Human Factors in Urban Water System Safety: Stage 1 - Initial Findings

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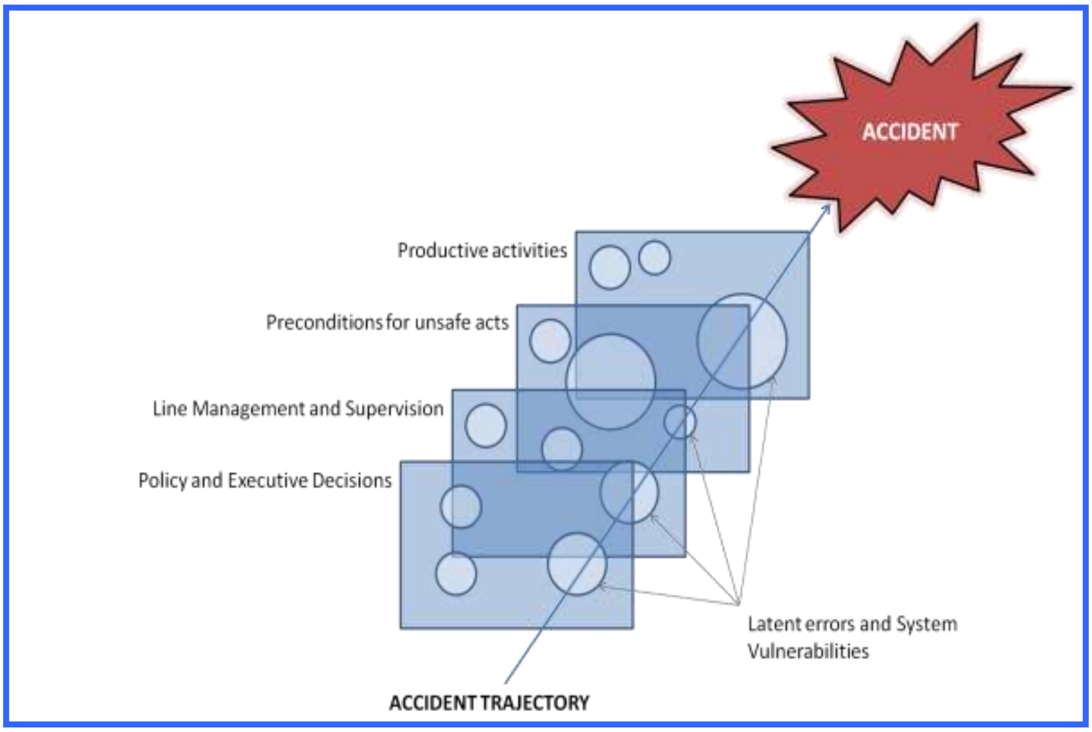
June 2011



Urban Water Security Research Alliance
Technical Report No. 46

Queensland Government
National Research FLAGSHIPS Water for a Healthy Country
CSIRO
Griffith UNIVERSITY
The University of Queensland AUSTRALIA

Urban Water Security Research Alliance Technical Report ISSN 1836-5566 (Online)
Urban Water Security Research Alliance Technical Report ISSN 1836-5558 (Print)

The Urban Water Security Research Alliance (UWSRA) is a $50 million partnership over five years between the Queensland Government, CSIRO's Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South-East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

For more information about the:

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Cloete, S., Horberry, T. and Head, B.W. (2011). *Human Factors in Urban Water System Safety: Stage 1- Initial Findings*. Urban Water Security Research Alliance Technical Report No. 46.

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Cover

Graphic - Dynamics of accident causation according to Reason's (1990) Swiss Cheese Model.

ACKNOWLEDGEMENTS

This research was undertaken as part of the South East Queensland Urban Water Security Research Alliance, a scientific collaboration between the Queensland Government, CSIRO, The University of Queensland and Griffith University.

Particular thanks go to a range of water industry informants who kindly provided information and insights concerning the operations of the water sector in South East Queensland. Individuals are not listed for reasons of confidentiality, but include key researchers, managers and water industry professionals.

This Stage 1 report was intended to rely primarily on analysis of publicly available documentation, but this material has been greatly enhanced by interviews with key representatives of several state and local authorities including the Department of Environment and Resource Management, the Queensland Water Commission, the Office of the Water Grid Manager, Seqwater, and Queensland Health.

FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a $50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at http://www.urbanwateralliance.org.au/about.html.

C. Davis

Chris Davis
Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

The urban water system in South East Queensland (SEQ) has been undergoing rapid organisational, technical and planning system changes in recent years, in response to the major drought of 2003-08 and the growing pressures of economic growth and urbanisation.

This report outlines the Stage 1 findings of the project on Human Factors in Urban Water System Safety, in response to priority issues identified by key stakeholders in 2009-10. It also provides details for a proposed Stage 2 extension of the research project during 2011 and 2012.

This project aims to address substantive research questions through a research program to advance the knowledge of the role, importance and risk mitigation of human factors in urban water system safety. The outcome from this research would help create a safe and resilient water system where the human elements of judgement, decision making, perception and management are well-integrated with the technical systems, risk management systems and quality control mechanisms.

This Stage 1 report outlines the changing character of the urban water system in SEQ and the types of risk factors that may be linked to the organisation of work processes. The report uses the methods of Human Factors Engineering (HFE), the discipline concerned with understanding the interactions among people and the other elements of a work system. It applies theory, principles, and analytical methods to specific design issues underlying system operations, in order to optimise human well being, safety and overall system performance. It can be applied to the design of all systems having a human interface, including hardware and software.

The research team employed multiple human factors research methods to undertake this Stage 1 work. This included a literature review (including an examination of 'internal' water industry documents), interviews with key representatives of relevant water organisations, and a site observational tour (including interviews with two operators) at a treatment plant.

The main findings at this stage are that:

- There has been little published research literature that has considered human element issues in water systems. Despite this, there has been a great deal of potentially useful human factors work done examining system safety in other domains. It is possible that the urban water system could learn important lessons from this literature, therefore a more detailed review of it is warranted; and further comparative research is proposed as a Stage 2 report.
- The interviews and site inspections revealed several potential areas worthy of more detailed human factors consideration in a future research project. These included: integration of different technologies, the appropriateness of alerting systems in control rooms, the investigation of operator error both retrospectively (through incident reports and detailed interviews) and prospectively (through human error audits), and a comprehensive review of best practice in other industries.

This Stage 1 report concludes that there is a strong base for undertaking further research examining the above two points. Undertaking a deeper investigation of human factors issues in Stage 2 would be designed to underpin more effective risk management of the human element in urban water system safety. The key issues are outlined in more detail later in this report.

1. INTRODUCTION

1.1. Purpose

This report outlines the Stage 1 findings of the project on Human Factors in Urban Water System Safety; it also provides details for the proposed Stage 2 extension of the project during 2011 and 2012.

This project arose from concerns expressed by some key government managers during 2009-10 concerning the extent to which water quality risk issues were well understood and integrated into best practice, especially in relation to operational judgments and behaviour concerning risk perceptions and risk responses.

The urban water system in South East Queensland (SEQ) has been undergoing rapid organisational, technical and planning system changes in recent years, in response to the major drought of 2003-08 and the growing pressures of economic growth and urbanisation. Coping with growth, with new technologies, and with implementation of new standards, has placed pressure on water professionals. As noted below, the restructuring of organisational roles added additional 'system-level' issues such as clarity of roles at each organisational level of the system and the need for shared capabilities in rapid and coordinated responses.

This project aims to scope out a range of substantive research questions and a research program to address the identified priority questions in order to advance the knowledge of the role, importance and risk mitigation of human factors in urban water system safety. The outcome from this research would help create a safe and resilient water system where the human elements of judgement, decision making, perception and management are well-integrated with the technical systems, risk management systems and quality control mechanisms.

1.2. What is 'Human Factors' Analysis?

Human Factors Analysis (or Ergonomics) is defined here as the scientific discipline concerned with the understanding of the interactions among people and the other elements of a work system, and as the profession that applies theory, principles, data and methods to design in order to optimise human well being, safety and overall system performance (Horberry, Burgess-Limerick and Steiner, 2010). As well as a scientific field and profession, Human Factors is also a way of looking at the world which has as its focus the capabilities, limitations, motivations, behaviours and preferences of operators.

The aim is to maximise efficiency, effectiveness, quality, comfort, safety and health by ensuring that systems are designed in such a way that the interactions are consistent with human capabilities, limitations, motivations, behaviours and preferences. The emphasis is on changing work systems to suit people, rather than requiring people to adapt to these systems. As with any industry which involves the complex interaction of people and technology, this approach can find application in water storage, treatment and distribution.

The Human Factors Analysis philosophy implies a scientific concern with obtaining information about the characteristics and capabilities of people, and this is achieved by drawing on knowledge from the underlying disciplines and fields including physiology, biomechanics, organisational psychology, management, work study, epidemiology, and public health. Another concern of Human Factors Analysis lies in design-based disciplines and fields such as product design, engineering, architecture and computer science, where the opportunity exists to influence the design of systems, equipment, and environments.

1.3. What are the Aims of Human Factors Analysis?

Human Factors Analysis can therefore be thought of as having two separate (but not competing) aims:

- **To improve work performance**. This includes quantity of work (eg, increased human-machine integration allowing more water to be processed), quality of performance (including accurate fault detection in maintenance work) and fewer errors, accidents and/or near misses.
- **To improve health, safety and wellbeing of the workforce and, where possible, the wider community**. For example, fewer occupational injuries or health problems (eg, noise induced deafness), less job related stress, increased usability of equipment in water treatment plants, and increased work motivation.

Of course, the underlying assumption is that using Human Factors data, principles, and methods will lead to better designed jobs, tasks, products or work systems. This central theme will be present throughout this report.

1.4. The Importance of Human Factors in Urban Water System Safety

As noted above, Human Factors Engineering (HFE) applies theory, principles, and methods to specific issues underlying system operations, in order to optimise human well being, safety and overall system performance. It can be applied to the design of all systems having a human interface, including hardware and software. Its application to system design improves ease of use, system performance and reliability, and user satisfaction, while reducing operational errors, operator stress, training requirements, user fatigue, and potential liability. Human Factors Engineering can offer many benefits for urban water system safety: increased productivity, efficiency and accuracy of outcomes, while at the same time maximising safety, maintaining harmony and minimising stress within teams that operate in high pressure environments. In addition, the Human Factors approach may contribute to the development of a more comprehensive risk management approach in the water sector by specifically focusing on the human element.

