the dynamic character of today's society has dramatically changed the types of models needed to understand the structure and behaviour of high-risk socio-technical systems. Factors such as the rapid pace of technological change, the high degree of coupling enabled by computerization and communication technologies and the volatility of economic and political climates each contribute to an environment in which the pressures and constraints that shape work practices are constantly shifting. Traditional modelling methods such as task analysis are inadequate as referents for understanding actual work practices because they depend on the assumption of a stable, tightly constrained environment (Vicente 1999). To fully appreciate how such systems work or why they sometimes fail, modelling tools are needed that provide an integrated view of the various contextual factors that directly and indirectly define how they operate.

2.1. *Structure*

Rasmussen's (1997) framework for risk management has two components. The first is a structural hierarchy describing the various actors—both individuals and organizations—in a complex socio-technical system. Figure 1 provides a representative example, although the precise number of levels and their labels can vary across industries. The bottom level describes the behaviour associated with the particular (potentially hazardous) process being controlled (e.g. nuclear power plant, water supply system, commercial aviation). Understanding this level usually requires knowledge of science or engineering. The next level describes the activities of the individual staff members that are responsible for interacting directly with the process being controlled (e.g. control room operators, water quality inspectors, airplane pilots). Understanding this level usually requires knowledge of human factors engineering. The third level from the bottom describes the activities of the management that supervize the staff. Understanding this level usually requires knowledge of management theories and industrial-organizational psychology. The next level up describes the activities of the company as a whole. Understanding this level usually requires knowledge of economics, organizational behaviour, decision theory and sociology. The next level describes the activities of the regulators or associations that are responsible for constraining the activities of companies in that particular sector. Finally, the top level describes the activities of government, both civil servants and elected officials, who are responsible for setting public policy. Understanding these last two levels usually requires knowledge of political science, law, economics and sociology.

Note that decisions at higher levels should propagate down the hierarchy, whereas information about the current state of affairs should propagate up the

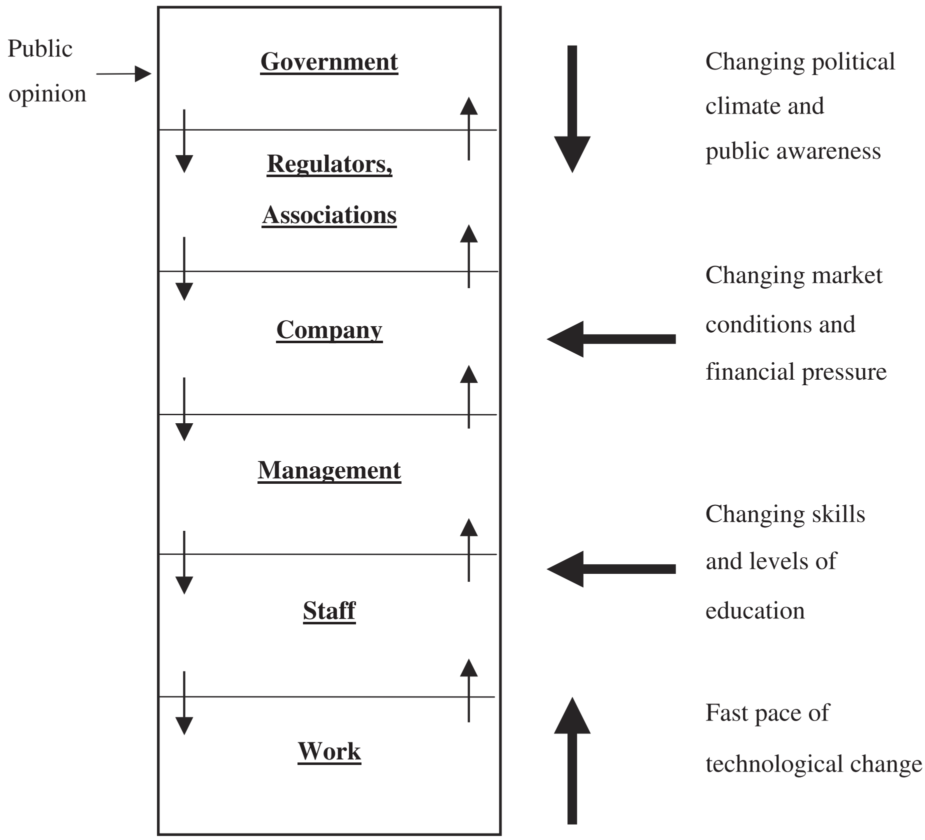

Figure 1. Various levels of a complex socio-technical system involved in risk management. Adapted from Rasmussen (1997) and reprinted from Vicente (2002), *Quality and Safety in Healthcare*, **11**, 302–304, with permission from the BMJ Publishing Group.

hierarchy. These inter-dependencies across levels of the hierarchy form a closed loop feedback system and are critical to the successful functioning of the system as a whole. If instructions from above (i.e. the control signal) are not formulated or not carried out or if information from below (i.e. feedback) is not collected or not conveyed then the system can become unstable and start to lose control of the hazardous process that it is intended to safeguard.

Under this view, safety can be viewed as an emergent property of a complex socio-technical system. It is impacted by the decisions of all of the actors—politicians, CEOs, managers, safety officers and work planners—not just the front-line workers alone. Consequently, threats to safety or accidents can result from a loss of control caused by a lack of vertical integration (i.e. mismatches) across levels of a complex socio-technical system, not just from deficiencies at any one level alone. All layers play a critical, albeit different, role in maintaining safety. As a corollary, threats to safety or accidents are usually caused by multiple contributing factors, not just a single catastrophic decision or action.

In turn, the lack of vertical integration is frequently caused, in part, by a lack of feedback across levels of a complex socio-technical system. Actors at each level cannot see how their decisions interact with those made by actors at other levels, so the threats to safety are not obvious before an accident occurs.

As shown on the right of figure 1, the various layers of a complex socio-technical system are increasingly subjected to external forces that stress the system. Examples of such perturbations include: changing political climate and public awareness, changing market conditions and financial pressures, changing competencies and levels of education or changes in technological complexity. In a dynamic society, these external forces are stronger and change more frequently than ever before.

