Available online at www.sciencedirect.com
SCIENCE DIRECT®
Reliability Engineering and System Safety 80 (2003) 253–269
RELIABILITY ENGINEERING & SYSTEM SAFETY
www.elsevier.com/locate/ress

Sociotechnical systems, risk management, and public health: comparing the North Battleford and Walkerton outbreaks

Dennis M. Woo[a], Kim J. Vicente[a,b,*]

[a]Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering, University of Toronto, Toronto, Canada
[b]Department of Aeronautics & Astronautics, Massachusetts Institute of Technology, Room 37-371, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA

Received 2 December 2002; accepted 1 February 2003

Abstract

Accidents in different complex sociotechnical systems are rarely compared using the same theoretical framework for risk management. We conducted a comparative analysis of two Canadian public health disasters involving drinking water distribution systems, the North Battleford *Cryptosporidium parvum* outbreak in April 2001 and the Walkerton *E. coli* outbreak in May 2000. Both accidents resulted from a complex interaction between all levels of a complex sociotechnical system. However, the low-level physical and individual factors differed in the two cases, whereas, the high-level governmental and regulatory factors tended to be the same. These findings may have implications for the design of public policies to minimize risk in complex sociotechnical systems.

Keywords: Risk management; System safety; Cognitive engineering; Human error; Accident analysis; Complex sociotechnical systems; Public health; Water distribution systems

1. Introduction

As economic competition increases, sociotechnical systems in various industrial sectors (e.g. water distribution plants, nuclear power plants, commercial airplanes, and hospitals) are continually being required to "do more with less". Indeed, the need for continuous improvement in both quality and productivity in the face of more constrained resources has increased drastically in recent years. This trend has caused engineering systems to become more complex than in the past, a trend that is sure to grow [14,20]. Increase in complexity, in turn, has led to a greater hazard potential because unanticipated events that threaten safety become more commonplace [12]. Therefore, the need to manage risk and safeguard public health in complex sociotechnical systems has never been greater. Yet, risk management continues to be somewhat of a hit and miss affair because each large-scale accident appears to be unique. Analyses of high-profile disasters [11,4,19] typically reveal an idiosyncratic set of factors that will likely never be repeated in the same system, let alone in other systems in the same sector or in other sectors.

Perhaps the problem is that analysts have generally not adopted a common theoretical framework to compare accidents in different complex sociotechnical systems. Analyses tend to be conducted in an atheoretical ad hoc fashion, and when a theoretical framework is adopted, it is rarely applied to multiple accidents. If the same theoretical framework was used to analyze various disasters in detail, then perhaps we could identify the risk factors that remain relatively invariant across particular scenarios, systems, and even sectors. Separating the wheat from the chaff would create a solid foundation for developing public policies to manage risk and protect public health in a more rigorous and systematic fashion.

This article aims to contribute to this goal by using Rasmussen's framework [15] for risk management to conduct a comparative analysis of two public health outbreaks originating in Canadian drinking water systems. In April 2001, the water distribution system in North Battleford, Saskatchewan became contaminated with the *Cryptosporidium parvum* protozoon. In a city of

* Corresponding author. Address: Department of Mechanical & Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario M55 3G8, Canada.
E-mail address: Vicente@mit.utoronto.ca (K.J. Vicente).

0951-8320/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0951-8320(03)00052-8

approximately 15,000 people, an estimated 5800–7100 residents, along with hundreds more from other communities and provinces, became ill. In May 2000, the water distribution system in Walkerton, Ontario became contaminated with *E. coli* bacteria. In a town of 4800 residents, seven people died and an estimated 2300 became sick. The total economic cost of the tragedy was estimated to be over $64.5 million.

These two outbreaks are well suited for a comparative analysis. First, both were high-profile events that compromised public health. Second, both outbreaks took place in Canada, which provides some measure of control for national cultural effects. Third, both outbreaks took place in public drinking water systems, which provide some measure of control for sector effects. Finally, there are reasons to suggest that public policies in this sector are still in need of improvement. Since the Walkerton outbreak, an alarming number of boil water advisories have been issued across Canada [2,3,18]. In the province of Saskatchewan alone, over 79 boil water advisories were issued during the last seven months of 2001 following the North Battleford outbreak [13]. These signs suggest that many communities may be operating their water treatment facilities in a manner that is jeopardizing public health, causing the public to be skeptical of the government's ability to provide safe drinking water. Thus, this comparative analysis has the potential to influence important public policy decisions in this particular sector, in addition to adding to our knowledge of risk management in other sectors.

The remainder of the article is organized as follows. First, Rasmussen's framework [15] for risk management will be described. Second, the detailed theory-based analysis of the Walkerton outbreak already conducted by Vicente and Christoffersen [23] will be summarized. Third, a detailed analysis of the North Battleford outbreak using Rasmussen's framework will be presented for the first time. Finally, a comparative analysis of the two accidents will be presented with the aim of identifying implications for public policies that can safeguard complex sociotechnical systems, and thus, public health.

2. Risk management in a dynamic society

Rasmussen's framework [15] was adopted in this work for three reasons. First, the framework represents the culmination of almost 40 years of systematic research on risk management in complex systems (see Refs. [16,20,21] for reviews). Second, the research program on which the framework is based has influenced other prominent researchers in the cognitive engineering and safety science communities [1,8,9,17]. Therefore, this theoretical perspective provides a representative state-of-the-art view of risk management in complex sociotechnical systems. Finally, this framework had already been used to analyze the Walkerton outbreak [23], thereby providing a basis for a comparative analysis.

2.1. Structure

Rasmussen's framework [15] for risk management has two components. The first is a structural hierarchy describing the various actors—both individuals and organizations—involved in a complex sociotechnical system. Fig. 1 provides a representative example, although the precise number of levels and their labels can vary across industries. The bottom level describes the behavior associated with the particular (potentially hazardous) process being controlled (e.g. water supply system, nuclear power plant, commercial aviation). Understanding this level usually requires knowledge of science and/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). Human factors engineering is usually required to understand this level. The third level from the bottom describes the activities of the management that supervise the staff. Knowledge of management theories and industrial-organizational psychology is used to understand this level. The next level in the diagram describes the activities of the company as a whole and usually requires knowledge of economics, organizational behavior, decision theory, and sociology. The following level describes the activities of the regulators or associations that are responsible for monitoring the activities of companies in that particular sector. Finally, the top level details the activities of the 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.

Decisions at higher levels should propagate down the hierarchy, and information about the current state of affairs should propagate up the hierarchy, creating feedback paths. These interdependencies across levels of the hierarchy are critical to the successful functioning and monitoring of the system as a whole. If instructions from above are not formulated or carried out, or if information from below is not collected or 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 is an emergent property of a complex sociotechnical 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, accidents and threats to safety can result from a loss of control caused by a lack of vertical integration (i.e. mismatches) across levels of a complex sociotechnical system, not solely from deficiencies at any one level alone. All layers play a critical, albeit different, role in maintaining safety. As a corollary, accidents and

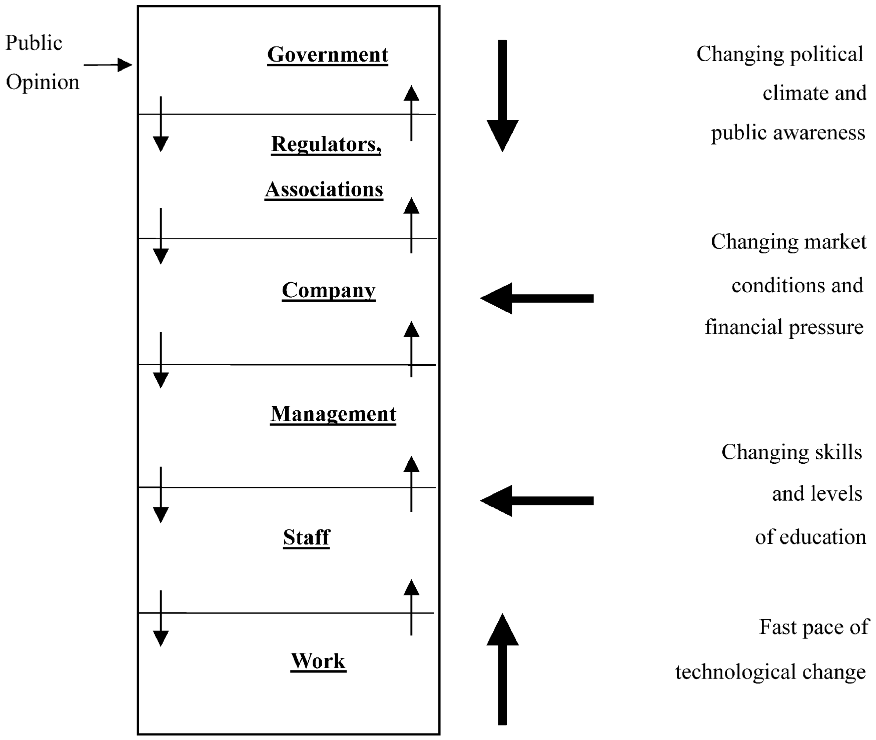

Fig. 1. Various levels of a complex sociotechnical system involved in risk management. Adapted from Ref. [15] and reprinted from Ref. [22]. Qlty Safety Healthcare 2002;11:302–4. With permission from the BMJ Publishing Group.

threats to safety can be caused by multiple contributing factors, not just a single catastrophic decision or action, making risk management a multi-faceted phenomenon.[1]

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

As shown on the right of Fig. 1, the various layers of a complex sociotechnical 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 today's dynamic society, these external forces are stronger and change more frequently than in the past.