As will be seen later in this report, areas considered in Urban Water System Safety include:

- individual factors (eg, fatigue, workload)
- equipment interface design (eg, alarm design)
- skills and training
- communication, internally and externally
- supervision and line-management
- rules, responsibilities and procedures
- wider organisational factors
- inter-organisational and cross-system factors.

Interest in the application of human factors principles to the water sector has grown recently among several stakeholders, spurred in no small part by the occurrence of reasonably well-publicised incidents in South East Queensland in which human error was identified as a contributory factor. These incidents were the North Pine Water Treatment Works Fluoride Dosing Incident in April 2009, and the Pimpama-Coomera Dual Reticulation cross-connection incidents of December 2009 and January 2010. Fortunately, no significant compromises to public health and safety resulted from these events, but they have revealed potential vulnerabilities in the sector and provided opportunities for investigation from a human factors perspective.

1.5. Institutional Background: Continuity and Change in the Urban Water System in SEQ

At the beginning of 2006, the Queensland Minister for Natural Resources noted that:

> *'There are 19 major water supply storages with 12 different owners in the regions. A total of 18 local governments deliver water to their ratepayers, while a number of adjoining councils obtain water from south-east Queensland.'* (Minister for Natural Resources, 27 January 2006)

He also noted that the state government was initiating a "review of the existing institutional arrangements for water in south-east Queensland", particularly arising from the need to provide water security in SEQ. This review was driven by senior Ministers and led to the following rapid changes in structures, roles and responsibilities for the urban water system:

- The Queensland Water Commission was created by legislation in June 2006, with a mandate to determine a uniform approach to regional water planning and water restrictions. The water regulation and licensing function was retained by the Department of Natural Resources and Water, later amalgamated with the EPA as the Department of Environment and Resource Management (DERM).
- A major consultancy report in mid-2007 recommended a highly integrated and centralised model of the urban water system, but with separation of policy, regulation, storage, distribution and retail functions (QWC 2007).
- A wave of local government amalgamations across the state led to a reduction in the number of councils in SEQ from 18 to 10.
- The state acquired the water infrastructure assets of the SEQ councils, and designated Seqwater as the single bulk water authority to own and manage water storage assets and water treatment plants. A number of the smaller water treatment plants inherited by Seqwater were of variable quality.
- The Councils subsequently reached agreement on joint ownership of three sub-regional water distributor/retail businesses, which now manage drinking water distribution as well as sewerage systems and sewage treatment, although individual Councils retained their responsibilities for stormwater management.
- The State financed the construction of three major infrastructure projects – the desalination plant at Tugun on the Gold Coast; the advanced wastewater treatment plants at Bundamba near Ipswich, and Luggage Point and Gibson Island in Brisbane; and the regional Water Grid network of pipelines linking major facilities. A statutory role of Water Grid Manager was created in 2008, to oversee the water market and manage the movement of water around the components of the Grid. The Water Grid is pictured in Figure 1 below.

For the purposes of the current report, the key implications are that the water system was very different in many respects from several years earlier and great effort was being applied to improving efficiency and effectiveness at the same time as new roles and responsibilities were being developed. Water professionals were in many cases primarily responsible for a specific element in the complex system, but their combined efforts and interactions had major impacts. Effective performance information and effective communication in the context of new roles became even more important.

There was no direct regulation of drinking water quality in Queensland before 2008. As a result of the combined pressures of drought, the complexity of the new water infrastructure in SEQ and the prospect of the addition of purified recycled water to drinking water supplies, the State government introduced the new *Water Supply (Safety and Reliability) Act 2008* in July 2008. This Act gave DERM the head of power to regulate providers of drinking and recycled water, and in particular to require that providers prepare plans for the management of drinking and recycled water.

At the same time, amendments to the *Public Health Act 2005* gave Queensland Health a head of power to set health standards for both drinking and recycled water, as well as the power to prosecute drinking water providers who supply "unsafe water", and recycled water providers who supply recycled water that is "unfit for use".

The new co-regulatory framework in Queensland is strongly based on the 12 elements of the Australian Drinking Water Guidelines (2004). As part of this regulatory framework, drinking water service providers are required to report to DERM the results of their water quality monitoring programs on a quarterly basis and, in particular, to report immediately whenever water quality standards are breached. This information is then supplied to Queensland Health which, when required, will assess the public health significance of the breach. The two agencies will then work co-operatively to ensure that public health is protected.

Figure 1: **The SEQ Water Grid (after 2008).**

2. APPROACH AND KEY FINDINGS

2.1. Methods

2.1.1 Literature Review

A targeted literature review was undertaken on human factors practices in the water sector. Search tools and databases included IWA Publishing, Scopus, Web of Science, Google Scholar and others. Various combinations of the following search terms were used: *Cognitive Engineering, Ergonomics, Human Error, Human Factors, Operator, Operator Error, Risk, Risk Management, Water, Water Treatment.* In addition, relevant academic journals in the areas of water treatment and delivery, human factors, safety science and risk management were searched with combinations of the above terms. A list of these journals is included as Appendix 1.

2.1.2 Interviews and Observations

2.1.2.1 Interviews

The research team contacted key stakeholders in the water sector between September and December 2010. For reasons of confidentiality, individuals will not be named. Representatives from the following organisations kindly consented to interviews and/or provided information:

- Allconnex (formerly Gold Coast Water, Logan Water and Redland Water)
- DERM: Office of the Water Supply Regulator
- Queensland Health
- Queensland Water Commission
- Seqwater
- SEQ Water Grid Manager

Interviews took an informal, semi-structured approach. Participants were asked about their roles and responsibilities in the water sector; their professional opinions regarding organisational structure, organisational culture, communication, risk management policies and procedures; and their understanding of human error issues in the specific water-industry context.

2.1.2.2 Observations (Site Visit)

On one occasion, Assoc. Prof. Tim Horberry and Dr. Steven Cloete conducted a site visit at the Mt Crosby Eastbank Water Treatment Plant, where they had opportunities to observe work practices, workplace layout, and human-technology interfaces, and opportunities to conduct interviews and discussions with operational staff.

2.2. Review of the Research Literature

It quickly became clear to the project team that very little human factors research has specifically targeted the water sector. The reason is not clear, because bulk water storage, treatment and delivery have much in common with other complex, technologically-dependent process control industries. The nuclear power industry, for example, has incorporated principles of human factors into its plant design and risk management philosophies for a very long time. Indeed, events like the 1979 Three-Mile Island nuclear disaster have spawned countless empirical investigations and have had a profound impact on the development of human factors as an academic discipline.

Given the similarities between the water sector and other industries in terms of the scale of infrastructure and delivery, human-technology interface and the potential for public disaster in the event of system failure, it is appropriate to consider research and best practice from a range of sources. Mining, power generation, transport, aviation and medicine have established human factors research programs, and in many cases the transfer of knowledge to the water sector may be of benefit.

2.2.1 Human Factors in Risk Management

The human element in complex socio-technical systems has gained increasingly greater importance in the study and application of risk and safety management. In recent decades, attribution of incidents and accidents to human and organisational error has been steadily increasing, which can be explained by two aspects of technological advances: 1) increases in the reliability of mechanical, electrical and information-processing components of systems; and 2) system complexity, and the often poorly-defined role of the human operator in the control loop.

Many industries now recognise the need to integrate human factors research and principles with risk management. For example, a risk management framework is now frequently adopted in contemporary mineral industries. The process starts with establishing an understanding of the broader context in which the work takes place before undertaking hazard identification and risk assessment (Horberry, Burgess-Limerick and Steiner, 2010). Assuming that the outcome of the risk assessment is that action is indicated, the risk control phase incorporates identifying and evaluating potential control options, before implementation and ongoing review. From the Human Factors perspective, the emphasis for risk control is on elimination or reduction of risk through design controls rather than focusing excessively on administrative controls such as training, selection or personal protective equipment.

Most importantly, this process also places emphasis on consultation with the people concerned at each step. This issue is at the core of 'participative ergonomics' approaches, which take as an underlying assumption the notion that the operators involved are the 'experts' and must be involved at each stage of the risk management cycle if the process is to be executed successfully (Horberry, Burgess-Limerick and Steiner, 2010). In an occupational risk management context, this implies in particular that employees and management participate through hazard identification, risk assessment, risk control and review steps of the risk management cycle. Such a participative approach can also be used for productivity and work efficiency gains by improving system design, procedures and even training.

2.2.2 'Human Error': Role in Accident Causality

The definition of *human error* is apparently self-evident, but advances in technological and organisational processes have necessitated reconsideration of the traditional understanding of this term. Following an influential discussion paper by Rasmussen, Nixon and Warner (1990) and others, there has also been a shift toward consideration of human behaviour in the wider context of complex, dynamic systems, rather than discrete fragments of behaviour which are labelled 'error'. Error is often now seen as the consequence, not cause, of deeper systemic issues (Simpson *et al.*, 2009).

In accident analysis, it was once acceptable to dismissively apportion responsibility to the actions of operators, ignoring the organisational, managerial and technological contributions which can have more far-reaching consequences. Contemporary approaches to understanding the causal factors of accidents consider not only the operator – often the most easily observable or reportable element – but also the role of higher-level decision-making and design processes. These can be present in the system for a considerable period of time without manifesting in an accident. In his influential book, Reason (1990) labelled these higher-level processes 'latent failures'; their effects on the system are alone insufficient to produce observable consequences, instead, they require a confluence of circumstances to manifest in a major incident or accident, including penetration of the system's designed and built-in defences.

Reason's *Swiss Cheese* model (1990) is well-suited to the analysis of accidents in the water sector because of its parallels with the 'Multiple Barrier' approach to hazard reduction. System defences or barriers are represented by slices or layers in depth, with holes representing compromises to these defences. The size and position of the holes change dynamically, which reflects the stochastic and inherently unpredictable nature of accident opportunity. The dynamics of accident causation according to the Swiss Cheese model are illustrated below.