2.2. *Dynamics*

The second component of the framework, shown in figure 2, deals with the dynamic forces that can cause a complex socio-technical system to modify its structure and behaviour over time. On the one hand, there are financial pressures that result in a cost gradient pushing the actors in the system to work in a more fiscally responsible manner. Indeed, budget cuts are becoming increasingly common over a wide range of private and public sectors. On the other hand, there are psychological pressures that result in an effort gradient pushing the actors in the system to work in a more mentally or physically efficient manner. People are always searching for easier ways to get a job done.

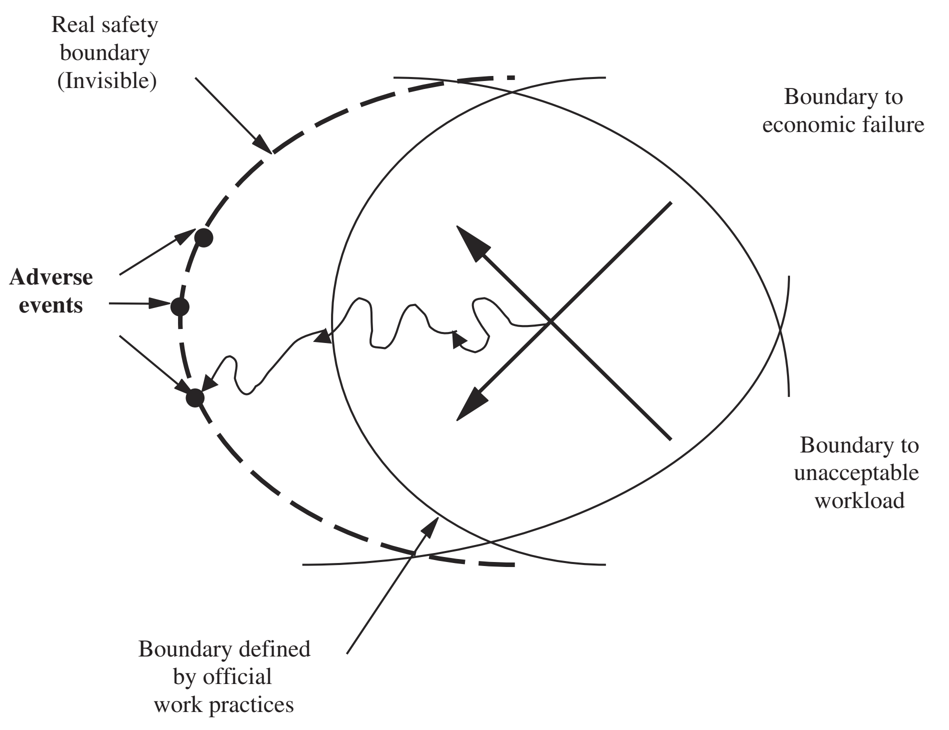

Figure 2. 'Brownian motion' model showing how financial and psychological forces can create behaviour gradients that cause work practices to migrate systematically toward the boundary of safety. Adapted from Rasmussen (1997), Copyright (2003), Kim. J. Vicente.

Although this effort gradient is sometimes interpreted negatively as a sign of human laziness, given the proper conditions, it can serve a positive—indeed, essential—role because it allows people to seek out more adaptive ways of getting the job done. This exploratory process can be particularly important when people are being asked or required to take on more responsibilities with fewer resources—the proverbial 'do more with less' that is so common in a dynamic society.

As a result of these two gradients, work practices will be subject to a form of 'Brownian motion', an exploratory but systematic migration over time. Just as the force of gravity causes a stream of water to inevitably flow down the crevices in a side of a mountain, these financial and psychological forces inevitably cause people to find the most economic ways of performing their job. Moreover, the migration of work practices can occur at multiple levels of a complex socio-technical system shown in figure 1, not just one level alone.

Over time, this migration causes people to cross the official boundary of work practices, shown on the near left in figure 2. People are forced to deviate from procedures and cut corners because they are responding to requests or demands to be more cost-effective. As a result, the system's defenses in depth degrade and erode gradually over time, not all at once.

One might think that this lack of procedural compliance and this degradation in safety would raise an immediate warning flag, but there are two reasons why they do not. First, the migration in work practices is required to get the job done, given the stresses that the system is undergoing. That is why 'work to rule' campaigns, where people do their job strictly by the book, usually cause complex socio-technical systems to come to a grinding halt. Secondly, the migration in work practices does not usually have any visible, immediate negative impact. The threats to safety are not obvious before an accident because the violation of procedures does not immediately lead to catastrophe. At each level in the hierarchy people are working hard, striving to respond to cost-effectiveness measures, but they do not see how their decisions interact with those made by other actors at different levels of the system. Yet, the sum total of these uncoordinated attempts at adapting to environmental stressors is slowly but surely 'preparing the stage for an accident' (Rasmussen 1997, p. 189).

As a result, the migration of work practices continues. People try harder and harder to work in more efficient ways and, with each new innovation, they are coming closer and closer to the real boundary of safety on the far left of figure 2. However, because that boundary is usually invisible, people do not have any idea whether the system as a whole is close or far away from disaster. Migrations from official work practices can persist and evolve for years without any breach of safety until the real safety boundary is reached. After an accident, workers will wonder what happened because they did not do anything drastically different from what they had been doing in the recent past. In other words, accidents in complex socio-technical systems do not usually occur because of an unusual action or an entirely new, one-time threat to safety. Instead, they result from a combination of a systematically-induced migration in work practices and an odd event that winds up revealing the degradation in safety that had been occurring all the while.

Table 1 summarizes the main predictions made by Rasmussen's (1997) framework. Note that, for each prediction, there is (at least) one alternative prediction. Thus, accidents need not have this set of characteristics, so Rasmussen's framework is falsifiable. How well does the Walkerton tragedy conform to these predictions?

Table 1. Predictions made by Rasmussen's (1997) risk management framework.