2.2. Dynamics

The second component of the framework, shown in Fig. 2, deals with the dynamic forces that can cause a complex sociotechnical system to modify its structure and behavior 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. 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 and innovative ways of getting a task 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 subjected 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 change the way in which they perform their job. Moreover, the migration of work practices can occur at multiple levels of a complex sociotechnical system shown in Fig. 1, not just at one level alone.

Over time, this migration causes people to cross the official boundary of work practices, shown on the near left in Fig. 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

[1] Of course, accidents can also be caused by other factors, such as forces of nature and deliberate acts of sabotage.

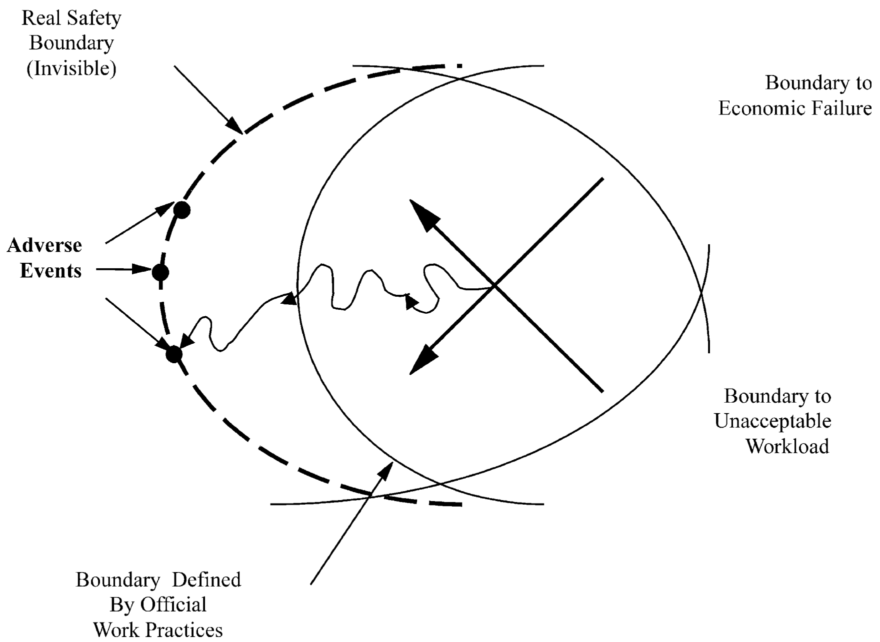

Fig. 2. 'Brownian motion' model showing how financial and psychological forces can create behavior gradients that cause work practices to migrate systematically toward the boundary of safety. Adapted from Ref. [15]. Copyright (2003), Kim J. Vicente

defenses degrade and erode gradually over time, not all at once.

One might think that this lack of procedural compliance and the resulting 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. This is why "work to rule" campaigns, where people do their job strictly by the book, usually cause complex sociotechnical systems to come to a grinding halt. Second, 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 violation of procedures does not immediately lead to catastrophe. At each level in the hierarchy, people are working hard, striving to respond to cost-effective pressures, but they do not see how their decisions interact with those made by other actors at different levels of the system. Yet, to use Rasmussen's phrase [15, p. 189], these uncoordinated attempts of adapting to environmental stressors are slowly but surely 'preparing the stage for an accident'.

But, because nobody is aware of this unintended effect, the Brownian motion 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 Fig. 2. 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 differently than they had been doing in the recent past. In other words, according to Rasmussen's framework, accidents in complex sociotechnical systems do not usually occur because of an unusual action or an entirely new, one-time threat to safety. Instead, catastrophes result from a combination of a systematically induced migration in work practices and an odd critical event that ends up revealing the degradation in safety that had been occurring all the while.

3. Summary of Walkerton outbreak analysis

Vicente and Christoffersen [23] adopted Rasmussen's framework [15] to conduct an analysis of the Walkerton *E. coli* outbreak using the evidence presented in the comprehensive 700 page report of a public inquiry report [10]. This section provides a brief summary of that research, providing a basis for the comparative analysis to be described later.

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). A&L Canada Laboratories was a private company that was contracted by WPUC to analyze their water samples.

Fig. 3 provides a graphical summary of the theory-based analysis [23]. Cattle manure and heavy rains caused Well 5 to be contaminated. Because of the geological bedrock and the shallow location of Well 5, natural water filtration was minimal and water contamination at that site was more likely than at any other location in Walkerton. Well 5 also lacked a continuous water monitor. These monitors were supposed to be installed on high-risk wells and would

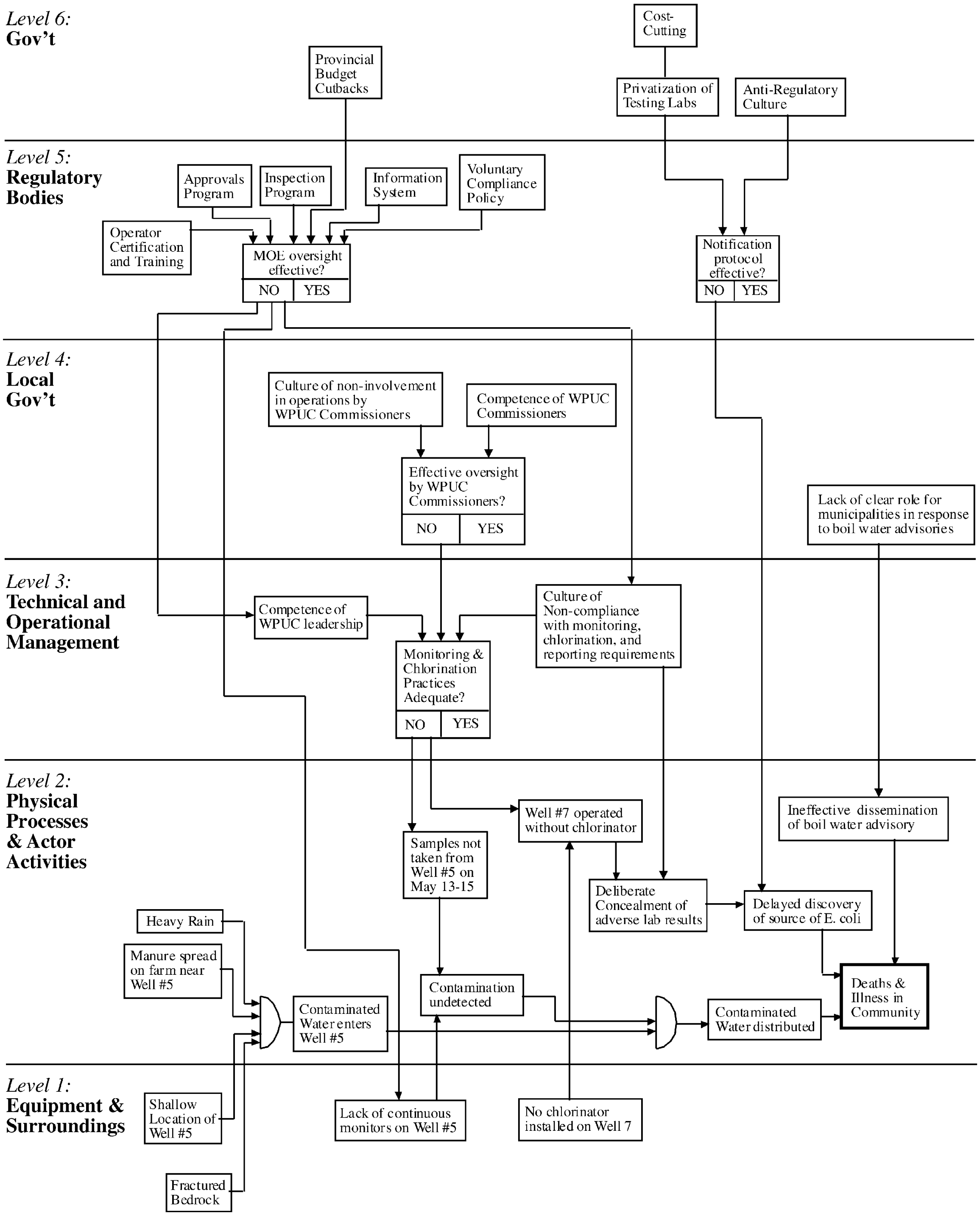

Fig. 3. Map of contributing factors in the Walkerton *E. coli* outbreak mapped onto the levels of a complex sociotechnical system identified in Fig. 1. From Ref. [23]. Copyright (2003). From " The Walkerton *E. coli* outbreak: A Test of Rasmussen's Frame work for Risk Management in a Dynamic Society." Theoretical Issues in Ergomonics Science, by Kim J. Vicente and Klaus Christoffersen. Reproduced by Permission of Routledge, Inc. part of the Taylor & Francis group.

automatically shut down the water pump in the well if contaminants entered the system. At another location in Walkerton, Well 7 did not have a working chlorinator during the period of May 3–19, a factor that indirectly contributed to the scope of the outbreak.