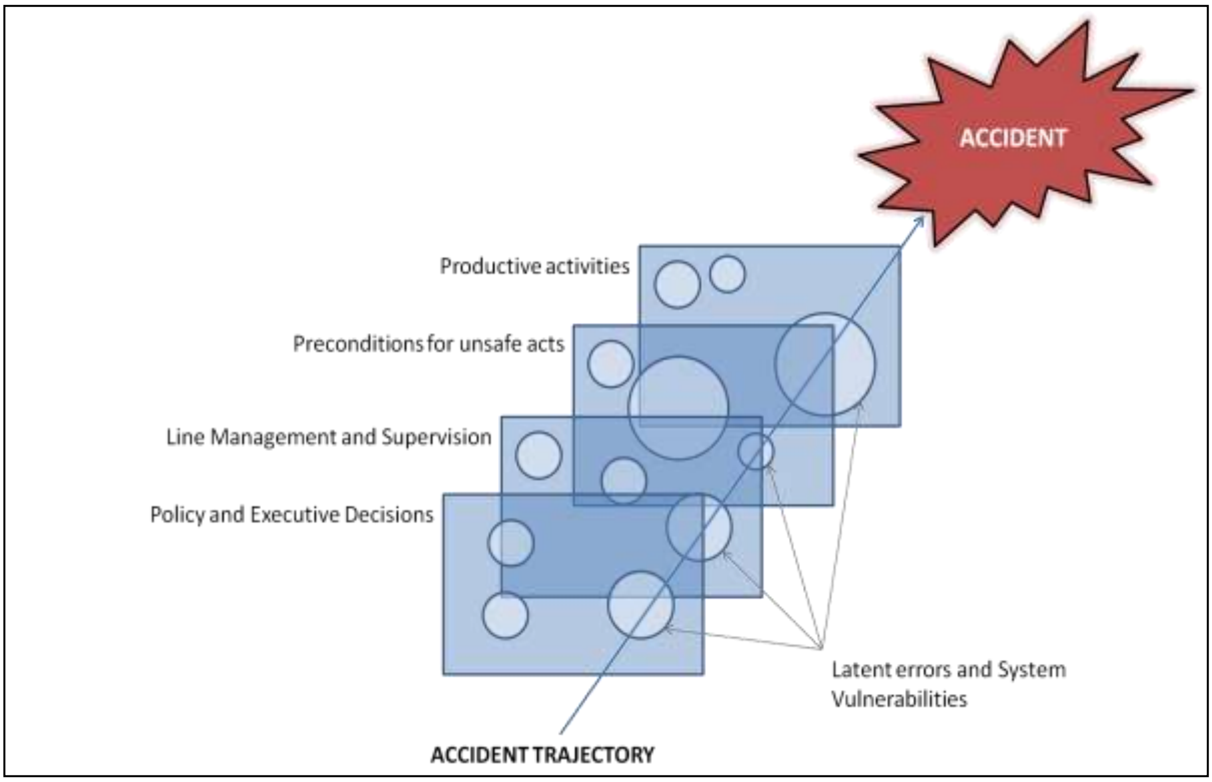

Figure 2: Dynamics of accident causation according to Reason's (1990) Swiss Cheese Model.

Failures can be further categorised according to Rasmussen's Skill, Rule and Knowledge (SRK) model of human performance (Rasmussen, 1983), which has a finer-grained focus on error production at the person level. Under this scheme, errors are classified as *Slips/Lapses*, *Rule-based Mistakes* and *Knowledge-based Mistakes*, and in a broader human error sense these can take the form of both active and latent failures.

A slip or lapse is an execution failure – it occurs when actions deviate from the intention, for example, forgetting to plug in a toaster before inserting the bread and depressing the lever. The distinction between slips and lapses is observability: a slip is readily apparent to other observers, but a lapse may only become apparent to the person committing it.

Rule-based Mistakes are errors that arise from deficiencies in planning; skill-based actions may be correctly undertaken, but rules governing the execution of these actions are misapplied. An example is driving the wrong way down a one-way street – the action of driving a motor vehicle is undertaken successfully, but the rules dictating the direction in which the vehicle may travel are broken.

Finally, Knowledge-based Mistakes arise when an individual incorrectly applies their training and expertise to solving a problem, or does not have the requisite knowledge to solve the problem. An example would be an operator ignoring a critical alarm because he/she believes it to be spurious.

2.2.3 Human Error in Water Treatment and Delivery

In an extension to comprehensive earlier work by Hrudey and Hrudey (2004), Wu *et al.*, (2009) analysed the contributions of human error to 61 cases of disease outbreak in water supply. They used a human error taxonomy derived from the Swiss Cheese model, categorised system failures along one of four dimensions, and determined the total contribution of each dimension to system failure. The four dimensions were:

1. **Physical system failures and extreme environmental conditions**
    a. Equipment failure
    b. Disease-carrying animals and animal waste
    c. Extreme weather

2. **Active errors**
    a. Mistaken belief in the security of a water system
    b. Failure to recognise and/or to take adequate measures on warnings
    c. Sanitary violations
    d. Failure to follow recommendations

3. **Latent errors**
    a. Design errors
        i. Lack of sufficient water safety barriers
        ii. Existing deficiencies in system
        iii. Raw water not isolated from animal waste
    b. Maintenance errors
    c. Operation errors
    d. Insufficiently qualified staff
    e. Inadequately trained operators
    f. Communication errors

4. **Influences from consumers and third parties**
    a. Failure to inform new residents and visitors consuming untreated surface water
    b. Failure to report warning signals
    c. Failure to appreciate the risk of disease transmission
    d. Lack of cooperation, interaction or communication among various parties responsible for water safety
    e. Failure of regulator to implement policy

Something particularly noteworthy about this analysis is that all 61 cases had contributory influences from multiple dimensions, which reflects the fact that errors do not occur in isolation. The distribution of active and latent error contributions were approximately equal at 38% and 37% respectively, with physical system failures (22%) and influences from consumers and third parties (3%) playing a much smaller role. This article (Wu *et al.*, 2009) is the first of its kind, and is an important step in publicising the incidence of human error in drinking water contamination. However, very little information is provided as to how incidents were categorised along the four dimensions, and specific details for each case are only rudimentary in form. Human error in a wider risk management context is best illustrated with a more detailed example.

Possibly the most serious, widely publicised and well-studied of these was the *E. coli* outbreak in Walkerton Ontario in May 2000. In a town numbering some 5000 residents, approximately half became ill as a result of ingesting contaminated water, and seven fatalities were attributed to the event. There was a likelihood of long term health consequences, particularly for infected children, and residents in the town of Walkerton and across the province of Ontario developed a serious mistrust of the water delivery authorities, and doubts about the future security of the water system. The economic cost in total was estimated at $64.5m CAD, which included an expensive nine-month official investigation (O'Connor, 2002). Investigation of this case revealed a unique combination of ineffective regulatory oversight, incompetent leadership, extremely poor monitoring procedures, and even deliberate concealment of adverse monitoring results. The diagram in Figure 3 below illustrates contributions to the cause and handling of the outbreak, from the higher-order levels including government and regulatory bodies, right down to low-level physical processes (Vicente and Christofferson, 2006).

Although the gross incompetence and deception on the part of employees of the Walkerton Public Utilities Commission (WPUC) were the most salient contributions to the disaster, the O'Connor (2002) investigation made it clear that the system was already vulnerable due to the presence of numerous 'latent errors'. The actions of individuals served only as a trigger. There were profound deficiencies in the physical treatment infrastructure, which were present from the very time it was installed and known to the WPUC leadership and the regulatory authority charged with oversight. The shallowness of one of the wells made it vulnerable to contamination via runoff, and additional contamination pathways were evident in local geographical features of the well site. Another well was not even equipped with a chlorinator for disinfection, which demonstrated the dire ignorance and lack of training of the WPUC leadership. This was also reflected in the lax approach to routine monitoring, which involved serious breaches of reporting requirements; monitoring was sporadic at best, and operators were encouraged to fabricate monitoring results in the official records. The culture of non-compliance was extreme, chronic, and seemingly invisible to the regulator. In sum, defences in the Walkerton supply grid were either absent or severely crippled by organisational culture and ineffective oversight, which allowed violations by operators and senior management to progress to an incident.

It is difficult to imagine a disaster of this scale and complexity occurring in Australia, so it serves as a pertinent reminder of the importance of system defences at all levels of service. Australia is a world leader in the development of regulatory instruments for the water industry, as evidenced by the comprehensive 2004 National Health and Medical Research Council (NHMRC) guidelines for drinking water quality. However, operations in the Australian industry are not immune from potentially large-scale incidents, such as the 1998 Sydney Water Crisis which was triggered by *Cryptosporidium* apparently by-passing treatment controls and entering the distribution network (Stein, 2000), although no illness resulted from the event.

Analysis of human factors issues in the water sector requires a systems-based approach examining organisational, technological and individual factors. The remainder of this literature review will focus on these issues in turn, beginning with the interface between human operators and water infrastructure.