	Prediction
1.	Safety is an emergent property of a complex socio-technical system. It is impacted by the decisions of all of the actors—politicians, managers, safety officers and work planners—not just the front-line workers alone.
2.	Threats to safety or accidents are usually caused by multiple contributing factors, not just a single catastrophic decision or action.
3.	Threats to safety or accidents can result from a lack of vertical integration (i.e. mismatches) across levels of a complex socio-technical system, not just from deficiencies at any one level alone.
4.	The lack of vertical integration is caused, in part, by a lack of feedback across levels of a complex socio-technical system. Actors at each level cannot see how their decisions interact with those made by actors at other levels, so the threats to safety are far from obvious before an accident.
5.	Work practices in a complex socio-technical system are not static. They will migrate over time under the influence of a cost gradient driven by financial pressures in an aggressive competitive environment and under the influence of an effort gradient driven by the psychological pressure to follow the path of least resistance.
6.	The migration of work practices can occur at multiple levels of a complex socio-technical system, not just one level alone.
7.	Migration of work practices causes the system's defenses to degrade and erode gradually over time, not all at once. Accidents are released by a combination of this systematically-induced migration in work practices and a triggering event, not just by an unusual action or an entirely new, one-time threat to safety.

3. Report of the Walkerton inquiry

Part 1 of the Walkerton report, which focuses on the events surrounding the accident, was used as the source document for the analysis (Part 2 described a set of recommendations and, thus, is not as relevant to this aim). A brief review of the process that the Commission used to conduct its inquiry shows that the resulting report is a comprehensive and authoritative account of the events (see chapter 14 of the report for a detailed account). The Commission was given wide powers of investigation and collected as many as one million documents from the provincial government alone in addition to thousands of documents from other sources. In the end, ~200 000 government documents were scanned into an electronic database. The Commission held 95 days of hearings over a period of 9 months, during which 21 686 pages of transcripts were generated and 447 exhibits, containing over 3000 documents, were introduced as evidence. A total of 114 witnesses testified, including Michael Harris, then Premier of Ontario. After the hearings, the Commission held nine town hall meetings all across the province to listen to the public's concerns and views. Part 1 of the final report was ~700 pages long, including appendices.

4. The events of May 2000

Before presenting the analysis of the Walkerton case, some background information will be helpful. The Walkerton water system was operated by the Walkerton Public Utilities Commission (WPUC), under the supervision of the general manager, Stan Koebel. The government body with oversight responsibility for the operation of water systems in the province of Ontario is the Ministry of the Environment (MOE).

Other relevant regulatory bodies include the Ontario Ministry of Health and the Bruce-Grey-Owen Sound (BGOS) Health Unit, which is the local public health unit for Walkerton, headed by the local Medical Officer of Health. A&L Canada Laboratories is a private company that was contracted by WPUC to analyse their water samples.

Table 2 provides a timeline of the proximal physical events and actions that contributed to the *E. coli* outbreak in Walkerton during May 2000. A later section

Table 2. Timeline of the most important events of May 2000 contributing to the Walkerton *E. coli* outbreak.

8–12 May 2000	Unusually heavy rains carry *E. coli* and *Campylobacter* bacteria to Walkerton Well 5 from nearby fields on which cattle manure had been spread; contaminants are thought to have entered Well 5 on or near 12 May.
13–15 May 2000	WPUC staff fail to take measurements of chlorine residuals* for Well 5.
15 May 2000	Samples from Walkerton distribution system and from a nearby construction site sent to A&L Labs for testing.
17 May 2000	A&L Labs advises Stan Koebel that samples from 15 May tested positive for contamination.
18 May 2000	First symptoms appear in community; inquiring members of public assured water is safe by WPUC.
19 May 2000	Scope of outbreak grows; paediatrician contacts local health unit on suspicion of *E. coli*.
	BGOS health unit begins investigation; in two separate calls placed to Stan Koebel, health officials are led to believe water is 'okay'; Stan Koebel fails to disclose lab results from 15 May.
	Stan Koebel begins to flush and superchlorinate the system to try to destroy any contaminants in water; chlorine residuals begin to recover.
20 May 2000	First preliminary positive test for *E. coli* infection.
	BGOS Health unit speaks to Stan Koebel twice; Koebel reports acceptable chlorine residuals; fails again to disclose adverse test results; health unit assures inquiring public that water is not the problem.
	A WPUC employee places anonymous call to MOE to report adverse test results from 15 May; on contacting Stan Koebel, MOE is told the only failing sample was from the construction site; Koebel does not reveal failed samples from Walkerton distribution system.
	Local Medical Officer of Health contacted by health unit; takes over investigation.
21 May 2000	Preliminary positive test for *E. coli* infection from 20 May confirmed; a second preliminary positive test is reported.
	A 'boil water advisory' is issued by the BGOS health unit.
	MOE and BGOS health unit both contact Stan Koebel; Koebel again fails to disclose adverse results from 15 May samples.
	BGOS health unit collects its own samples from Walkerton water distribution system.
22 May 2000	MOE begins its own investigation; Koebel turns over documents including test results from 15 May samples.
	First death due to outbreak; eventually seven people die and over 2300 become ill.
23 May 2000	Samples collected by health unit come back positive; on being informed, Stan Koebel reveals results from 15 May samples to health unit.

*Chlorine residuals are an indicator of how much chlorine is being consumed in the process of disinfecting the water. A low chlorine residual indicates that contaminants in the water are exerting an increased demand on the disinfectant capacity of the chlorine, reducing the safety margin.

will describe other pre-existing factors that helped set the stage for this proximal sequence of events.

5. Analysis

This section compares the reasons for the Walkerton outbreak with Rasmussen's (1997) framework by seeing how well the findings of the Commission report (O'Connor 2002a) map onto the type of structure identified in figure 1. Following this discussion, the extent to which predictions in table 1 are supported by the available evidence is evaluated.

5.1. *Physical circumstances and equipment / Equipment and surroundings*

This paper begins by examining factors related to the physical circumstances of the events of May 2000. Table 2 described how heavy rains and the use of cattle manure on local farm fields combined to introduce contaminants into Well 5. Four important pre-existing physical factors, listed at the bottom of figure 3, also contributed to the contamination.