As shown in Level 2 of Fig. 3, failure to take samples from Well 5 coupled with the lack of a continuous monitor caused the contaminated water to be undetected and distributed to the community causing death and illness. Because he had knowingly operated Well 7 without a chlorinator—a clear violation of provincial requirements—Stan Koebel deliberately concealed poor lab results from the regulatory bodies, delaying the discovery of the *E. coli* source. By the time the city became aware of the immediate danger to the public, a water boil advisory was issued but poorly disseminated to members of the community.

As indicated in Level 3 of Fig. 3, many of the inadequate monitoring and operating practices, such as the deliberate concealment of poor lab results, were directly related to the inadequate competence of the WPUC management. Both the foreman and the general plants manager inherited their water operator's certifications, and thus had not been required to complete any training course or examination. As a result, the key people in charge of the Walkerton water distribution system lacked the education and expertise necessary to understand the water treatment process and to produce potable water. In addition, for 20 years, there was a local culture of non-compliance that caused operators to fail to take water samples, record fictitious data, and take samples for incorrect locations that were more convenient. This culture contributed to the concealment of the adverse lab results obtained from A&L Canada Laboratories.

Level 4 of Fig. 3 details the role that the City of Walkerton played in the events of May 2000. WPUC commissioners had limited knowledge of the process of water filtration and did not involve themselves with the technical details of operating the water plants, focusing almost entirely on financial matters. As a result, WPUC commissioners relied on Stan Koebel, the general plants manager, to identify and resolve any concerns related to the technical operations of the water system. The city of Walkerton also contributed to the ineffective dissemination of the boil water advisory. At the time, there was no clear, pre-defined role for the city in responding to a boil water advisory. Consequently, the city did not take an active role and missed an opportunity to reduce the scope of the outbreak.

The main regulatory agency with responsibility for overseeing the operation of the municipal water systems in the province of Ontario is the MOE. As shown in Level 5 of Fig. 3, five factors contributed to MOE's ineffective oversight of the water system in Walkerton. The operator certification and training conducted by MOE was inadequate, causing actors at multiple levels of the system (i.e. management, operators, etc.) not to have a full appreciation of the technical issues related to drinking water safety. MOE's lenient inspection program allowed infractions in the operation of water treatment plants to continue and encouraged a culture of non-compliance from communities (see Level 3 of Fig. 3). The lack of a proper information system hindered MOE's ability to monitor and track high-risk water sources and non-submitted water samples in Ontario. Without readily accessible feedback regarding small communities' waterworks departments, approval programs and compliance policies were compromised. The poor notification protocol in the province of Ontario was a major contributor to the delayed discovery of the source of *E. coli*. In 1996, the provincial laboratory had been privatized and communities were forced to use private laboratories, such as A&L Canada, but no legislation was enacted to require private laboratories to notify the MOE of adverse test results. Therefore, when WPUC sent its water samples to A&L Canada Laboratories in May 2000, A&L only informed Stan Koebel, and not MOE, of the adverse test results.

As shown at the top level of Fig. 3, the Ontario provincial government contributed to the events of May 2000 in two significant ways. First, its continual budget cutbacks eventually forced MOE to reduce its role in inspection and compliance activities, allowing dangerous practices at WPUC to continue. In the 2 year period between 1996 and 1998 alone, the budget was cut by over $200 million, with an ensuing staff reduction of over 30% (more than 750 employees). If MOE had the necessary funds to conduct a proper inspection program, the lack of continuous monitors and chlorinators in Walkerton's wells likely would have been detected and corrected. Second, the Ontario government's "distaste for regulation" [10, p. 368] laid the foundations for a waterworks system without concrete policies, guidelines, and regulations. This resulted in the lack of a mandatory notification protocol for private testing laboratories. Because of the government's non-involvement in regulation, A&L did not inform MOE of any adverse results.

3.1. Summary

Rasmussen's framework [15] for risk management provided a useful frame of reference for describing the multi-faceted factors that contributed to the Walkerton *E. coli* outbreak. The sequence of events reveals a complex interaction between all of the levels in a complex socio-technical 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.

Can the same framework do an equally good job of accounting for the North Battleford outbreak? If so, what can a comparative analysis of these two accidents tell us about how to improve risk management in complex sociotechnical systems?

4. The report of the North Battleford inquiry

Our new analysis was based on the Report of the Commission of Inquiry into the matters relating to the safety of the public drinking water in the City of North Battleford, Saskatchewan [7]. The Commission's aim was to uncover why people became ill from *C. parvum* and to review the adequacy and effectiveness of the actions taken at all levels of government and management in response to the water contamination. The inquiry report detailed the events surrounding the *C. parvum* outbreak as well as providing background information about the regulations, policies, and practices of all those involved with the North Battleford water treatment facility. The process that the Commission used to conduct its inquiry was based on the procedures used by the Honorable Dennis R. O'Connor in the Walkerton, Ontario *E. Coli* inquiry [10].

The Commission was given wide powers of investigation. The inquiry heard the oral testimony of 32 witnesses and received 120 exhibits and documents over 33 days of hearings. The investigation was conducted over 251 days and is the most comprehensive, authoritative, and accurate account available of the events surrounding the April 2001 outbreak. The final report authored by the Honorable Mr Justice Robert D. Laing was approximately 400 pages long, including appendices.

5. The events of April, 2001

Some background information is required to interpret the events of April, 2001. The North Battleford water system was operated by the Plants Department under the supervision of Mr Ivan Katzell from January 1981 to December 2000. Mr Randall Strelioff was the Director of Public Works for the city and was Mr. Katzell's direct superior. The government body with oversight responsibility for the operation of water systems in the province of Saskatchewan was the Saskatchewan Environment and Resource Management (SERM). The Battlefords Health District was the local public health unit for North Battleford and was headed by the local Medical Officer. Public health inspector, Mr Kenneth Startup, investigated the second case of cryptosporidiosis under the supervision of the senior public health inspector for the Battlefords Area, Mr Richard Koroluk. Dr Geoffrey Lipsett was a family physician in North Battleford and reported to Dr Gerharde Benade, physician for the Battlefords Health District. Both individuals played a key role in detecting the *C. parvum* outbreak. Mr John Yarske was the CEO of the Battlefords Health District and was Dr Benade's direct superior. Other relevant regulatory bodies included Saskatchewan Health, the Saskatchewan Water Corporation, and the Drinking Water Safety Committee. The Provincial Laboratory was responsible for the testing of contaminated patient fecal samples. EPCOR Water Services, Inc. was the external company that conducted several studies concerning the hazards of the North Saskatchewan River as a drinking water source. Reid Crowther and Partners Ltd was the external company hired by North Battleford to conduct audits of both the surface water treatment and sewage treatment facilities.

Table 1 provides an approximate timeline of the physical events and actions that contributed to the *C. parvum* outbreak in North Battleford during April 2001. Pre-existing factors that helped to stage this sequence of events will be discussed next.

Table 1
Timeline for North Battleford, Saskatchewan *C. parvum* outbreak

Date	Incident
March 2001	North Saskatchewan River experienced large turbidity fluctuation as well as high concentrations of fecal material during the spring months
September 2000–April 2001	No bacterial samples were submitted by North Battleford during this period
20-March-01	At the water treatment plant, SCU settling problems were detected and operators were without supervision
20-March-01	The SCU at the water treatment plant was drained, cleaned and no sludge was left in the unit
4-April-01	First recorded outbreak: A child who lived 13 km North of North Battleford
5-April-01	Second recorded outbreak: A case of diarrhea going around St Vital's School in Battleford. Sibling was also infected shortly after
9-April-01	Mr Strelioff authorized the purchase of bentonite to be added to the SCU to improve floc formation. Adequate floc formation was not established prior to April 24, 2001
12-April-01	Dr Benade received positive confirmation that the second outbreak case was in fact caused by *C. parvum*
12-April-01	The link between the possible *C. parvum* outbreak and increased anti-diarrheal sales was made by Dr Lipsett
13-April-01	Dr Benade projected 10 cases of infection per day and noticed that his own family had also experienced diarrhea. He then identified the North Battleford water supply as a possible source of the outbreak
17-April-01	Third finding of *C. parvum* detected in a fecal sample by the provincial laboratory
18-April-01	Mr Startup became ill with *C. parvum*
19-April-01	Fourth outbreak case detected in a patient living in Turtleford, Saskatchewan (80 km from North Battleford)
23-April-01	Dr Benade indicated that North Battleford could be the common factor, and that *C. parvum* could be water-borne
23–24 April-01	Dr Benade sent a memorandum to the Battlefords Health District advising them of a possible *C. parvum* outbreak
24-April-01	Two additional positive tests for *C. parvum* were confirmed
24-April-01	Mr Startup asked Mr Strelioff if there were any problems with water treatment plant to which Strelioff answered no. Mr Strelioff informed Mr Startup of the inability to establish a proper floc blanket. Mr Startup did not know the public health implications of this problem
24-April-01	Mr Strelioff attended a meeting with Dr Benade, Mr Startup, Mr Koroluk, and Mr John Yarske (CEO of the Battlefords Health District). Prior to the meeting, Mr Strelioff did not meet with the water treatment plant operators and reemphasized that the inability to form a floc blanket was not affecting the quality of drinking water being produced
24-April-01	SERM was notified of the situation in North Battleford
25-April-01	SERM issued a precautionary drinking water advisory
26-April-01	Advisory upgraded by the Battlefords Health District to boil water orders