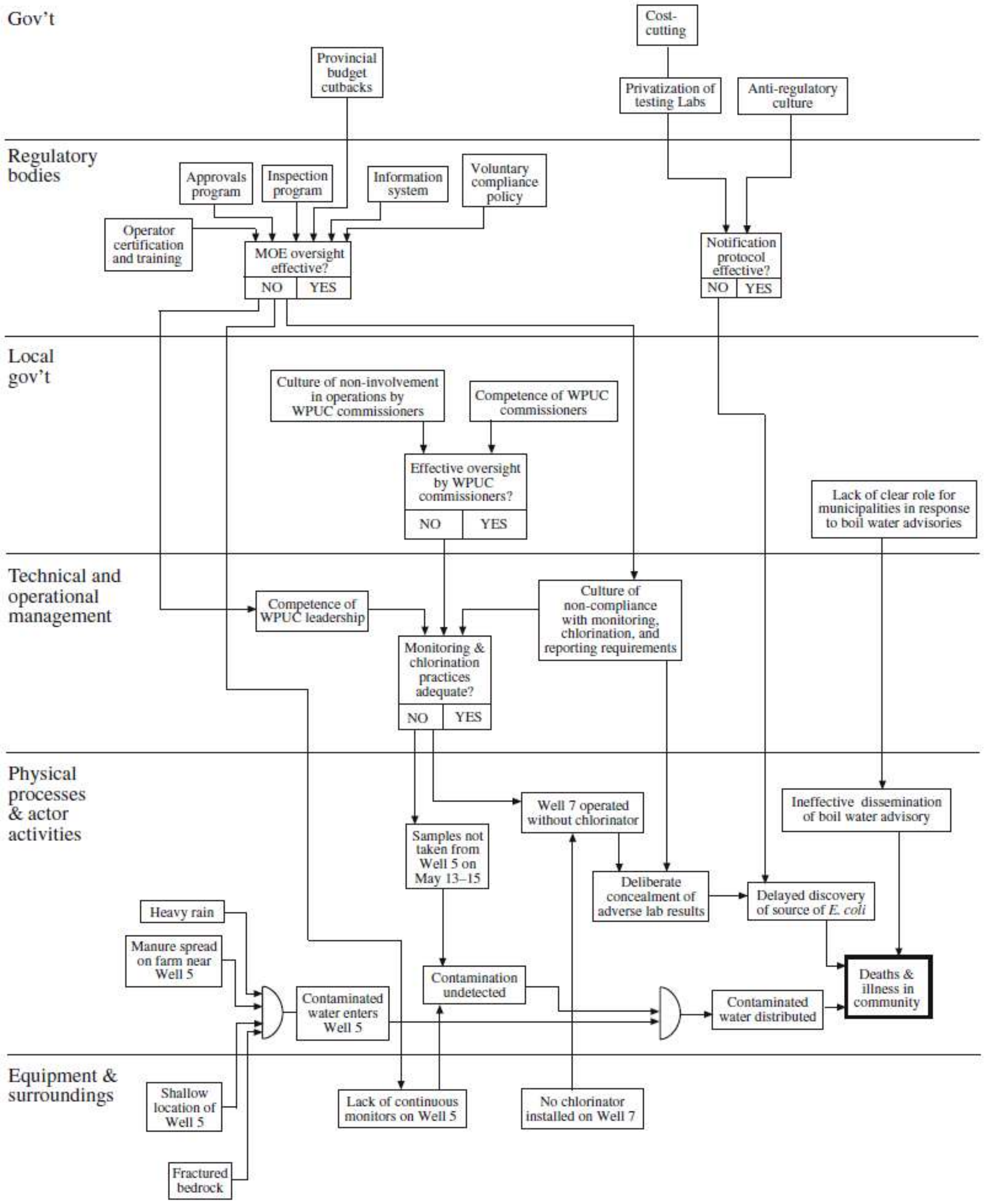

Figure 3: Analysis of the Walkerton *E. coli* outbreak (Vicente and Christofferson, 2006).

2.2.4 The Control Room: Displays and Alarms

The availability of cheap computing power has enabled the automation of many work activities, which has seen the overall role of the human operator in process control shift from interactivity at a manual level to monitoring and decision-making at a supervisory level. In many instances, the advantages of automation in productivity terms are obvious, as are the advantages of removing workers from dangerous environments and preventing them from performing dangerous work. However, an unintended consequence of automation has been the development of control and warning interfaces which are ill-suited to the perceptual, cognitive and anthropometric capabilities of operators (see Figure 4).The following two sections will describe human factors principles of supervisory control of complex water systems.

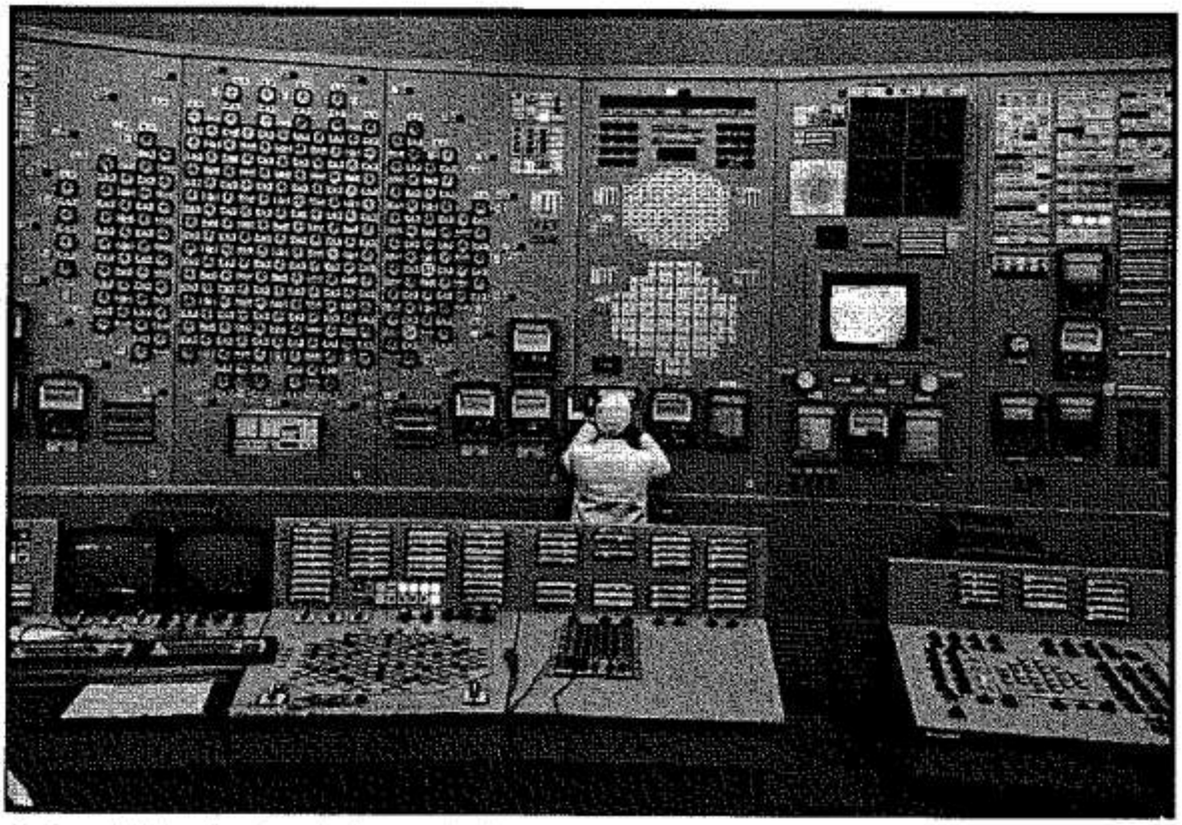

Figure 4: Control room of a Soviet-era nuclear power station (Adapted from Strauch, 2002).

2.2.4.1 Supervisory Control and Data Acquisition Systems and Displays

In process control industries with large and complex physical plants and high levels of automation, remote supervisory control is often now the only effective option for system monitoring and fault diagnosis. The design of the Supervisory Control and Data Acquisition (SCADA) interface must take into account the perceptual and cognitive capacities of human operators, ensuring, among other things, that the display elements are legible, sufficiently conspicuous and easily comprehended (Wickens *et al.*, 2004). The last point requires that the display configuration carefully matches the operator's *mental model* of the system. The display should look and behave like the variable it represents; for example, for most dynamic linear quantities with defined high and low points, a vertical scale with a moving indicator point is appropriate, whilst for circular quantities like directional heading, a dial or circular display should be used. Displays should embody a high degree of *consistency*, particularly with respect to elements such as colour and shape, eg, red should always mean the same thing. Parts of the display depicting different kinds of information should be easily discriminated between to avoid confusion and, where possible, should exploit *redundancies*. For example, the colour and position of traffic lights are redundant – different colours never occupy the same position. The use of pictorial elements which resemble the physical plant with respect to spatial layout and process trajectory is also routinely recommended.

As systems increase in complexity, the mental model concept becomes more important, along with the subsequent manner in which displays are organised and visually grouped. *Configural displays* integrate data from a number of variables to produce an image, which can be very effective at indicating departures from normal operating conditions. The configural method of presentation is characteristic of the *ecological interfaces* movement (Vicente and Rasmussen, 1992), which emphasises graphical representation of plant processes, flexibility with respect to the level of abstraction presented (eg, concrete – the actual physical fault or process disruption, abstract – the implications for safety and productivity), and a high degree of integration among operating parameters. This design philosophy makes extensive use of informative emergent features. For example, representing eight system variables in a polar plot produces a symmetric octagon shape when the parameters are within normal ranges – an emergent feature of routine operating conditions – and a distorted polygon under suboptimal conditions (Woods *et al.*, 1981).

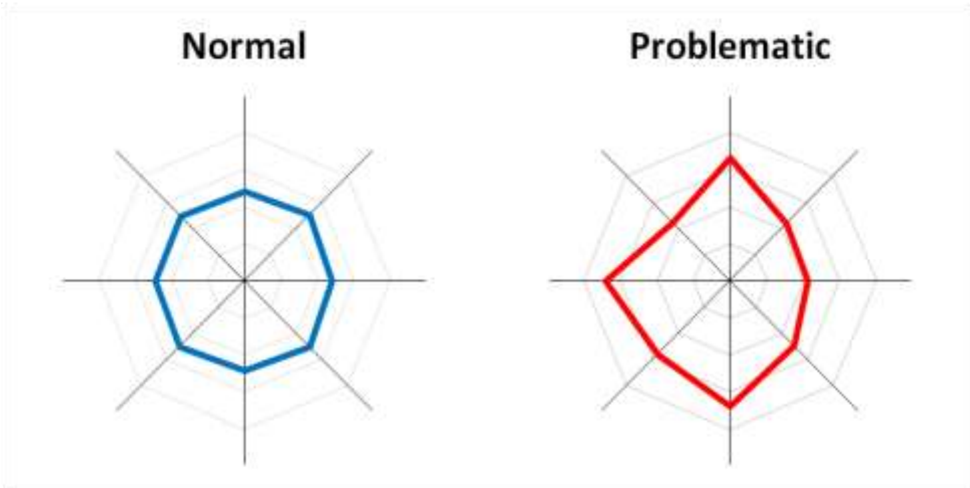

Figure 5: A configural display of 8 plant operation variables represented on radial axes: routine operation produces the emergent property of a symmetrical octagon shape, non-normal operation produces an irregular polygon.