Two of these factors—the shallow location of Well 5 and the fractured bedrock in the local geology—were based on physics. Well 5 was a shallow well, drilled to a depth of just 15 m. In contrast, Wells 6 and 7 were drilled to depths of 72 and 76 m, respectively. In addition to its shallow depth, Well 5 was drilled in an area where the bedrock was highly fractured and porous. The overburden (i.e. soils, sands, silts and clays covering the bedrock) was also relatively shallow in the area of Well 5. Because of these factors, there was minimal natural filtration provided by the overburden and bedrock. Also, a breach in the overburden could potentially leave a relatively direct route between the surface and the aquifer. As a result, Well 5 was particularly vulnerable to contamination from surface water (e.g. runoff from rainfall).

In addition, two equipment-related factors contributed to the vulnerability of Well 5 to surface contaminants. Wells known to be exposed to the risk of contamination by surface water are normally required to have continuous chlorine residual monitors installed. Such a monitor could have automatically shut down the pump at Well 5 when the contamination entered the system. For reasons that will be discussed later, Well 5 did not have a continuous chlorine residual monitor installed. A second equipment-related factor was the absence of a working chlorinator in Well 7 between 3–19 May. With Stan Koebel's full knowledge, Well 7 was operated for several days during this period, supplying unchlorinated water to the distribution system in clear violation of provincial requirements.

5.2. *Physical events and actor activities / Physical processes and actor activities*

This second level is described in detail in table 2, so it will not be discussed again here. The main points are summarized at the second level in figure 3.

5.3. *Technical and operational management*

As shown in figure 3, the primary contributing factors at this level concern the operating practices of the WPUC under the supervision of Stan Koebel.

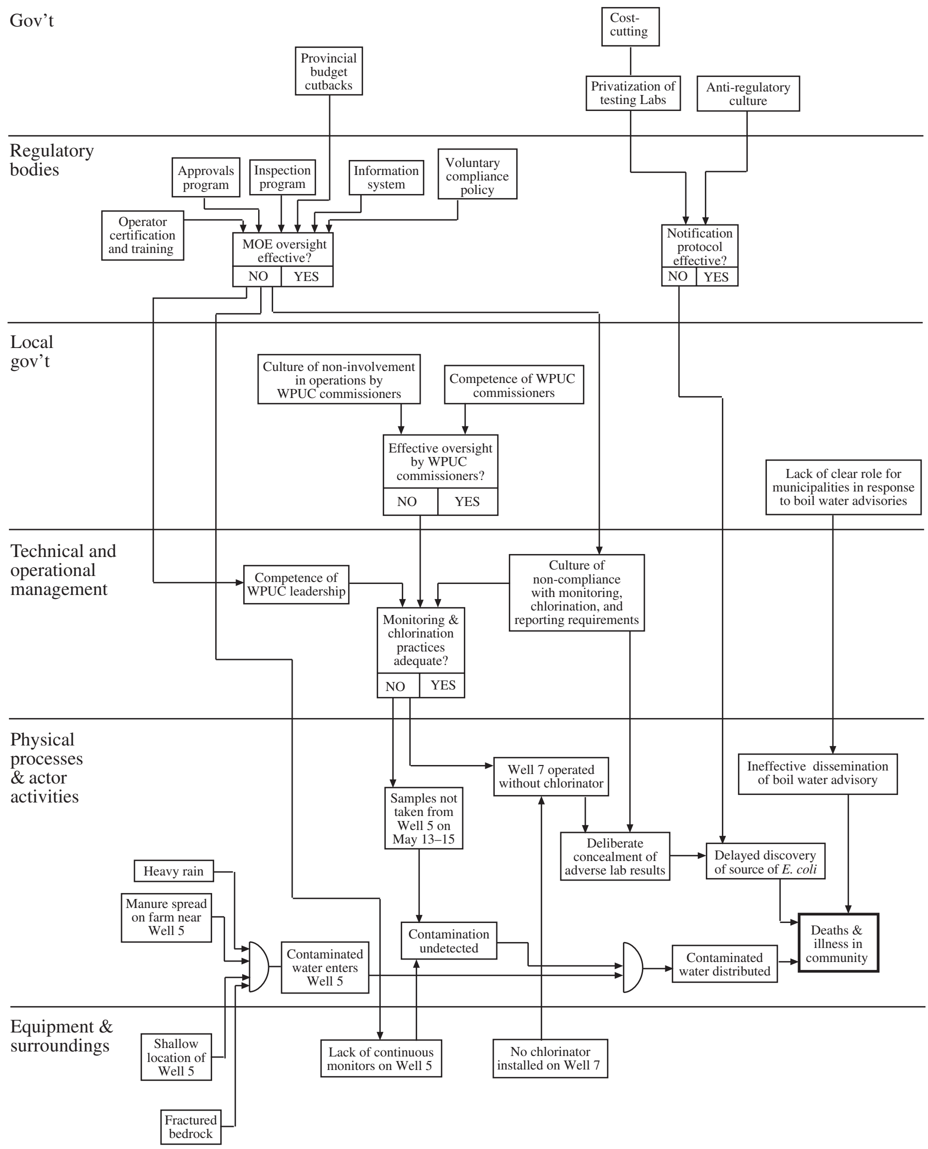

Figure 3. Map of contributing factors in the Walkerton *E. coli* outbreak mapped onto the levels of a complex socio-technical system identified in figure 1.

As described earlier in table 2, the failure of the WPUC to take chlorine residual measurements at Well 5 between 13–15 May and the active concealment of the results of the microbiological samples collected on 15 May both played important roles in the outbreak. However, an analysis of the technical and operational management level revealed that these were not isolated incidents: '*for more than 20 years*, it had been the practice of [WPUC] employees not to measure the chlorine residuals on most days and to make fictitious entries for residuals in the daily operating sheets' (O'Connor 2002b, p. 7, emphasis added). The general pattern of improper operating practices at the WPUC also included deliberately misstating the locations from which microbiological samples had been collected, collecting insufficient numbers of microbiological samples, failing to use adequate doses of chlorine and submitting false annual reports to the MOE.