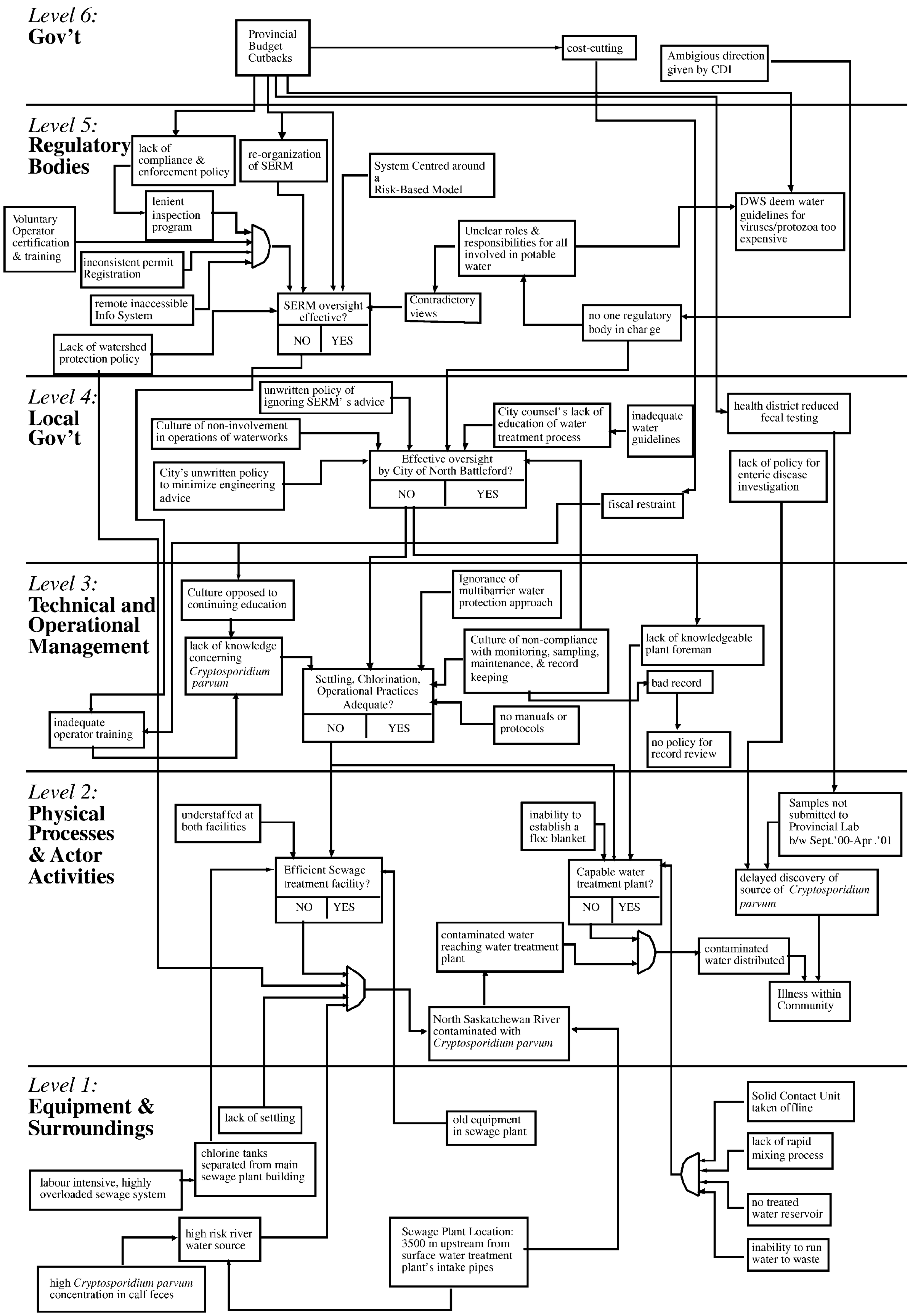

Fig. 4. Map of contributing factors in the North Battleford *C. parvum* outbreak mapped onto the levels of a complex sociotechnical system identified in Fig. 1.

6. North Battleford outbreak analysis

This section describes an analysis of the factors that contributed to the North Battleford outbreak using Rasmussen's theoretical framework [15], thereby complementing the analogous analysis of the Walkerton outbreak [23].

6.1. Equipment and surroundings

As indicated at the bottom of Fig. 4, there were several major physical circumstances relating to the North Saskatchewan River that initially contaminated the water source in North Battleford. Calf feces are known to contain high concentrations of *C. parvum* and due to the significant agricultural activity within the area of North Battleford combined with the heavy rainfall in the springtime, the river watershed can be easily contaminated. Another possible source comes from the sewage treatment plant located upstream from the raw water intake of the surface water treatment plant. Combined with a lack of river settling, an inefficient sewage treatment facility, as well as the absence of a watershed protection policy, the North Saskatchewan River has the highest probability of being contaminated with *C. parvum* during the spring months.

Before the river water reaches the intake pipes of the water treatment plant, it must first pass through the sewage treatment facility. The sewage treatment plant of North Battleford was not operating at industry standards partly due to the inadequate practices of the technical and operational management staff (see Fig. 4, Level 3). The provincial regulator had voiced concerns regarding the sewage effluent quality produced by the plant dating back to 1963. Indeed, in 1968—a full 33 years before the outbreak—regulators wrote to the City of North Battleford, stating: "We were surprised to find the coliform count so high… it would appear effluent is still reaching the river channel from which the intake draws water" [7, p. 48]. A year later, in 1969, another letter stated: "we feel the situation is potentially very dangerous… unless remedial action is taken this year. The only other alternative, which we feel certain (city) council would not wish to consider, would be to shut down the number two water plant unless the raw water quality is considered suitable for treatment" [7, p. 48]. On March 20, 1993, the provincial regulator warned the city about the "extremely contaminated water" [7, p. 51] in the river samples taken at the water treatment plant. They subsequently requested immediate action by the city to rectify the situation before March 31, 1994. The provincial regulator's request was ignored.

As shown near the bottom of Fig. 4, operators of the sewage treatment plant stated that the plant was physically exhausting to operate because of the plant's old equipment. Also, both the sewage treatment system and the operators were overloaded. For example, the chlorine tanks were separated from the main sewage plant building. Operators would be required to leave their stations in the main building to fill the chlorine tanks in a separate building while the plant was still in operation. The overloading of the sewage treatment facility of North Battleford caused it to be inefficient in terms of producing high quality sewage effluent and effortful to operate well.

One of the most significant environmental factors leading to the *C. parvum* outbreak in North Battleford was the fact that the sewage treatment plant was located only 3500 m upstream from the surface water treatment plant's intake pipes. It was known that the sewage effluent contained contaminants that could be potentially hazardous to the production of potable water if they reached the surface water treatment plant's raw water intake pipes. In 1989, and again on September 29, 1992, the provincial regulator organization, SERM, had conducted dye studies to track the effluent being produced by the North Battleford sewage treatment plant. The results indicated that combined with the topology of the area, river turbidity, as well as river flow, sewage effluent was reaching the surface water intake pipes more often than not. During an external audit of the sewage treatment plant in 1995, Reid Crowther and Partners Ltd deemed its location problematic and made strong recommendations to the city to consider relocating the sewage plant.

If the water treatment plant had been capable, the fact that contaminated water was entering the water plant should not be of immediate concern. Proper safety boundaries and chlorination units would ensure the production of potable water even if the raw water source was contaminated. However, this was not the case in North Battleford. The Commission report indicated that several key components of the surface water treatment were discovered to be either missing or offline prior to the outbreak of April 2001, rendering the water treatment plant incapable.

As indicated on the bottom right of Fig. 4, North Battleford's water treatment plant was missing a rapid mixing process that is required to facilitate charge neutralization during the coagulation and flocculation process. After flocculation, water then proceeds to the Solids Contact Unit (SCU). The SCU removes large water particulate in order to limit particle loading on the filter before water passes through the filters. Policy required that the SCU be totally cleaned once a year, usually sometime during the low demand winter months. During the events surrounding the outbreak, the SCU was offline and cleaned during the early spring on March 20, 2001. After restarting the SCU, operators reported settling problems within the SCU to city officials. For smaller communities dealing with complex raw water sources, it is almost a necessity to maintain treated water reservoirs on site to increase chlorine contact time to properly kill parasites. At the time, the North Battleford water treatment facility did not have a treated water reservoir and there was no plan to design one.

Running water to waste is a fail safe for most water treatment plants anytime the parameters of performance have exceeded the plant's capacity and threaten to undermine the quality of drinking water. The inability of the water treatment plant to run water to waste was one of the major limitations of the plant prior to April 2001. Due to a design flaw, the plant's elevation was such that running water to waste would flood the lower section of the plant and hence designers opted not to allow raw water wastage.