Ecological interfaces are effective at communicating system function holistically, without hindering the user's ability to attend to individual variables, and are more effective at supporting fault diagnosis and management (Vicente, 2002).

The design and evaluation of supervisory control is informed by task analysis, directed by user-centred design and tested by operator-centred evaluation methods such as usability and acceptance testing. Task Analysis is a formal process used in cutting-edge Human Factors research. As the name suggests, the process seeks to understand the exact tasks performed by operators, the information they use, the skills and capabilities they require, the inputs they receive and the outputs/control actions they are required to make. The process also looks at how tasks are prescribed to be performed versus how they are actually undertaken in the field. The Task Analysis process uses structured observations, in-depth interviews, document reviews, incident data and ergonomic audits. A variety of task description methods are available, and in this context they would focus on the design of the interface and associated visual displays.

2.2.4.2 Alarms

Auditory alarms can provide crucial and effective information to control room operators, often by supplementing visual information and warnings. The advantages of presenting alerting information to the auditory channel are numerous; responses to auditory signals are generally very fast, continuous monitoring of visual information is not necessary, and reductions in mental workload can be achieved (Stanton and Edworthy, 1999). However, with increases in automation the temptation for many designers has been to take a 'better safe than sorry' approach, incorporating warning functions into the system design as a matter of course, even if there are misgivings as to their necessity (Edworthy and Adams, 1996).

Improperly designed alarms can have negative consequences for operator performance in both the short and long term, ranging from physiological problems including stress and hearing loss, to psychological and even social disruption. Distraction and annoyance from frequently triggered alarms can be relatively harmless. However, the ability of a highly salient auditory stimulus to interfere with the attention capacity of workers engaged in already demanding and/or dangerous tasks is a matter of serious concern. In the longer term, overreliance on auditory alarms (as with any form of automation) can lead to operator passivity in the process of routine monitoring, but perhaps the most serious consequence of over-implementation of alarms is the breakdown of trust and credibility of the warning signal. High incidence of false alarms can lead to operators routinely ignoring alarm signals or even physically disconnecting or disabling the alarm system (Bliss, 1999). There are many instances in aviation and medicine where alarm set-points or thresholds have been set too low for routine operating conditions, leading to frequent false alarms and a conditioning of operators to ignore the alarm. Any effective warning signal, auditory or visual, must be noticed, comprehended, and ultimately complied with, and to ensure the appropriateness and effectiveness of an auditory alarm, it must be designed with the following considerations in mind (from Stanton and Edworthy, 1999);

1. the warning message (ie, alarm) must be simple, short and call for immediate action, and must relate to events occurring in time, not space. Conditions eliciting more complex warning signals, events that do not require immediate action or events occurring in space are better communicated with visual warning signals if viewing conditions permit;
2. an alarm must be sufficiently salient and exhibit frequency characteristics appropriate to the environment, eg, frequency makeup and volume of background noise, distance the alarm needs to travel, presence of obstacles, etc. To guarantee detection, the alarm must be 30dB greater than the background noise (Patterson, 1990); and
3. it must appropriately reflect the urgency of the conditions it is signalling, eg, a high-intensity alarm should not be used for situations which are not critical. Likelihood alarm systems (Sorkin, Kantowitz and Kantowitz, 1989) provide signals with varying levels of alert, which is a logical and effective means of supporting the operator's response.

In addition to the above considerations, involving the user population in the design and testing of warning systems is recommended, along with properly understanding the work environment and tasks performed by operators (Horberry, Burgess-Limerick and Steiner, 2010).

2.2.5 Operator Fatigue, Workload and Work Cycles

Shiftwork has long been a source of concern, and usually an economic necessity, in many work domains. The water industry is no exception.

2.2.5.1 What is Fatigue?

A distinction that is often not considered (but which is often used in the scientific literature) is between muscular and general fatigue. Muscular fatigue comes from heavy physical work and is localised in overstressed muscles. Of more concern here is general fatigue. General fatigue can be viewed as an accumulation of all of the stresses of the day (including the duration and intensity of physical and mental work, time of day the work is performed, and the amount of prior sleep that an operator has had); and these need to be balanced by rest and recovery.

2.2.5.2 Working Hours

Looking more at time on task, four hours working continuously on a single task that requires high levels of concentration (eg, operating equipment) can increase errors and incidents. Such errors might be 'micro events', like not responding to a communication device. These are often more marked after seven to eight hours on shift (especially where an operator had an insufficient amount of preceding sleep). Therefore, as will be seen below, planning correct working periods and breaks is essential.

Interestingly, in the industrial environment, many studies have found that increasing the length of the working day does not increase output. For example, increasing the working hours from eight to ten for a heavy manual job may even reduce overall daily output, as workers tend to 'pace' themselves in longer working days. But this is, of course, not so for machine-paced work (ie, some industrial tasks) where it is impossible to ease-off, and instead greater fatigue may result.

Likewise, although the evidence is not conclusive (see Cliff and Horberry, 2008), shift durations of over eight hours often tend to increase the risk of errors and incidents (Mine Safety and Health Administration (MSHA, 2002). However, although limiting shift length may be physiologically optimal, it needs to be balanced against practicalities: tasks still need to be performed (especially maintenance tasks), some equipment cannot easily be shut down, and pay is sometimes higher for longer shifts.

2.2.5.3 Night Work

Night work and other shiftwork are virtually indispensable in industry; often it is economically essential to run a 24-hour operation. Many human bodily functions fluctuate in a 24-hour cycle called the 'circadian rhythm', these include core body temperature and blood pressure. These bodily functions usually peak during daylight hours and are lowest at night and early morning hours. It is not just physical functions; this trend is also associated with alertness levels. It is very difficult to alter circadian rhythms completely; often several weeks are needed to do this, so, where they are needed, quick rotation shifts are now often recommended in industrial operations (Grech *et al.*, 2008).

Many studies have found that more work errors (leading to incidents or accidents) are likely to occur at night, with the 12-4am period especially prone to problems when an operator often needs to fight to stay awake. As much as possible, where dangerous or demanding tasks involving equipment operations or maintenance need to be performed (eg, scheduled maintenance tasks involving multiple operators and a large amount of complex support equipment), they should be done when personnel are most likely to be alert (Cantwell, 1997). However this, of course, can be difficult to achieve. Where fixed night schedules are likely, then adaptation to them is possible, especially if the operator is helped to re-synchronise by means of meals, exercise, social interaction and light. Such adaptation can help improve the operator's health and job satisfaction.

2.2.5.4 Strategies to Combat Operator Fatigue

Naps and coffee. Where appropriate, two short term strategies for helping to manage fatigue associated with operating or maintaining equipment are short naps and/or coffee. However, the caffeine in coffee, when used incorrectly or to excess, can cause both a dependency and a tolerance to develop, and can also modify sleep patterns. Techniques such as fresh air, showering, communicating with colleagues or stretching are not usually effective for more than a few minutes, and are often not possible in the work environment. The best solution is to obtain proper (ie, good quality) sleep, but for night shiftworkers this can be difficult due to daytime noise and light. Where it can be done, preventing fatigue from occurring in the first place (eg, through better designed shift schedules etc) is, of course, the best way to control the risk, especially in a high hazard industry.

Rest breaks. From the scientific literature (and from personal experience of many workers), it is consistently found that rest breaks in shifts are very necessary - often they can actually increase daily output, despite slightly fewer hours being 'worked' (as noted by Grech *et al.*, 2008). There are different types of breaks/pauses, such as prescribed ones (eg, a maintenance worker is relieved of duties for a 20-minute lunch break), or more 'implicit' breaks (for example an operator does something different, or a break due to the nature of the work, such as a haul truck driver waiting for the truck to be loaded).

Kroemer and Grandjean (1997) stated that pauses/breaks can be especially good for:

- training (so a new operator has time to reflect on techniques just learnt, a break of 30 minutes or more can be useful);
- extreme machine paced work. This is especially for the older workers, who often would ideally work slightly slower;
- heavy work (so as not to exceed daily physiological capacity for work, eg, in terms of energy expenditure, a couple of 15-30 minute breaks in an 8 hour shift is sometimes recommended);
- social contacts (when an operator is working in 'isolation');
- heat (to allow the body to cool down);
- close visual work (eg, to prevent temporary myopia/eyestrain amongst maintenance workers undertaking a visual inspection of, for example, components for wear or corrosion); and
- mental work (which benefits from regular short breaks, even if only 5 minutes per hour).

From this, where shiftwork (especially nights) is needed in industry, a few recommendations (adapted from Kroemer and Grandjean, 1997) are:

- ensure adequate break(s) per shift for nourishment and short rest;
- where legally possible, only use operators aged between 25-50 for shift/night work;
- only employ healthy, emotionally stable workers;
- have at least 24 hours break after working a series of nights (especially if two or more nights are in the series), and plan some free weekends into the shift schedules; and
- avoid or limit extreme-machine paced work, where the operator has no flexibility in setting the pace, and fatigue results more quickly.

Of course, some of these recommendations are not practical in every situation, but they do provide some guidance about what is best practice in industrial operations and maintenance.

2.2.6 Management and Organisational Factors

The South East Queensland Water Grid, despite its conglomerate and networked nature, can be classified and analysed as a High Reliability Organisation. The main defining characteristic of these organisations is that the consequences of system failure are dire; they can include large-scale loss of life, destruction of infrastructure and severe compromises to public health and safety, which can be very long-term.

Given the hazards which need to be controlled by these organisations, the need for comprehensive and effective risk management is paramount. The development of mature risk management philosophies is strongly influenced by organisational learning, and this area is where High Reliability Organisations face particular challenges (Weick, 1987). Learning strategies unique to these organisations arise from the complex interdependencies between systems and the inability to utilise trial-and-error approaches due to the potential for catastrophic outcomes (Weick *et al.*, 1999). Additionally, these industries are subject to intense public scrutiny when accidents occur, which has implications for knowledge management and the free flow of information required for effective learning.