As shown in figure 3, at least two factors contributed to this pattern of non-compliance. First, the level of competence of the WPUC leadership, particularly Stan and Frank Koebel, was inadequate. Both Koebels had received their water operator's certificates through a 'grandfathering' process. Neither had been required to complete any training or pass any examinations to receive their certification. They each believed that the sources for the Walkerton water system were generally safe. Indeed, both men routinely drank untreated water at the well sites because it 'tasted better'. Even over the weekend of 20–21 May, after he knew of the adverse test results, Stan Koebel 'continued to drink water from a fire hydrant and a garden house and on 22 May he filled his daughter's swimming pool with municipal water' (O'Connor 2002a, p. 72). It is clear that neither of the Koebel brothers had a full appreciation of the health risks posed by distributing under-chlorinated water or of the specific risks of bacterial contaminants. In fact, both admitted to not even knowing what *E. coli* was, let alone that its presence in drinking water could be lethal.

A second, related contributing factor involves the priorities of the WPUC staff. There was a general tendency to avoid the effort required to uphold proper sampling practices. Water samples were often collected at convenient sites, including at times the operators' homes or the WPUC workshop and then simply labelled according to where the samples were supposed to have been taken. When asked why he and his brother followed such practices, Stan Koebel replied: 'Simply convenience' (O'Connor 2002a, p. 62). When operating deficiencies were pointed out by several inspections, Stan Koebel made, but never carried out, promises to rectify the problems. This attitude and the resulting practices 'show a serious disregard for MOE requirements and repeated failures by Stan Koebel to do what he said he would' (O'Connor 2002a, p. 188).

Although this does not justify his actions, it is interesting to note that the Walkerton residents had sometimes told Stan Koebel—their neighbour and friend—that the water tasted too much like chlorine, so in an effort to respond to the wishes of his small, tight-knit community, he acquiesced by reducing the amount of chlorine introduced into the system.

5.4. *Local government*

As shown in figure 3, the local government played an important part in the events of May 2000 in three ways. First, even though the WPUC commissioners were the elected body responsible for 'control and management' of the WPUC, they did not concern themselves with the details of system operation, focusing instead on budgeting and financial matters. Secondly, the WPUC commissioners had very little knowledge of water safety or of the nature of operating a waterworks. (This level of knowledge and involvement was consistent with the traditional role of the WPUC commissioners, which was likened in the inquiry report to that of the directors of a corporation.) As a result of these two factors, the WPUC commissioners relied almost exclusively on the WPUC senior management, primarily Stan Koebel, to identify and resolve any concerns related to the operation of the water system. For example, when a 1998 MOE inspection report indicated serious problems with the operation of the water system, including the presence of *E. coli* in treated water samples, the commissioners simply accepted Stan Koebel's assurances that he would look after the situation. They did not inquire into how the problems had arisen, nor did they follow up afterwards to ensure that Stan Koebel had actually addressed the concerns. As became clear later, Koebel failed to follow through on his assurances. The inquiry report concluded that it was reasonable to have expected the commissioners to take more of an active role in responding to the 1998 MOE inspection report.

The third factor where local government played a role in the outbreak concerns the dissemination of the boil water advisory issued by the local health unit on 21 May. It is estimated that only about half of Walkerton's residents actually became aware of the advisory on 21 May. Some members of the public continued drinking the Walkerton town water until as late as 23 May. The inquiry report suggested that this was partially attributable to the failure of Walkerton's mayor, David Thomson, to take an active role in building public awareness of the advisory after he was informed of it by Dr Murray McQuigge, the local Medical Officer of Health. The Mayor was not specifically asked by Dr McQuigge to assist in publicizing the advisory and there is some dispute as to whether the seriousness of the situation was effectively communicated to the Mayor. In any case, there was no clear, pre-defined role for the Mayor and by extension the municipality in responding to any boil water advisory issued by the health unit. As a result, the Mayor took no action, relying on Dr McQuigge to handle the situation. The inquiry report did not place responsibility on Mayor Thomson, but observed that his inaction represented a missed opportunity to have reduced the scope of the outbreak.

5.5. *Regulatory bodies*

The main regulatory agency with responsibility for overseeing the operation of municipal water systems in the province of Ontario is the MOE. As shown in figure 3, MOE practices contributed to the Walkerton outbreak in six ways. This study has already mentioned the fact that, partially due to the structure of the MOE's operator training and certification programmes, Stan and Frank Koebel did not have a full appreciation of issues related to water safety, including the public health risks posed by contaminants such as *E. coli*. They both held the belief that untreated water from the Walkerton wells was essentially safe for human consumption. This lack of knowledge was a likely contributor to their consistent improper operating practices.

A second significant factor contributing to the sub-standard operating practices at the WPUC was the weak response of the MOE to evidence of repeated violations uncovered by its own periodic inspections. Inspections conducted in 1991, 1995 and 1998 consistently revealed deficiencies in treatment and monitoring at the WPUC. After each of these inspections, MOE made recommendations to address the deficiencies, but each time Stan Koebel consistently put off or ignored those recommendations. No strong (i.e. legally enforceable) measures were ever taken by the MOE to ensure that the concerns identified in the inspections were addressed. Instead, the MOE relied on voluntary compliance with its recommendations. The inquiry report concluded that, as a result of the MOE's soft stance, Stan Koebel came to believe that compliance with the recommendations and guidelines was not a high priority.

The third contributing factor at this level was the lack of important feedback to allow the MOE to monitor the state of affairs at lower levels:

> The MOE did not have an information system that made critical information about the history of vulnerable water sources, like Well 5, accessible to those responsible for ensuring that proper treatment and monitoring were taking place. On several occasions in the 1990s, having had access to this information would have enabled ministry personnel to be fully informed in making decisions about current circumstances and the proper actions to be taken (O'Connor 2002b, p. 29).

This lack of feedback across levels of the socio-technical system enabled two other factors that contributed to the outbreak.

One of those was related to the MOE approvals programme. As described previously, Walkerton Well 5 did not have continuous chlorine residual monitors installed. When Well 5 was initially approved by the MOE in 1979, it was identified as being susceptible to contamination from surface water. However, consistent with MOE practices at the time, no special conditions (e.g. for monitoring) were attached to the approval. By the 1990s, special conditions for monitoring and treatment were routinely attached to approvals for wells similar to Well 5. Nevertheless, the MOE did not attempt to retroactively apply such conditions to previously granted approvals, partly because it did not have an integrated information system to provide feedback to allow tracking of older certificates of approval.