6.2. Physical processes and actor activities

This second level is described in detail in Table 1, so it will not be discussed here again. The main points are summarized in Level 2 of Fig. 4. Over the period of many years, the demands being placed on the plant operators increased to the point where one of them wrote a prescient memo in 1988—13 years before the outbreak—warning: "If the present work load continues unaided by additional staff and future department responsibilities are added, I feel that my capabilities to handle the work load will be stretched beyond what is acceptable. This can only lead to poor department operation and poor staff morale" [7, p. 89].

6.3. Technical and operational management

As shown in the middle of Fig. 4, the major contributing factor at this level dealt with the lack of education and a culture of non-compliance. These two factors played a significant role over the years leading up to and including the *C. parvum* outbreak.

A majority of the operators and the management staff did not have any knowledge concerning the relationship between water quality and *C. parvum*. Continuing education and adequate operator training programs were both lacking within the plants department. Prior to December 2000, none of the employees had attended any additional water treatment courses beyond the initial basic correspondence course required by the city. Operators testified that "it was difficult for operators to receive additional training and continuing education with respect to sewage treatment and water treatment because of a shortage of manpower in the plants department" [7, p. 83].

Another operator indicated that the plant foreman's management style did not encourage operators to seek advice from anyone other than himself. In addition, the plant foreman himself did not remain up to date regarding industry practices and water guidelines, yet he provided little or no incentive for operators to educate themselves. In his testimony, he admitted to never having addressed the issue of *C. parvum* with his operators.

In addition, there were no manuals or protocols for the operation of the plant that could help inform the operators on how a problem with the turbidity or settlement could be handled based on procedure or past experience. Operators were left to their own limited knowledge to solve the problem. One operator stated: "You are running a lot of the time by the seat of your pants", and judgments were based on common sense rather than protocol [7, p. 72].

Mr Strelioff was hired by the city on the premise that management skills were the main focus of the job and technical knowledge was irrelevant. He stated that he did not have any detailed knowledge of water treatment when he commenced his job on November 15, 1999 and relied completely on Mr Katzell for expertise in operating the plants. He stated that "any time there was a question or an issue (Mr Katzell) seemed to have a good answer for it, and it seemed to make sense—based on what little technical experience I had" [7, p. 97].

After December 2000, Mr Katzell retired as plant foreman and a new inexperienced foreman from a different department was assigned to perform administrative tasks. The new foreman did not have any knowledge or experience in water treatment. On January 12, 2001 operators wrote a letter to the city outlining their concern about the need for a knowledgeable plant foreman to ensure the proper operation of both the sewage and water treatment plants, but their suggestions were not acted upon. From December 2000 to August 2001, operators were "left to their own devices in operating the plant" [7, p. 80].

As shown in Fig. 4, there was also ignorance of the multi-barrier water protection approach to prevent potable water contamination. During a meeting on April 24, 2001, Mr Startup, Public Health Inspector for the Battlefords Health District, met with Mr Strelioff to discuss the current status of the water treatment facility. At this specific time, more than half a dozen cases of *C. parvum* had been confirmed. Mr Strelioff assured Mr Startup that the water treatment plant was producing potable water and that the only 'minor' problem was the inability to form a proper floc blanket at the water treatment plant due to low river turbidities. In fact, the inability to establish a floc blanket is a major problem with severe public health consequences. Mr Strelioff's underestimation of the severity of the situation shows that he did not fully appreciate the multi-barrier protection approach to risk management.

While Mr Katzell did have prior knowledge concerning *C. parvum*, he did not fully appreciate the coagulation, flocculation, and sedimentation process as a barrier for water parasites. During testimony to the Commission, he stated that he was under the impression that enteric diseases such as *C. parvum* were a bigger concern in quiet surface waters than in flowing waters such as the North Saskatchewan River. This misunderstanding, the lack of detailed knowledge about *C. parvum*, and the lack of appreciation for the multi-barrier approach was confirmed by his actions regarding the removal of the SCU and the continual operation of the water treatment plant during the months leading to the outbreak.

The culture of non-compliance in relation to monitoring, sampling, maintenance, and record keeping directly affected the documentation procedures at the treatment plant. There were two fundamental problems with the record keeping system. First, it was the practice of the operators to manually take down readings and equipment malfunctions by hand and at a later date, time permitting, enter them into a records database. The flaw within the database was that it would provide a date stamp automatically for when the data was entered, not when it had been recorded. This led to poor records and maintenance scheduling since operators occasionally recorded readings only by hand, omitting the computerized records database. Second, the default mechanism of the computerized recording process was flawed. If information was not entered with respect to any one of a number of matters recorded in the manual log, the computer would default to the previous reading that had been entered. This reduced the value of the computer record because it was necessary to still maintain the manual log to see if a given recording was an actual value or a default value. Since there was no formal policy for both internal and external record review and a lack of enforcement from upper levels of government, these deficiencies within the system were allowed to remain and grow over time.

6.4. Local government

As detailed in Level 4 of Fig. 4, the local government also played a significant role in the propagation of the events of April 2001. According to s.14 of *The Public Health Act*, 1994, it is the municipality's responsibility to provide potable water to its population. In terms of administrative, financial, and technical responsibilities, the City of North Battleford failed to perform its civic duties.

First, each of the city management persons who testified indicated that they had a lack of technical education regarding the water treatment process and were ignorant of what was needed to produce safe, clean drinking water. The city, like Mr Strelioff, relied solely on Mr Katzell's expertise until his retirement in December 2000.

Second, it was the city's culture and unspoken policy to maintain non-involvement in the operation of the waterworks department. It was a golden rule to "leave matters of administration to the administrators without providing guidelines on how the administrators' jobs should be performed or what information council should receive" [7, p. 197]. North Battleford Mayor Ray emphasized that the role of the city was general policy and budget, not operational issues. Yet during the events of April 2001, the cause of the outbreak was not determined in a timely manner in part due to a lack of an enteric disease investigation policy, part of the city's jurisdictional responsibilities. As uncovered by the Commission, the city did not have any written guidelines with respect to the production of potable water. Prior to the *C. parvum* outbreak of April 2001, there was no quality control/quality assurance program with respect to the operation of water treatment plants.

The city also had many unwritten policies that indirectly encouraged accidents to occur. Knowing the outdated and antiquated state of its waterworks system, the City of North Battleford continued to maintain artificially low water utility rates throughout the 1990s. While cutting the waterworks' annual budget, the city assumed that the plants department would continue to produce drinkable water. Another unwritten policy was the city's tendency not to obtain professional engineering advice to operate the plants department. The city justified this by stating that they have always relied on outside consultants for technical advice and hiring a professional engineer to manage the plants would be financially unadvisable. There was only a single occasion when a consultant engineer was retained throughout the decade of the 1990s to look at the water treatment plants. Mr Mark Getzlaf, Manager for the Environmental Protection Section of SERM expressed concern about "how (the city) expected to run a very complex set of treatment facilities without a manager/foreman and City engineering" [7, p. 168].

Another deficiency at the local government level of Fig. 4 was the lack of communication and feedback between the city, SERM, and the Battlefords Health District. As mentioned before, the SCU was taken offline on March 20, 2001 and experienced settling problems when the SCU was restarted. The operators promptly informed the city who then failed to notify SERM and the Battlefords Health District of this problem.

One of the strongest contributors to the events of April 2001 was the city's continual dismissal of SERM's advice, recommendations, and warnings. Following the *E. Coli* outbreak in Walkerton, Ontario in May 2000, the regional manager for SERM wrote to communities to emphasize the importance of proper maintenance and bacteriological testing on a regular basis to produce potable water. The City of North Battleford took exception to the letter and deemed it a "cover your butt" communication [7, p. 106].

The culture against continuing education at the Technical and Operational Management Level of Fig. 4 was further hindered by fiscal restraint coming from the local government level. The city of North Battleford, contrary to available information and statistics, believed that budget cuts to the water department were necessary. Operators' and management's adamant requests for more staff were denied by the city. On October 18, 1994, a video entitled "Understanding the Cryptosporidium Challenge: Preventing Water-borne Disease" was produced to educated water suppliers about this pathogen. The video was never purchased and was never made available to the operators in North Battleford. In contrast, the Prince Albert treatment plant, a similar size of treatment plant, had purchased the video and required its operators to review the video on several occasions.

Finally, because of budget cutbacks imposed by the provincial government (see Level 6), the North Battleford Health Districts decided to reduce the amount of fecal testing. This decision helps explain why no samples were submitted to the Provincial Laboratory between September 2000 and April 2001 (see Level 2, Fig. 4).

6.5. Regulatory bodies

SERM is the main regulatory agency with responsibility for overseeing the operations of the province's municipal water systems. Several policies and practices within SERM contributed to the outbreak. As previously mentioned, SERM's inability to establish a proper watershed protection policy was directly related to the North Saskatchewan River being contaminated with *C. parvum*. The absence of this policy permitted fecal material from the grazing calves located on the agricultural land near the North Saskatchewan River to contaminate the river's water. Had this policy been in place, it would have limited the source of contamination to only the sewage treatment plant and the events of April 2001 could possibly have been averted.