As Weick and Sutcliffe (2007) point out, High Reliability Organisations are characterised by the following five qualities to keep them working well when facing unexpected situations (often termed *mindfulness*):

1. preoccupation with failure, and detailed analysis of actual and potential failure as essential for organisational learning;
2. reluctance to simplify interpretations, and seeking a diversity of views on organisational issues;
3. sensitivity to operations ie, one or more individuals having an understanding of the state of the operational system, and the organisation placing emphasis on the understanding of operations;
4. commitment to resilience, often by defence in depth, especially to eliminate hazards or prevent incidents. Resilient organisations are robust yet flexible, and have the ability to recover from irregular variations and disruptions of working conditions to prevent control being lost (Hollnagel, Woods and Leveson, 2006); and
5. deference to expertise, especially having an organisation flexible enough to allow responsibility for decision making in emergency situations to be passed to experts close to the situation.

Most of the work with High Reliability Organisations has come from outside the water industry, with nuclear power and air traffic control being two examples where this sort of approach has been most commonly applied. Although very few examples could be found in the open literature of systematic attempts to incorporate organisational maturity models in water operations, it is expected that this could be an area of particular benefit for this domain. This is especially pertinent in the light of the research team's discussions with Water Grid stakeholders, many of whom expressed concerns about the general immaturity of risk management within the sector.

2.3. Data Collected concerning the Water System in SEQ

2.3.1 Interviews with Key Stakeholders

Our semi-structured interview approach uncovered a range of opinions concerning risk management policies, procedures and practices in the sector. The people we spoke with were generally optimistic about the maturity and operability of risk and emergency management procedures, but they also indicated that there was significant room for improvement. The following is a summary of some key areas of concern.

2.3.1.1 Organisational Culture

The recent restructuring of the water sector in SEQ was reported to have caused uncertainty among at least some staff in the water sector, particularly long-serving members, and there was concern about subsequent possible resistance to the introduction of new policies, operating procedures and reporting requirements. When we asked about how human error is incorporated into the sector's risk management philosophy, there was an overall consensus that a reactive, rather than proactive, approach is generally taken. In some ways this is understandable, given that the water treatment and delivery system is generally robust, and also that reportable incidents are rare and by their very nature unpredictable. Issues of general importance were:

- change management - adaptation to new organisational structure;
- leadership in the context of emergency response;
- compliance with standard operating procedures; and
- reactive approach to dealing with incidents involving human error.

2.3.1.2 Communication, both Within and Across Entities

Nearly all of our interviewees flagged communication as a potential problem, both at a broader organisational level and by way of specific micro-level examples. At the time of our discussions (October-December 2010), the newly completed Emergency Response Plan (ERP) had been subject to testing via a desktop simulation by staff at the Water Grid Manager. Among other things, this document describes procedures for establishing incident levels, escalation, and lines of communication in the event of an emergency. Some of our interviewees were optimistic about the performance of the ERP, others were less so. Concerns were raised about the efficiency and timeliness of the ERP communication protocols; according to one informant, over 600 email messages were generated in the desktop simulation. We did note that the simulation was an extreme hypothetical disaster involving multiple, simultaneous and independent system failures – in other words, the worst-case scenario imaginable. At the time of the interviews, we had no insights or evidence concerning the likely performance of the ERP for incidents of a less spectacular nature. The January 2011 floods may have provided a real-world test case of a different type for the ERP, and an examination of communication dynamics in response to these events would obviously provide much more valuable lessons than any simulation.

Other communication-related issues were raised in the interviews, the most concerning of which was the embedded reluctance of entities to share information. According to one interviewee, communication between entities may be hindered to the extent that legal advice has sometimes been sought before data has been shared. The key points were:

- appropriateness of communication protocols in Emergency Response Plan;
- openness and transparency;
- collection and dissemination of data; and
- evaluation, iteration and feedback of the performance of the ERP.

Communication problems were identified in the investigation into the North Pine Water Treatment Works Fluoride Dosing incident (Pascoe, 2009), which is discussed further in this report (see section 2.3.3.2). At the operational level, no existing communication protocols – ie, a tagging system and/or operator log – were in place between maintenance and operations staff, which meant that operators were not aware that a crucial flow control switch had been disabled. Communication problems were also inherent in the subsequent incident management process; notification to the regulator and Queensland Health did not occur in the prescribed timeframes and few technical discussions between grid stakeholders took place. These problems ultimately led to an incorrect initial assessment of which consumers were likely to have been affected.

Combined with the findings of our interviews, issues raised in the Pascoe report indicate that communication may be a systemic problem in the sector. It is possible that communication difficulties reflect a settling-in period following the restructuring of the sector, and may become resolved on their own as individuals become more aware and more comfortable with their redefined roles and responsibilities. Organisational culture and change management issues are crucial to risk management, but are areas outside the general domain of human factors analysis as presented in this report. While considerable gains can be made by in-depth comparisons with change and risk management approaches in similar industries (as proposed in section 3.3.1), our informal suggestion would be that the sector could engage the services of HR professionals or organisational psychologists to address these issues at an operational level.

2.3.1.3 Technology, Infrastructure and Training

The SEQ water grid assets feature a wide range of treatment and production technologies, ranging from relatively low-tech coagulation-filtration-disinfection plants to the recently commissioned Gold Coast desalination plant. In our interviews, serious concerns were raised about the capacity of standard risk management to address the unique set of technological challenges faced by the sector. At least one interviewee viewed the North Pine fluoridation incident as a consequence of poor infrastructure-related decisions made under intense political pressure. Another informant queried whether training requirements for operational and maintenance staff were relatively homogeneous given the size and variability of the Grid. Deficiencies were pointed out in some technological matters, notably the notification systems used in some facilities (eg, alarms and alerts being sent via SMS), whilst other aspects such as automation and supervisory control were generally looked upon favourably. A summary of the major points is presented below:

- lack of large-asset experience in SEQ;
- lack of integration and centralisation in some types of assets:
  - 50 water treatment facilities in SEQ, but only nine in the Sydney Metropolitan Area;
  - variability in age and quality of assets;
- potential mismatch of human-machine interfaces to technology; and
- rapid accumulation and near simultaneous rollout of new technologies, eg, desalination, recycled water, the water grid and fluoride dosing.

In conjunction with our other investigative approaches, our interviews revealed that the technology and work domain is where the best opportunities for further research lie. Integration of automation and supervisory control with treatment and delivery technology is essential for a well-functioning system, and our analyses of recent incidents and our site visit to the Mt Crosby treatment plant showed that there is indeed room for improvement.

Preliminary findings from our interviews were established on the basis of rapid review and only a relatively small number of interviews/discussions. Data collection and interviews would need to be more thorough, and would require a more targeted approach, in Phase 2. It is proposed that this should be undertaken in conjunction with a cross-industry benchmarking exercise (see section 3.3.1).

2.3.2 Site Visit: Seqwater Mt Crosby (Eastbank) Water Treatment Facility

Team members A/Prof Tim Horberry and Dr Steven Cloete conducted a site visit at the Eastbank Mt Crosby Water Treatment Facility on 14 December 2010. The team was given a guided tour of the plant, conducted interviews and discussions with two operators, and undertook informal inspections and evaluations of Human-Machine Interfaces, including the Supervisory Control and Data Acquisition (SCADA) system, which operates as a control and monitoring hub for other treatment plants in the Brisbane metropolitan area. Further site visits are proposed for Stage 2.

2.3.2.1 SCADA System, Alarms and Other Technological Matters

Although the project team did not conduct a formal ergonomics interface review, the complex SCADA interface appears to be generally well-designed, clutter-free and easily navigable. The operator assisting us expressed some satisfaction with the design and operation of the system, although we note that he was a long-serving member of staff with highly detailed knowledge of the plant and SCADA interface. However, even after a brief tour of the facility, we were able to recognise major components of the treatment process in the SCADA interface, ie, water uptake, coagulation, filtration and transport to the disinfection facility, which is indicative of sensible design. The graphic and pictorial elements were generally informative, but we noted that much monitoring information is presented in a numerical and/or tabular format. These display modes are appropriate under some circumstances, but there are substantial movements in the literature toward more ‘ecologically valid’ displays, which incorporate more symbolic and graphical elements, including the use of configural displays.

Discussions with the operators also revealed that diagnosis of equipment failure in some instances can only be made on the basis of indirect monitoring; ie, failure of a particular pump is not signalled directly in the SCADA, but affects the concentration or flow rate of a particular chemical at a particular point in the process. Better signalling and integration can avoid ‘second-order’ monitoring issues which are highly undesirable in modern supervisory control, and can also reduce the demand for site-specific training.

The visual-auditory alarm system seems to be appropriately designed, although we noted that alarms can be disabled from within the system (see Figure 6).

Figure 6: Ability to disable alarms is built into the Mt Crosby SCADA system.

According to some members of the Human Factors community, the inclusion of functionality to disable alarm systems is effectively an admission of poor design and/or performance. The frequency of low-level alarms (which may not require immediate action) can be high enough to become a source of distraction which, aside from interrupting other work activities, can affect the credibility of the alarm signal. In addition, failures of situational awareness concerning the status of the alarm systems, for example, forgetting or otherwise being unaware that the alarms have been disabled, could be highly problematic. Perhaps more importantly, inappropriate response to a fluoride alarm was identified as one of the root causes of the North Pine Fluoridation incident, which suggests to us that further consideration of the design and operation of the alarm systems is useful. Supplementary training, as recommended by the Pascoe report, is unlikely to be fully effective if the alarm system behaves erratically, or in a fashion which is not consistent with users' expectations.

Staff expressed a desire for operators to be included in the design and consultation process for upgraded facilities and new equipment, citing the onsite fluoride dosing equipment as an example of new facilities being installed with less consultation and operational training than desired. This comment echoes some of the recommendations stemming from the Pascoe report; ie, supplementary training targeting the operation and control philosophy of the equipment. However, involvement of technical staff in much earlier decision-making concerning plant equipment is a more proactive approach, because they are the end-users and have considerable experience with what works and what does not. Involvement of operational staff is a cornerstone of the 'participative ergonomics' movement, and the sector could have much to gain in future technological developments and infrastructure upgrades.

2.3.2.2 Training

As each water treatment facility is different, so too are the training requirements for technical and operational staff. Our discussions with Mt Crosby staff indicated that training is provided in a site-specific apprenticeship/traineeship model. It was unclear to us whether training for the management of non-normal or emergency operating conditions (eg, power failure) was provided proactively, or whether senior staff wait for these conditions to eventuate, as they inevitably do, and guide less experienced operators through the process. In any event, comprehensive, proactive emergency management training may not be feasible because of the inherent unpredictability – and in many cases *novelty* – of adverse events.