The other contributing factor was related to the MOE inspections programme. In 1994, the 'Ontario Drinking Water Objectives' (ODWO), a provincial guideline, was amended to require continuous (rather than the usual daily) monitoring of chlorine residuals and turbidity for wells at risk of surface contamination. Again, no attempt was made to systematically review existing certificates of approval to determine if conditions should be added to require continuous monitoring. In addition, MOE inspectors were not directed to notify water system operators of the ODWO amendment nor to assess existing wells during inspections. In fact, there were no criteria available from MOE to guide inspectors in determining whether or not a given well was at risk. The MOE inspections in 1991, 1995 and 1998 failed to recognize the vulnerability of Well 5, even though the relevant information was already available in MOE records. However, these were archived and, therefore, difficult to find, rather than readily accessible in an information system. As a result of this combination of factors, continuous monitors were never installed for Well 5. As mentioned previously, such monitors could have drastically reduced or even prevented the outbreak.

There is at least one other very important factor at the level of regulatory bodies that contributed to the Walkerton outbreak. In 1996, laboratory testing of drinking water quality was privatized by the Conservative Provincial government. Municipalities, like Walkerton, were forced to switch from using government-run facilities to using private laboratories, but no legislation was enacted to require private laboratories to notify the MOE of adverse test results. The ODWO included a guideline to this effect, but it was not legally enforceable and some laboratories were not even aware that it existed. Despite awareness of this problem and its risks for public health, leading to high-level discussions between the Ministries of Health and of the Environment, the government had not acted to remedy this loophole. During May 2000, the WPUC was sending its samples to A&L Canada Laboratories. A&L was not aware of the notification protocol outlined in ODWO, nor was it legally required to follow it. Therefore, on 17 May, when the microbiological samples collected on 15 May were found to be heavily contaminated, A&L only notified Stan Koebel of the results. No notice was sent to the local MOE office or health authorities. Because of the subsequent concealment of this information by Stan Koebel, the weak notification protocol led to delays in discovering the source of the outbreak and, thus, seriously exacerbated its impacts.

5.6. *Government*

These shortcomings of the MOE are due, at least in part, to actions of the Provincial government during the years leading up to the Walkerton tragedy. During this time, the MOE's budget had been reduced by nearly half. In the 2 year period between 1996–1998 alone, the budget was cut by over $200 million CAD, with an ensuing staff reduction of over 30% (more than 750 employees). The potential harm arising from these reductions was known, yet:

> Despite having knowledge that there could be risks, no member of Cabinet or other public servant directed that a risk assessment and management plan be conducted to determine the extent of those risks, whether the risks should be assumed, and if assumed, whether they could be managed (O'Connor 2002a, p. 411).

Even without any risk assessment, 'the Cabinet approved the budget reductions in the face of warnings of increased risk to the environment and human health' (O'Connor 2002b, p. 35). The inquiry report concluded that these budget cuts substantially reduced the likelihood that MOE's approvals and inspections programmes could have uncovered the need for continuous monitors or the improper operating practices at the WPUC.

The second major role played by the provincial government concerns its 'distaste for regulation' (O'Connor 2002a, p. 368) and its resulting decision to privatize laboratory testing of drinking water. The events at Walkerton were impacted by the failure to enact legislation requiring private labs to notify MOE and health authorities of adverse test results. The evidence presented at the inquiry clearly showed that high levels of government were aware that the lack of such legislation posed a potential risk. However, by 1995–1996, the newly elected government began an effort to reduce regulation and created a 'Red Tape Commission' to eliminate 'complicated and unnecessary paperwork', such as that resulting from reporting requirements. For similar reasons, the government did not act to require mandatory accreditation of private testing labs. The opinion of MOE officials was that any move to legislate a notification requirement or accreditation would 'likely have been "a non-starter", given the government's focus on minimizing regulation' (O'Connor 2002b, p. 33).

5.7. *Assessing the predictions of Rasmussen's framework*

Table 3 summarizes how well the predictions made by Rasmussen's (1997) framework account for the factors contributing to the Walkerton *E. coli* outbreak.

Table 3. Test of the predictions in table 1 for the Walkerton *E. coli* outbreak.

Prediction
1. Safety is an emergent property of a complex socio-technical system. It is impacted by the decisions of all of the actors—politicians, managers, safety officers and work planners—not just the front-line workers alone.
Figure 3 dramatically reveals the truth of this statement. A very large number of decision-makers and decision-making bodies, from the Government of Ontario on down to individuals such as Stan Koebel, shaped the conditions and course of events in such a way that allowed the events of May 2000 to take place. In the words of the inquiry report, 'It is simply wrong to say, as the government argued at the Inquiry, that Stan Koebel or the Walkerton PUC were solely responsible for the outbreak or that they were the only ones who could have prevented it' (O'Connor 2002b, p. 24).
2. Threats to safety or accidents are usually caused by multiple contributing factors, not just a single catastrophic decision or action.
None of the factors illustrated in figure 3 are solely responsible for the occurrence of the outbreak in Walkerton. For example, four independent factors were jointly responsible for the entry of the contaminants into the Walkerton water system. Had any one of these not been in place, the events may never have occurred at all. Other critical events or vulnerabilities, such as the failure to detect the contamination and the ineffective dissemination of the boil water advisory also have multiple contributors. It is impossible to point to a single 'root cause' that was both necessary and sufficient to lead to the outbreak.
3. Threats to safety or accidents can result from a lack of vertical integration (i.e. mismatches) across levels of a complex socio-technical system, not just from deficiencies at any one level alone.
Construed broadly, a lack of vertical integration refers to the idea that interactions between individuals or organizations at different levels of the socio-technical system are dysfunctional with respect to effective control of the monitored process. For example, organizations at different levels of a socio-technical system can develop different, possibly conflicting, working priorities or objectives due to the specific pressures that each is operating under. Also important are breakdowns in the propagation from higher levels of constraints on the activities of lower levels or the corresponding feedback mechanisms. Figure 4 presents a map of some of these types of interactions across levels and their results in the socio-technical system involved in control of the operation of the Walkerton water system.
4. The lack of vertical integration is caused, in part, by a lack of feedback across levels of a complex socio-technical system. Actors at each level cannot see how their decisions interact with those made by actors at other levels, so the threats to safety are far from obvious before an accident.
The WPUC was effectively isolated from other levels of the socio-technical system responsible for the control of Walkerton's water system (cf. figure 1). Because both the MOE and the WPUC commissioners failed to take steps to ensure that MOE recommendations were being followed, a critical feedback loop was missing from the system. The MOE and the WPUC commissioners were essentially acting, repeatedly, without the information that would allow them to tell if their 'control actions' had been successful. The lack of a proper information system at the MOE played a particularly influential role in this regard.
When water quality testing was privatized by the provincial government in 1996, a significant barrier to failure was removed from the system. Many private labs were unaware of the reporting guideline in ODWO or chose not to conform with it (to protect their clients' confidentiality). Consequently, yet another critical feedback mechanism had been significantly degraded. Indeed, evidence presented at the inquiry suggested that the number of adverse results reported to the MOE dropped significantly after privatization. It was clear that Stan Koebel and the other WPUC employees did not understand how their improper operating practices interacted with these events. Nor did the government anticipate the situation at the WPUC. Only afterwards, when the inquiry commission developed a global view of the socio-technical system, did the relational structure between the decisions and practices at each level become clear.