SERM was also unclear about its roles and responsibilities with respect to the production of potable water. The Drinking Water Safety Commission was divided among two government departments, SERM and Saskatchewan Health, in addition to a Crown corporation, the Saskatchewan Water Corporation. No regulatory body was in charge and this led to confusion since there were no formal jurisdictional boundaries drawn by the Cabinet Decision Item (CDI) for the three regulatory bodies in charge. The ineffectiveness of the regulatory setup was demonstrated when the Drinking Water Safety Commission deemed formal water guidelines for parasites too expensive to implement and incorrectly assumed that such guidelines, if implemented, would not improve the province's drinking water quality.

In 1993, SERM abandoned its inspection program of surface water treatment plants and subsequently adopted a reactive risk-based model, based on bacteriological monitoring. However, as the Inquiry Report observed, "The risk-based model employed by SERM… was arrived at on the basis of economic considerations (i.e. what SERM or the government thought they could afford based on priorities), and has nothing to do with how best to safeguard the health of the population, all of whom consume water" [7, p. 276]. Under this model, only municipalities who voluntarily chose to submit bacteriological samples were monitored. The Inquiry Report indicated that the last time the North Battleford surface water treatment plant had been inspected was in 1991—10 years before the outbreak. With the adoption of this new risk-based model, SERM's inspection program was formally disbanded and inspection was occasional at best, allowing municipalities such as North Battleford to operate below industry standards. "The lack of inspection by SERM of the North Battleford surface water treatment plant… had a direct bearing on the events of April, 2001" [7, p. 226].

SERM also lacked timely information on how any particular plant was being operated. As the Inquiry Report pointed out, "The absence of a flagging system that would allow SERM to detect municipalities who do not comply with the requirements for submitting water samples is a serious shortcoming in its monitoring capability" [7, p. 183]. Without a comprehensive information system accessible by all the municipalities and without an ongoing inspection program, it was impossible to assess quantitatively the risks associated with the water being produced in a particular plant.

The lack of a compliance and enforcement policy allowed communities operating on the border of safety regulations to continue. SERM simply lacked the financial support to fully enforce safe water guidelines. Mr Scott Meekma, Environmental Protection Officer for SERM, testified that he believed "the enforcement policy with private industry was always more rigorous than it was with municipal governments because it was assumed private industry had the financial resources to implement best industry practices" [7, p. 226]. Moreover, SERM was aware of the adverse consequences of their withdrawal from compliance and inspection activities. Within the province, rates of non-compliance by communities for drinking water systems with the current legislation in Saskatchewan were alarmingly high due to SERM's lenient inspection program. During the 1999–2000 fiscal year, 57% of municipalities submitted less than 80% of the required bacteriological samples required by their permits. Had an organized follow-up compliance/enforcement policy and a more vigorous inspection program been in place for communities not submitting required samples, North Battleford's lack of compliance would have been detected by SERM and a *C. parvum* outbreak could have been avoided.

Inconsistent permit registration between water treatment plants within Saskatchewan was also of concern. SERM issued a different operating permit to the City of Prince Albert compared to that of North Battleford, even though both cities obtain raw water from the North Saskatchewan River. This inconsistency was partly due to the organizational structure of SERM. At the time, various regions within Saskatchewan were divided into EcoRegions and each EcoRegion was responsible for renewing operating permit registrations for water treatment plants within its riding. Prince Albert's operational permit detailed more stringent guidelines than North Battleford's.

SERM's voluntary operator certification and training program was directly coupled with the lack of a compliance/enforcement policy. One of the problems with the certification program was that there was no examination required to obtain a certificate. In 1991, SERM conducted a review of the voluntary certification program because of the province's poor level of compliance with the provincial regulations and poor attendance at training events. At the conclusion of the review, it was discovered that operators of water treatment plants in the province were poorly trained and that one-half of all operators currently working in Saskatchewan had attended one or no workshops in total. Yet, just 2 years later in 1995, "SERM basically withdrew from direct participation in operator training" [7, p. 226], thereby abdicating part of its oversight function, contributing to the inadequate operator training observed at lower levels of Fig. 4.

As shown in Level 5 of Fig. 4, on April 1, 1993, SERM was structurally reorganized as a result of continuing provincial budget cuts. Previously, SERM had been organized into environmental protection branches around land, air, and water. During restructuring, SERM was redivided along 'client lines' consisting of three new environmental protection branches: commercial, industrial, and municipal. As a result of the reorganization, the eight regional environment officers, who until this time had only been concerned with water and wastewater management, became part of the municipal branch which was responsible for solid waste management and air pollution as well. Additional duties were assigned to them including inspection and compliance activities for solid waste management systems. According to Mr Bob Ruggles, Assistant Deputy Minister for SERM, regional officers were instructed to assign priority to the landfill program because "the Department up until that time had been unable to properly assess landfill systems across the province" [7, p. 220]. The reorganization of SERM placed more stress on the staff at SERM and indirectly compromised SERM's ability to effectively oversee water and wastewater activities in the province of Saskatchewan.

SERM relied on the assumption that "the poorest, smallest communities had the resources, the knowledge, and the will to operate a safe water treatment program and distribution system" [7, p. 276]. This incorrect assumption required SERM to assume that all municipalities would not only meet minimum guidelines set out in the Municipal Drinking Water Objectives but would adopt the best industry practices to minimize the risk of water-borne pathogens, such as *C. parvum*, which were not covered by the guidelines. "SERM made this assumption knowing that only 25% of the operators in the province were registered with the voluntary certification program, and that only a small percentage of operators regularly attended continuing education courses" [7, p. 276]. By 1996, SERM knew that many municipalities were not submitting the required samples, and of those communities that did, a significant percentage were not meeting the minimum guidelines.

6.6. Government

The deficiencies within SERM are partly due to the actions of the Provincial Government of Saskatchewan during the years leading up to and including the events of April 2001. By directly controlling the fiscal budgets of the regulatory bodies below them, the Provincial Government of Saskatchewan also indirectly affected the municipal funding allocations, resulting in financial constraints. Pressures were felt throughout the system.

SERM's budget was reduced by almost 25 percent to $86.8 million over the course of the 5 years leading to the *C. parvum* outbreak, reflecting a staff reduction of 92 FTEs. Faced with such budget restrictions, SERM decided to exit from its field monitoring, advising, and inspection programs and activities in the water and wastewater departments. This was followed by a proposition to eliminate the eight regional officers plus three additional positions within the water and wastewater departments in order to save $700,000 per annum. Included within the $700,000 was the withdrawal of SERM from the voluntary certification program for operators. While the Government approved the reduction in the municipal water/wastewater advisory services that the regional officers provided, it did maintain the voluntary certification program as a necessity. SERM knew that its withdrawal from monitoring and inspection programs would have adverse effects on the drinking water quality of small municipalities. In a commentary offered by SERM in its budget review document, it stated that communities will no longer have access to the expertise in the drinking water programs causing the health of people in Saskatchewan communities to be at risk, and that SERM will not be meeting its mandated and legislated responsibilities because of the provincial budget cuts [7]. SERM recognized that it did not have enough resources to manage the water department.

The Government of Saskatchewan, represented by the Cabinet Ministers who constitute the Treasury Board, was aware of the consequences of SERM's choice to withdraw from water quality management due to financial constraints and also that SERM would be unable to meet its legislated mandate to regulate drinking water in the province. With the restructuring of SERM in 1993, stresses within the organization grew and were exacerbated by the continued budget reductions by the provincial government.

Following the *E. coli* outbreak in Walkerton, Ontario, the public health and safety ministers of the provincial government of Saskatchewan took renewed interest in drinking water safety. On June 9, 2000, a CDI addressing the need to improve the safety of drinking water in Saskatchewan was presented to the Premier and all the cabinet ministers. The CDI detailed the problems with the current water system and made recommendations on how those problems could be rectified. The CDI appointed SERM, Saskatchewan Health, and Saskatchewan Water Corporation to be responsible for the implementation of the new water program. Having three regulatory bodies with separate budgets and different priorities was a serious weakness to the program. That coupled with the ambiguity of the monitoring and compliance program outlined by the CDI, compromised SERM's ability to safeguard the quality of the drinking water, and thus, the health of the province's citizens. As the Inquiry Report pointed out, "the end result was that the quality drinking water program was sacrificed as a matter of choice, not necessity. The choice was made knowing the result would be a reduction in the overall quality of drinking water in the province" [7, p. 223].