2.3.2.3 Work Cycles and Fatigue

The operational staff at Mt Crosby work standard 8-hour shifts on a rotating 3-shift pattern (8am-4pm, 4pm-12am, 12am-8am). We were informed that the option of a 12-hour shift cycle was voted down, which suggests that the present work cycle is generally well-liked. As it is in line with good practice in other industries, we see no reason to investigate this topic further in Stage 2.

2.3.3 Brief Human Factors Analysis of Recent Incidents Involving Human Error

Contemporary thinking in human factors analysis indicates that actions of individuals trigger events that are only made possible by the presence of latent system vulnerabilities. Very important lessons for the discipline have been learnt in the aftermath of disasters. Indeed, events like Three-Mile Island and Challenger have inspired a great deal of empirical research, sometimes to the extent that a paradigm shift has occurred. Although the goals of this research project are somewhat more modest, there are still valuable lessons to be learnt through the post-hoc analysis of incidents. In recent years, two such incidents have occurred in the SEQ water sector, neither of which resulted in significant compromises to public health and safety. Given the potential seriousness of both incidents, this in itself can be taken as an indication that the procedures in place for incident recovery are relatively robust, which is encouraging news for the sector. What can be gained from incident analysis, however, is a better understanding of how the incident trajectory bypassed existing system defences, and consideration of additional safeguards that can be employed.

2.3.3.1 The Pimpama-Coomera Cross-Connection Incidents

In December 2009 and January 2010, cross connections were detected in dual reticulation systems in several Pimpama-Coomera properties. The water retailing entity responsible for supplying the affected properties - (Gold Coast Water until July 2010 and Allconnex thereafter) - was alerted to the problem by taste-odour complaints from consumers. We were unable to obtain detailed root cause analyses of the incidents because they are confidential, being the subject of an ongoing class action. Our understanding of the events was furnished by confidential and anonymous discussions with water sector professionals, and our reading of the Pimpama-Coomera Cross Connections Summary Report, dated 19 June 2010 (Allconnex, 2010a). Our knowledge of the specific circumstances surrounding the events remains limited, so the following analysis should be looked upon as preliminary.

The incident occurring in December 2009 was the result of failure to remove an intentional network cross-link, which resulted in delivery of diluted recycled water to the potable water network servicing around 600 homes. This appears to have been an isolated event and the rectification measures recommended should prevent future occurrences. In contrast, the incidents of January 2010 seem to have had a more systemic basis and, in the estimation of the research team, a much higher likelihood of re-occurrence given that potential on and off-lot cross-connection points probably outnumber intentional network cross-links. Three types of error are portrayed in Figure 7 below.

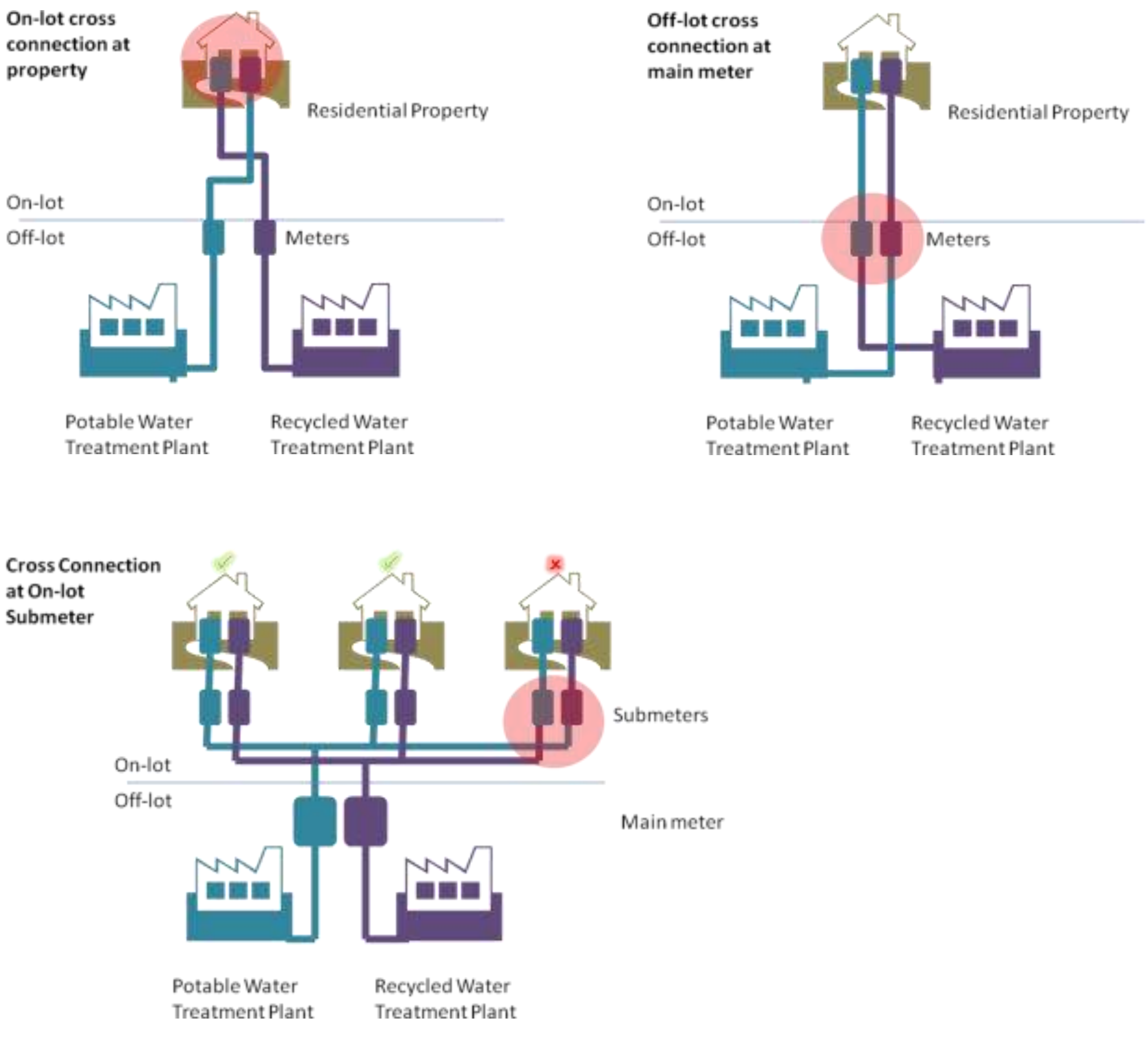

Figure 7: Three types of cross connection error detected in January 2010.

Under AS/NZS 3500.1 (2003), fittings and pipes for use in domestic dual reticulation systems for recycled water are required to be coloured purple for identification. In principle, this is an effective and easily implemented risk mitigation strategy, but it clearly failed in the cross-connection incidents of January 2010. The subsequent recommendations concerning detection in dual reticulation installations are comprehensive, including on-lot conductivity testing at each household fitting, off-lot audits and communication and training provisions to building/plumbing industry groups. These recommendations are aimed predominantly at *detection* of existing cross-connections; there has been comparatively little consideration of *design-related measures* to reduce the possibility of cross-connection errors occurring.

The January 2010 on-lot cross-connections occurred because it was possible for plumbers to attach recycled water pipes and fittings to the potable water supply points, despite the existing AS/NZS 3500.1 requirements for colour-coded identification and the specification of opposite thread directions for inlets and outlets to recycled water meters. A strong design solution is to further increase the incompatibility between recycled and potable water fittings, while retaining the colour code as a form of redundancy gain. Using principles of industrial design there are several ways this could be achieved, most obviously with thread direction and fitting diameter. Recycled water meter inlets and outlets have opposite thread directions specified in the relevant standard (AS/NZS 3500.1), and a recommendation stemming from the summary report is to use different diameter threads on recycled and potable water meters. Given that meters provide at least two opportunities for cross connection errors, it is pleasing that an additional design-related countermeasure has been recommended. While a determined plumber could easily circumvent any such measure, it provides another layer of protection against potential cross-connection errors, which is consistent with the 'Multiple Barrier' approach to risk reduction.

Additional safeguards - fittings. The use of a left-hand thread has been undertaken for Class A recycled water tap fittings, but according to an Allconnex Fact Sheet for plumbers (Allconnex, 2010b), this requirement has been suspended to ensure 'user-friendliness' and compatibility with vacuum breakers (recycled water tap fittings are also further differentiated with a different thread diameter to potable water taps). Compatibility treatments for outdoor recycled water taps aid only in the identification of the outlet as one providing recycled water and prevent homeowners from attaching standard tap fittings to recycled water connections, they are not intended as a cross-connection mitigation strategy *per se.*

Additional safeguards – recycled water additives. A recent study by the Sydney Water Corporation (Storey *et al.*, 2007) explored the use of recycled water additives to reduce the likelihood of accidental ingestion. Detection thresholds and cost considerations for colourants and anti-ingestion agents (mostly commercially available bitter-tasting compounds) were investigated. Some anti-ingestion additives were potentially very cost-effective (eg, $0.02/kL for citric acid), but highly variable detection thresholds, odour and chlorine demand rendered them unsuitable. The potential for staining ruled out the use of colourants, given that domestic laundry is one of the main intended uses of recycled water.

Identifying exactly how the existing barriers were breached in this instance was not possible. As indicated later, an in-depth retrospective analysis of the cross-connection incidents is proposed for Stage 2.

2.3.3.2 The North Pine Treatment Facility Fluoride Dosing Incident

The North Pine Water Treatment Works fluoride dosing incident was another well-publicised event which affected the SEQ water grid in April/May 2009. A sample collected from the delivery main on April 29 and analysed on May 11 had fluoride content far in excess of Australian Drinking Water guidelines. This monitoring result led Seqwater to declare an incident and notify SEQWGM, Queensland Health and the Office of the Water Supply Regulator. The incident occurred when the treatment plant was offline. A malfunctioning flow control meter sent a signal which initiated automatic fluoride dosing, and a backup flow control switch had been disabled for maintenance. The flow meter was owned and operated by Linkwater, and was known to be malfunctioning at the time of the incident, but was not given a high priority for repair. Over a period of five hours, a large volume of concentrated fluoride solution was dosed into the delivery main, contaminating approximately 400kL of treated water. A high fluoride alarm was triggered, which was acknowledged by the operator at Mt Crosby, but not acted upon further. This was presumably because the operator knew the North Pine plant was offline, and so assumed the alarm was spurious.