(*continued*)

Table 3. Continued.

Prediction
5. Work practices in a complex socio-technical system are not static. They will migrate over time under the influence of a cost gradient driven by financial pressures in an aggressive competitive environment and under the influence of an effort gradient driven by the psychological pressure to follow the path of least resistance.
There are many instances in which work practices of different individuals and organizations migrated over time in ways that increased the likelihood of the events of May 2000. The sub-standard practices of Stan Koebel and the WPUC provide an example of behaviour driven primarily by an effort gradient. Normally, one would expect a strong counter-gradient to be present due to pressure from oversight bodies, but this was missing due to the failure of MOE to follow-up on its inspections and the lack of close involvement by the WPUC commissioners. Another important counter-gradient was missing due to the Koebels' lack of appreciation of the risks involved in their practices. Their lack of training in water safety issues meant that they did not regard their actions as posing a significant risk to public safety.
The changing practices of the MOE, on the other hand, can be seen as responses primarily to an economic gradient. In the preceding years, budget pressures led the MOE to gradually shift responsibility for operation of water systems onto the municipalities themselves, thereby decreasing their own oversight burden. While this can be viewed as a reasonable response to tightening resource constraints, the inquiry found that 'the MOE went too far in this direction' (O'Connor 2002a, p. 272). Particularly with respect to the inspections programme, the ongoing budget cuts and staff reductions forced the MOE into an increasingly reactive stance. Its ability to take a proactive role in detecting and preventing problems was systematically eroded due to a lack of resources. A former deputy minister of the MOE Operations Division testified at the inquiry that proactive inspections and follow-ups took on reduced priority because 'the day was eaten up with reactive work' (O'Connor 2002a, p. 318). Between 1994–1995 and 1999–2000, the number of planned inspections by the local MOE office responsible for Walkerton fell by 60% and the amount of employee resources dedicated to communal water decreased by almost half.
6. The migration of work practices can occur at multiple levels of a complex socio-technical system, not just one level alone.
The previous points show how migration occurred at levels both close to and distant from the physical events in Walkerton. Similar patterns can be seen even at the highest levels of the socio-technical system. For example, the political forces that helped bring the new provincial government to power in 1995 served to create an atmosphere that led to a Red Tape Commission, discouraging the passing of notification legislation after water quality testing was privatized. An additional example concerns the very lowest level of the system: the physical circumstances of the Walkerton water system. When Well 5 was originally constructed, it was intended to be a temporary solution to water supply problems that existed in Walkerton at the time. It appears that, over time, both the PUC and the MOE implicitly grew to accept the idea that Well 5 was an acceptable permanent solution given that, at least until the 1990s it had an unremarkable history of operation. Thus, one can see how the phenomenon of migration can span all levels of the socio-technical system.
7. Migration of work practices causes the system's defenses to degrade and erode gradually over time, not all at once. Accidents are released by a combination of this systematically-induced migration in work practices and a triggering event, not just by an unusual action or an entirely new, one-time threat to safety.
Some of the forces that created the conditions surrounding the Walkerton tragedy had been actively shaping the system for a long time before May 2000. The improper operating practices at the WPUC were found to date back over 20 years. The budgetary pressures at the MOE began to accumulate in the early 1990s. The increased pressure to privatize government services began with the election of the new government in 1995. By May 2000, these factors had aligned in such a way that a few days of unusually heavy rainfall were enough to trigger the chain of events that led to seven deaths and over 2300 illnesses.