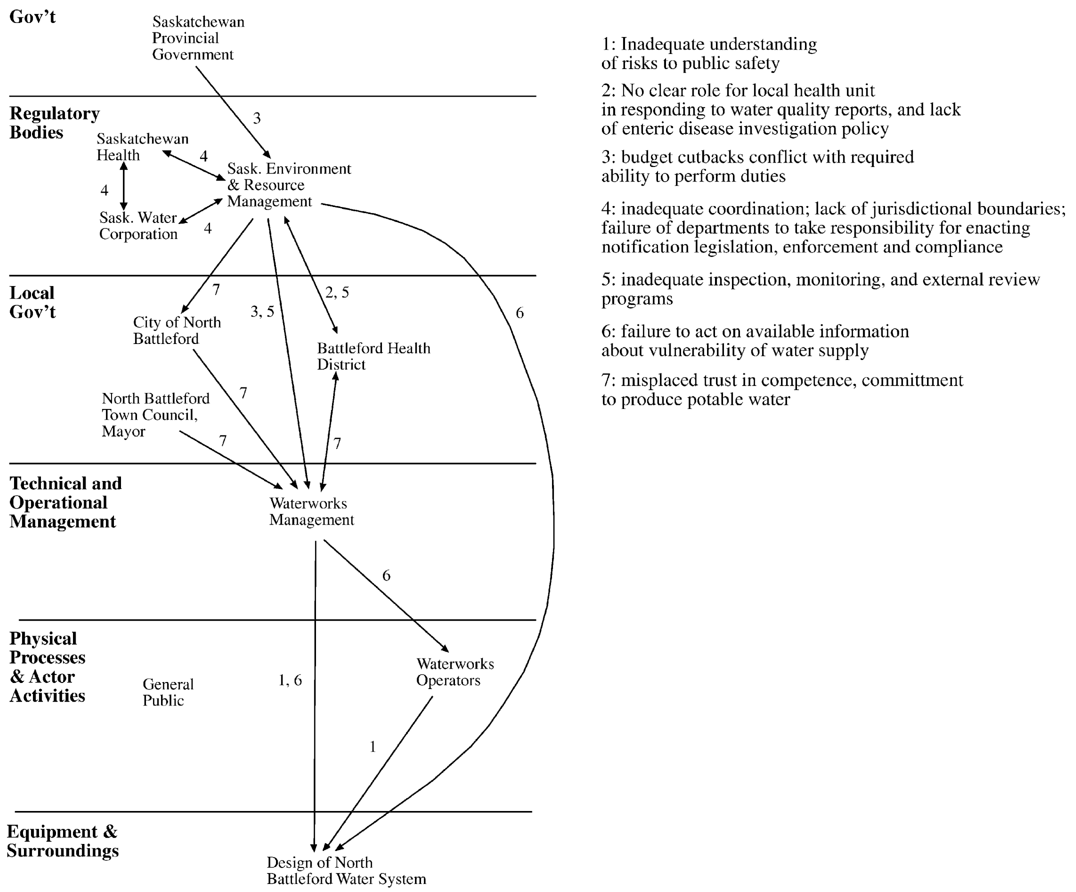

Fig. 5. Counter-productive interactions (mismatches) between actors at different levels of the sociotechnical system involved in control of the North Battleford water system.

6.7. Summary

Rasmussen's framework [15] also provided a useful frame of reference for describing the multi-faceted factors that contributed to the North Battleford, Saskatchewan *C. parvum* outbreak. The sequence of events again reveals a complex interaction between all the levels in a complex sociotechnical system. The mismatches between these factors are summarized in Fig. 5. Furthermore, the dynamic forces that led to the accident had been in place for some time—some going back over 30 years—yet the feedback to reveal the safety implications of these forces was largely unavailable to the various actors in the system.

By using the same theoretical perspective to analyze two different outbreaks, we are now in a position to conduct a comparative analysis to determine the similarities and differences between these two public health disasters, and the implications of those similarities and differences for risk management and the safeguarding of public health.

7. Comparative analysis

Fig. 6 provides a graphical summary of the theory-based comparison. Four patterns stand out. First, both accidents resulted from a complex interaction between all the levels in a complex sociotechnical system. Furthermore, both cases exhibited a systematic migration of work practices fueled by effort and financial gradients over several decades. These observations suggest that Rasmussen's framework [15] has some explanatory power in accounting for the factors that contribute to accidents in complex sociotechnical systems, at least in the Canadian public drinking water sector.

Second, despite the fact that both outbreaks are from the very same sector, the specific low-level factors dealing with the source of the outbreak, the equipment and surroundings, and the physical processes and actor activities tend to be unique to each outbreak. For example, the threat to public health was *E. coli* in the Walkerton case, and *C. parvum* in the North Battleford case. Also, the shallowness of Well 5 was a critical environmental contributor in the Walkerton case, whereas the relative locations of the sewage and water treatment plants were critical environmental contributors in the North Battleford case. These divergences would be even greater if we compared accidents in different sectors (e.g. public drinking water vs. petrochemical plants) because the technologies and physical processes used across sectors differ markedly. This finding of variable technical causes, even within a sector, reinforces the prevalent perception that accidents in complex systems are unique, singular events.

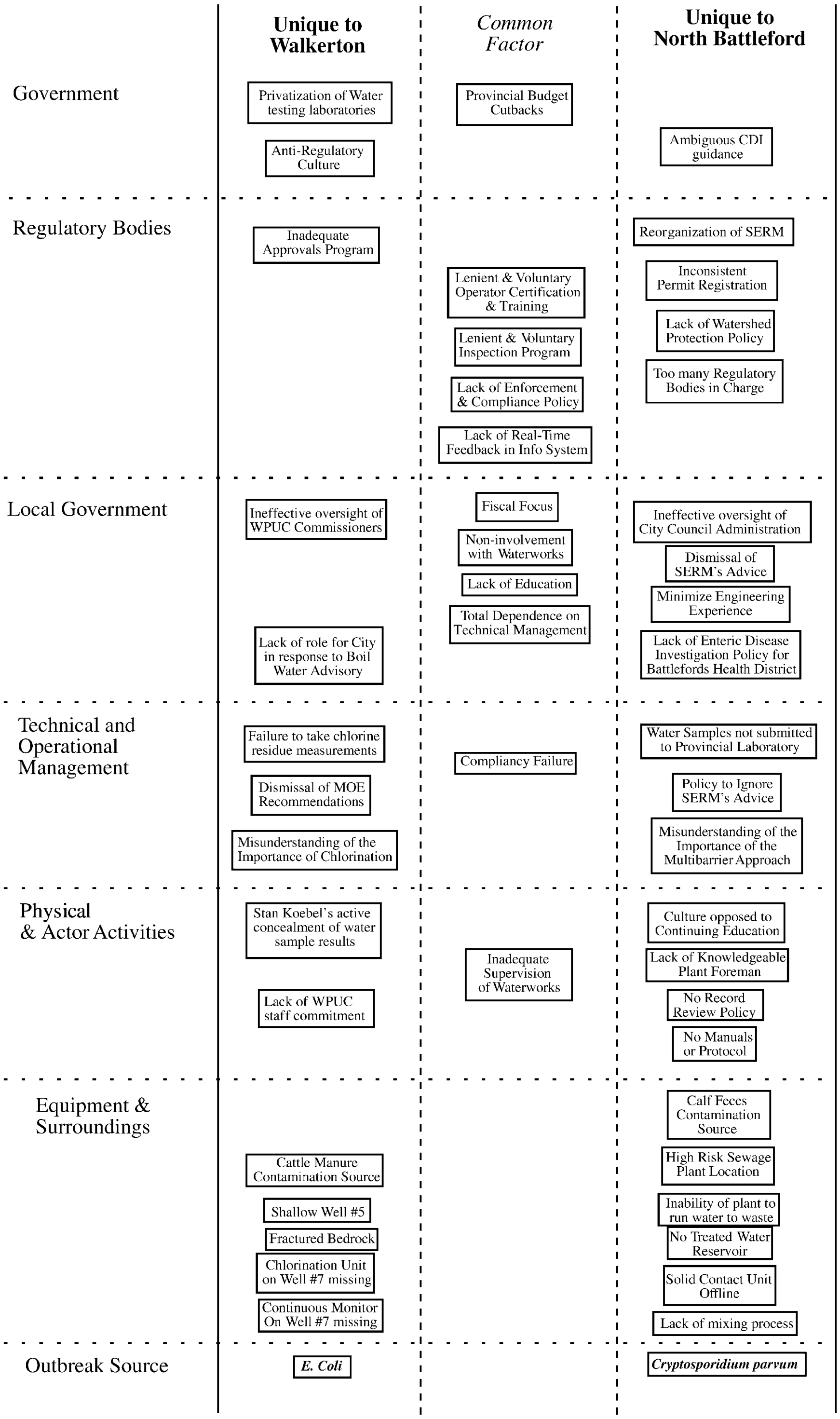

Fig. 6. Comparative analysis of the North Battleford and Walkerton outbreaks summarizing the factors that were unique to each accident (outer columns) and the factors that were common to both accidents (middle column).

Third, some of these low-level factors are not only variable, but also very difficult to anticipate. The most salient example is Stan Koebel's active concealment of water sample results and his lack of understanding—he did not know what *E. coli* was, let alone that it was lethal [10]. It would be extremely unlikely for system designers to think of such an unlikely scenario when deciding what safeguards to build into a drinking water distribution system to protect public health. The variable and unanticipated nature of the technical factors contributing to accidents—even in the same sector—suggests that it would be difficult to identify a systematic approach to the management of risk in complex sociotechnical systems. If the target is chaotic, how can there be an orderly remedy?

Such a conclusion would be premature, however, because the fourth pattern to emerge from the comparative analysis is that the specific high-level contributing factors dealing with government and regulation tend to be common to both outbreaks. For example, provincial budget cutbacks played a crucial role in both cases. Similarly, insufficient attention to operator certification and training, inspection programs, enforcement and compliance policies, and inadequate feedback at the regulatory level played a deciding role in both outbreaks. This regularity in high-level organizational factors appears to generalize beyond the two case studies reviewed here. For example, Hopkins [5, p. 7] analyzed one accident from the mining industry and another from the petrochemical industry using a comparable framework and found that a similar set of government and regulatory factors played a key role in both those cases too, leading him to conclude that "the technical causes vary from one accident to another but the organisational failures which accident analyses reveal seem remarkably similar".

Note, however, that these regularities across accidents would not necessarily come to light if a different framework was adopted for the comparative analysis. For instance, Hrudey et al. [6] compared the Walkerton case to 15 other outbreaks in drinking water systems (including the North Battleford accident) using a theoretical framework based on five categories of barriers that can threaten drinking water safety: source, treatment, distribution, monitoring, and response. The strongest pattern to emerge from that comparative analysis was that runoff from heavy snow melt or heavy rainfall contributed to source contamination in several of the outbreaks. Yet, the magnitude of the similarities was not great—only 40% of the outbreaks had this factor in common. Other categories in the framework, such as distribution, failed to reveal any common patterns at all across the 15 outbreaks. Moreover, even the strongest observed commonality is limited to public drinking water systems; source contamination from heavy rainfall would be very unlikely to be a contributing factor in a petrochemical or hospital accident, for instance.

The fact that other frames of reference may not capture the accident patterns that were identified by Rasmussen's framework [15], not only across but even within sectors, has important practical implications because different findings will likely lead to different recommendations for improving safety. Using the framework described above, Hrudey et al. [6, p. 18] came to the conclusion that "poor attitude or complacency" was the over-riding contributing factor across outbreaks, which led to a suggestion to replace "the pervasive culture of complacency" with "a culture of personal accountability and vigilance". In contrast, by explicitly identifying government, regulatory, and organizational factors as contributing strongly to accidents in consistent ways, Rasmussen's framework [15] suggests that the problem is not so much with the complacency of particular individuals or organizations as with common systems design failures. People appear to be complacent, not by choice, but because they are working within, and responding to, a system that was not designed to provide adequate feedback, resources, oversight, and competencies to safeguard public health. If these structural factors were changed, then perhaps people would behave differently. After all, no individual or organization deliberately set out to harm the public in any of the outbreaks that Hrudey et al. and we analyzed. From our theoretical vantage point, then, the remedy is in system design rather than in greater personal accountability or vigilance. We cannot expect people to be superhuman or infallible, but we may be able to design systems to create the proper conditions for safety. Therefore, it may be possible to adopt a systematic approach to risk management.

Are the two cases we investigated and the two examined by Hopkins [5] unique outliers or widely representative of sociotechnical systems that have breached safety? This question can only be answered empirically by applying Rasmussen's framework [15] to other cases. There are very few such studies, perhaps because the effort required to analyze all the levels in the framework is large. For example, the Walkerton inquiry took almost 2 years, cost over $10 million CAD, and collected as many as one million documents from the provincial government alone, in addition to thousands of documents from other sources [10]. Only when equally comprehensive analyses are conducted for other cases, can we firmly establish the generalizability of the patterns observed by us and by Hopkins [5].

8. Conclusions

This comparative analysis of two Canadian public drinking water outbreaks suggests a set of hypotheses that must be tested through additional research. It may be difficult to predict all of the physical processes and actor activities that can go wrong in a complex sociotechnical system. Human behavior in particular has a tremendous range of variability, as evidenced by the extraordinary sequence of events in the Walkerton outbreak. Nevertheless, the types of safeguards that need to be put in place at the governmental and regulatory layers to cope with unanticipated threats to public health may be relatively consistent across scenarios. For example, we may not be able to anticipate the behavior and competency level of Stan Koebel, but if we have the proper administrative controls in place, even such extreme behaviors might be detected and corrected before public health is threatened. Indeed, one could argue that this is precisely the role that government and regulatory oversight should be designed to fulfill.

Rasmussen's framework [15] is helpful in this regard because it has public policy implications for how to design a 'vertically integrated' system that can safeguard public health in the face of unanticipated events and environmental stressors. Specifically, the framework recommends that the following conditions be satisfied for effective risk management:

1. identify the various actors in the complex sociotechnical system;
2. make the work objectives at each layer explicit;
3. provide feedback about the actual state of affairs at each level;
4. ensure that the actors at each level have the required competencies;
5. ensure that the actors at each level are committed to safety (i.e. each level have a positive safety culture).

These conditions are high-level and are not completely original, being based on a control-theoretic perspective. Nevertheless, it is important to note that they do not require designers to identify a rigid and detailed set of procedures for each actor in the system to follow. Such efforts are doomed to failure because rote procedures are too brittle to handle the rich nuances that are required to control complex systems effectively [20]. These five conditions also do not require designers to anticipate all the things that can go wrong in a complex sociotechnical system. Such efforts are also doomed to failure because the number of threats to safety is far too great to enumerate. Instead, the objective behind Rasmussen's recommendations is to design an adaptive system that is flexible enough to be economically competitive, yet structurally robust enough to cope with the unanticipated, thereby protecting public health.

Future research should assess whether the findings of this comparative analysis are generalizable across a broader set of cases within a sector as well as across other safety-critical sectors, such as health care, nuclear power, and aviation.

Acknowledgements

This research was sponsored by the Jerome Clarke Hunsaker Distinguished Visiting Professorship at MIT, by a grant from the Natural Sciences and Engineering Research Council of Canada, and by a Premier's Research Excellence Award awarded to the second author. We would like to thank the editor, the reviewers, Liz Mulholland, and the Honourable Mr Justice Robert D. Laing for providing very helpful comments.

References

[1] Amalberti R. The paradoxes of almost totally safe transportation systems. Safety Sci 2001;37:109–26.

[2] Canadian Press. Boil water order issued to Montrealers. Toronto Star; July 17, 2002. Available at http://www.torontostar.com, July 18, 2002

[3] CBC News. Good news, bad news, for New Brunswik drinking water. CBC News; July 17, 2002. Available at http://www.cbc.ca, July 18, 2002

[4] Commission of Inquiry on the Blood System in Canada, Final report. Ottawa: Canadian Government Publishing; 1997.

[5] Hopkins A. Lessons from Longford: the Esso gas plant explosion. Sydney: CCH Australia Ltd; 2000.

[6] Hrudey SE, Huck PM, Payment P, Gillham RW, Hrudey EJ. Walkerton: lessons learned in comparison with waterborne outbreaks in the developed world. Paper presented at the 10th National Conference on Drinking Water, Halifax, Nova Scotia, April 27–30, 2002

[7] Laing RD. Report of the commission of inquiry into matters relating to the safety of the public drinking water in the City of North Battleford, Saskatchewan. Regina, Saskatchewan: The Office of the Queen's Printer; 2002. Available at http://www.northbattleford-waterinquiry.ca, January 26, 2003.

[8] Moray N. Ex Risø semper aliquid antiquum: sources of a new paradigm for engineering psychology. In: Goodstein LP, Andersen HB, Olsen SE, editors. Tasks, errors, and mental models: a festschrift to celebrate the 60th birthday of Professor Jens Rasmussen, London: Taylor & Francis; 1988. p. 12–17.

[9] Norman DA. Things that make us smart: defending human attributes in the age of the machine. Reading, MA: Addison-Wesley; 1993.

[10] O'Connor DR. Report of the Walkerton Inquiry. Part I. The Events of May 2000 and related issues. Toronto: Ontario Ministry of the Attorney General; 2002. Available at http://www.walkertoninquiry.com, November 29, 2002.

[11] Oversight Hearings, Accident at the Three Mile Island nuclear power plant. Washington, DC: US Government Printing Office; 1979.

[12] Perrow C. Normal accidents: Living with high-risk technologies. New York: Basic Books; 1984.

[13] Peterson D. Safe drinking water for rural Canada. Proceedings of the Conference on Safe Drinking Water Production in Rural Areas: Issues, Challenges and Future Directions, Saskatoon, Saskatchewan: Safe Drinking Water Foundation; 2002. Available at http://www.safewater.org/conferences/proceedings/peterson.htm, January 26, 2003.

[14] Pool R. Beyond engineering: how society shapes technology. New York: Oxford University Press; 1997.

[15] Rasmussen J. Risk management in a dynamic society: a modelling problem. Safety Sci 1997;27:183–213.

[16] Rasmussen J, Pejtersen AM, Goodstein LP. Cognitive systems engineering. New York: Wiley; 1994.

[17] Reason J. Human error. Cambridge, UK: Cambridge University Press; 1990.

[18] Torstar News Service, Another water alert: Thousands may have been exposed to *E. coli* bacteria, province says. Metro Today June 13, 2002;1.

[19] Vaughan D. The Challenger launch decision: risky technology, culture, and deviance at NASA. Chicago: University of Chicago Press; 1996.

[20] Vicente KJ. Cognitive work analysis: toward safe, productive, and healthy computer-based work. Mahwah, NJ: Erlbaum; 1999.

[21] Vicente KJ. Cognitive engineering research at Risø from 1962–1979. In: Salas E, editor. Advances in human performance and cognitive engineering research, vol. 1. New York: Elsevier; 2001. p. 1–57.

[22] Vicente KJ. From patients to politicians: a cognitive engineering view of patient safety. Qlty Safety Healthcare 2002;11:302–4.

[23] Vicente KJ, Christoffersen K. The Walkerton *E. coli* outbreak: a test of Rasmussen's framework for risk management in a dynamic society. Submitted for publication