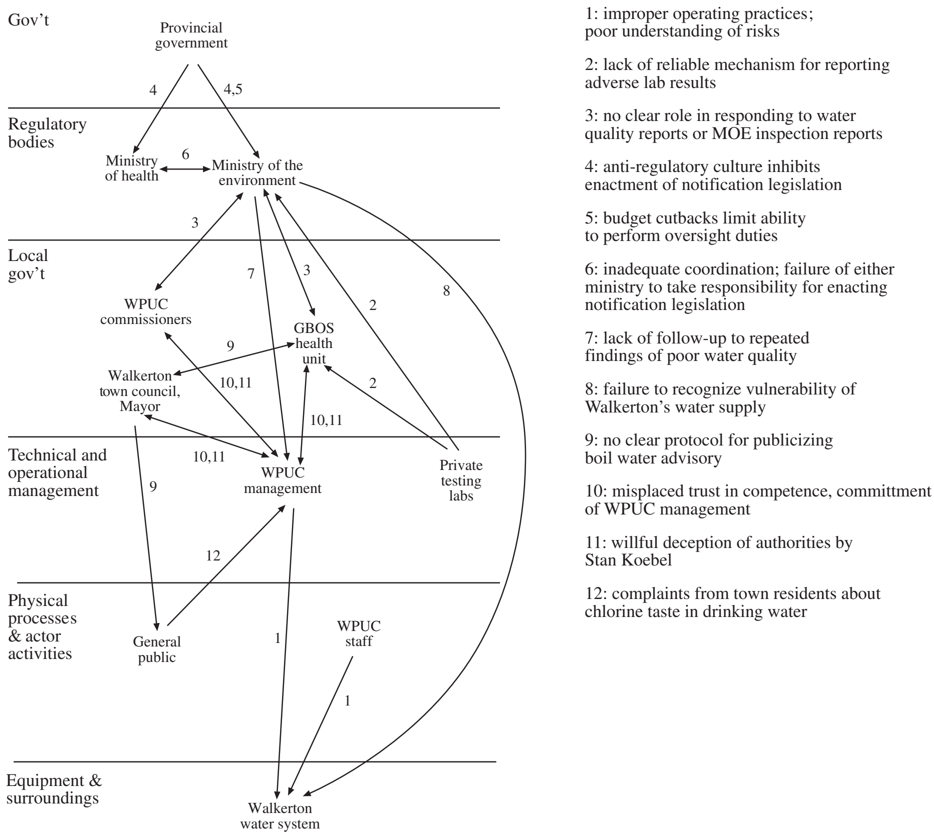

Figure 4. Counter-productive interactions (mismatches) between actors at different levels of the socio-technical system involved in control of the Walkerton water system.

6. Discussion

> For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled (Feynman 1988, p. 237).

This research appears to be the first comprehensive and independent test of Rasmussen's (1997) framework for risk management in a dynamic society. All of the predictions made by the framework were confirmed by the events surrounding the Walkerton *E. coli* outbreak. However, there was one contributing factor that the framework did not anticipate, namely Stan Koebel's deliberate deception and concealment of the adverse test results. As mentioned earlier, this cover up can be attributed in part to ignorance about the lethal effects of *E. coli* and in part to a wish to hide his violation of MOE requirements (i.e. operating Well 7 without chlorination). If the tendency to hide personal wrong-doing is a frequent contributor to accidents—a fact that can only determined by additional tests of the framework—then an addition to the framework would be warranted, perhaps in the form of an additional gradient that can shape the behaviour of actors at various levels of the system (since presumably this type of behaviour could occur at any level). Overall, however, the framework appears to have some promise as a theoretically-driven way to explain how and why accidents occur in complex socio-technical systems.

This research has several limitations that motivate future research questions. First, only one accident was analysed here so it is important to test the generalizability of Rasmussen's (1997) framework independently by using it to account for other accidents, particularly in sectors other than water supply (an analogous analysis of another water supply outbreak has since been conducted, see Woo and Vicente 2003). Secondly, now that this framework has been independently shown to have some validity, it would be useful to contrast its predictions with those of other comparable risk analysis frameworks so that theoretical understanding of safety science can evolve and mature. Finally, this article only tested the framework's capability to explain an accident *a posteriori*. The ultimate test of any engineering theory is how useful it is. Accordingly, a natural, albeit ambitious, extension of the present research would be to test the framework's ability to prevent accidents before the public interest is harmed.

Indeed, one of the potential benefits of Rasmussen's (1997) framework is that it does not just try to explain why accidents occurred; it also suggests how they might be prevented (Rasmussen and Svedung 2000, Svedung and Rasmussen 2002). Adding more defenses in depth alone is unlikely to work in the long run because the new defenses will just delay the inevitable degradation that is caused by the financial and psychological gradients in figure 2. Creating more awareness through public relations or educational campaigns alone is also unlikely to be a viable long-term solution because the same two counter-forces will always be there, urging people to migrate to more cost-effective ways of doing business.

From the perspective of this framework, the only long-term solution to managing risk in a dynamic society appears to involve admitting that external stressors, such as budget cuts and market competitiveness, are not going to go away entirely and to deliberately build systems that can respond and adapt to these pressures without compromising safety. In other words, the goal is to allow systems to operate 'at the edge' to maximize competitiveness or efficiency, but without actually breaking the envelope of safety and incurring accidents. To operate at the edge, vertical integration via feedback across levels must be achieved so that each person and organization in the system can see how their actions impact safety, not just the bottom line. More concretely, the usually invisible boundary to safety on the extreme left in figure 2 must be made visible so that all levels of the system can see how close they are to disaster.

To evaluate whether the framework is indeed capable of enhancing safety in this way, government and corporate policy makers would have to adopt this approach to design or redesign the growing number of increasingly complex technological systems that surround us. This will not be a simple task for at least two reasons (Rasmussen 1997). First, a great deal of knowledge from different disciplines is required, including science, engineering, human factors, psychology, management, sociology, economics, law and politics. Given the notorious silos created by traditional academic boundaries, bringing together this cross-disciplinary expertise will be a challenge. Secondly, Rasmussen's framework runs counter to many management theories. Since the goal is to achieve vertical integration across the various layers of a particular complex socio-technical system, the framework must be implemented in an industry-specific fashion. After all, the information needs and competencies of each level of a complex socio-technical system will necessarily be context-dependent, varying from one sector to another. For example, the laws, regulations, economics, competencies, education and technology that make for safe health care are not the same as those that make for safe drinking water. In contrast, many popular management theories are relatively context-free because they advocate a narrow focus on financial operations, irrespective of the type of hazardous process being controlled (see Saul (1992) for an incisive critique of this trend).

While these two obstacles to implementation are not trivial, in the end, the potential gains to be had by confronting them may very well outweigh the costs. The Walkerton tragedy and others like it show that, when it comes to complex socio-technical systems, governments and companies cannot afford to wait for a lethal accident to happen before figuring out how to reduce the level of risk to the public. The harm to society is far too great and simply unacceptable in today's political climate.

The political fallout after the Walkerton tragedy provides a case in point. The Ontario provincial government had won two consecutive elections by a majority by running on a 'common sense revolution' platform of smaller government and cost reductions. However, after the Premier was interrogated at the Walkerton hearings, polls showed that voter support for the government plummeted to the point where it was 25% behind the opposition party. If Rasmussen's (1997) framework turns out to be as successful at preventing accidents as it seems to be at explaining them, then it could help serve a political imperative by keeping tragedies such as Walkerton from becoming commonplace occurrences, as the winds of change continue to blow in a dynamic society.

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