Investigation of the incident by Pascoe (2009) revealed a combination of technical faults and inappropriate actions by operators and maintenance contractors as the primary cause. At least four failures contributing to the incident could be classified as human error:

1. no action taken in response to a high fluoride alarm;
2. inadequate communication – operational staff were not notified by maintenance staff that a back-up flow control switch had been disabled;
3. inadequate analysis of recorded information – consumption of dry fluoride powder, which indicates that the fluoride dosing equipment has been active – was recorded by a North Pine operator despite the plant being offline; and
4. ambiguous understanding of how the fluoride dosing equipment is controlled. For example, operators at the North Pine facility were told by the installation contractors that the operation of the equipment was 'fully automated'.

As always, the operator errors contributing to this incident occurred in a broader system context. Taking information from our confidential discussions with water industry participants and the findings of the Pascoe report, we conducted a preliminary analysis of the incident using a systems-based framework modelled on Rasmussen (1997). Working back from the incident (see Figure 8), it is clear that several independent system vulnerabilities were active at all levels of the analysis hierarchy, right up to pressure from the state government to implement fluoride dosing in SEQ within strict time limits. The Pascoe report was also critical of the approach to incident management and investigation, in particular the failure of Seqwater to properly identify the physical processes leading to contamination. This led to a secondary 'incident', in that the scale of the incident had been overestimated, consumers potentially affected were not correctly identified, and notification was sent to residents who were never at risk of ingesting contaminated water. While this is an example of erring on the side of caution, there are serious risks to the reputation of the water industry.

The recommendations of the Pascoe report did address broader systemic issues, including revisions of operating procedures and communication protocols for maintenance work, and design-centred solutions such as additional interlocks. However, the report did not seem to consider the alternative hypothesis that inappropriate functioning of the fluoride alarm system was potentially one of the stronger contributory factors. The recommendation in this regard was for additional training on the importance of alarm response procedures. This makes the implicit assumption that the design of the alarm system is appropriate, and that the (in)action of the Mt Crosby operator was aberrant. In the view of the research team, there could be additional important opportunities concerning fundamental improvements to plant ergonomics. This point is explained further in section 3.3.3.

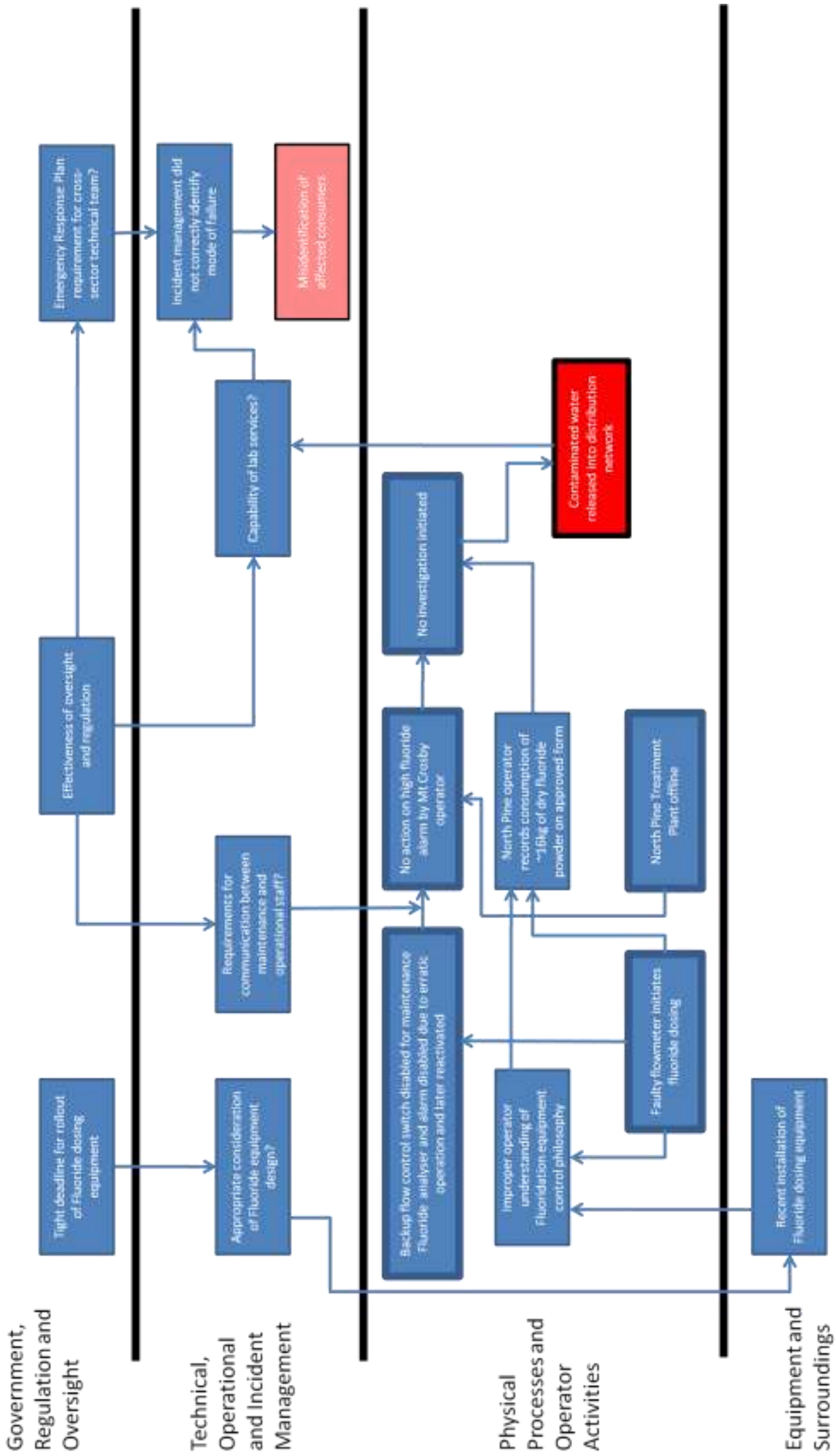

Figure 8: Systems-based summary of North Pine fluoridation incident.

2.4. Key Findings

There has been little published research literature that has considered human element issues in water systems. This gap is very surprising because the work that is available shows that the impact of human error on the water sector is similar to patterns of risk in other high-hazard, high-reliability industries.

The interviews, site inspections and analysis of recent incidents revealed several potential areas worthy of more detailed human factors consideration in a future research project. In addition to the communications, training and ergonomics issues detailed above, these included:

- The perceived impact of broader organisational factors, especially in the context of recent restructuring; and
- The identification of potential system vulnerabilities arising from the improper integration of new or different technologies, which is also linked to recent organisational changes.

3. HUMAN FACTORS IN URBAN WATER SYSTEM SAFETY: PROPOSALS FOR STAGE 2

3.1. The Case for Further Research

Stage 1 has essentially been a broad review of the key human factors issues in the SEQ urban water system. With a range of investigative techniques, the research team identified high level ergonomics/human factors deficiencies, but due to the scope of the current work it did not conduct detailed investigations of these revealed areas. Stage 2 is planned to deliver more comprehensive exploration and analysis of potential human factors research questions, which will help to better understand and manage risks associated with the human element. These questions will be informed by the key findings of Stage 1, with a particular emphasis on addressing the issues raised by water grid personnel. The sections below present the case for future research. The proposed program will address two broad human factors content areas.

3.1.1 Organisational Culture, Management and Learning

The first content area will be explored in the context of recent organisational changes. Uncertainties surrounding these changes may have led to a relatively poor understanding of roles and responsibilities within the sector, which, if unresolved, will allow compromises to overall system security at the highest level. It is proposed that organisational factors in the water sector be explored more thoroughly through further discussions with key personnel and analysis of internal documents. The aim is to develop a higher-resolution picture of the sector's approach to risk management, which can then be benchmarked against risk management in other domains. There are many industries which operate with simultaneously high degrees of risk and reliability, such as aviation, mining and nuclear power generation. A mature understanding of the human element is characteristic of their approaches to risk management, and contributions to the human factors research literature from these industries are vast. Many have also undergone sweeping changes due to external forces like policy change and privatisation, and also internal changes such as technological improvement. Although the similarities to water treatment and delivery may not be readily apparent, a detailed review and analysis of best practice within these industries will provide a valuable sounding board for the sector.

3.1.2 Interactions Involving People, Technology and Work

Our investigations in Stage 1 revealed a number of technology-related issues, several of which have their origins in the recent transfer of asset ownership from local government to state government-owned entities. For example, Seqwater is responsible for a very large number of treatment plants which vary in age, quality and reliability, capacity and technology. Considerable gains can be made by a better understanding of how operators accept and interact with infrastructure, and our proposal is for a three-pronged approach.

Firstly, the recent incidents described in this report indicated a major role played by operator error. Although these incidents have been subject to root-cause investigations, they shed little light on the decisions made by operators at critical junctures. The Critical Decision Method is a qualitative, retrospective analysis tool which has found application in a large number of industries including aviation, nuclear power and medicine. The use of this technique to analyse the incidents described in this report will involve confidential in-depth interviews with operators, maintenance personnel and other relevant parties. This investigation will hopefully shed more light on the circumstances leading to some of the poor decisions made. Lessons from the Pimpama-Coomera cross-connection incidents will be particularly revealing, because considerable defences were already built into design and installation standards for recycled water meters and fittings.

Secondly, system vulnerabilities can be identified in more detail through the application of Human Reliability Analysis and Cognitive Task Analysis to routine operating procedures. This form of prospective analysis has the potential to reveal design and work-related deficiencies which are invisible to the less formal analysis methods used in Stage 1.

Thirdly, the capability of supervisory control systems should be assessed, in particular the effectiveness of alarm systems. For example, the recent acquisition of fluoride dosing equipment was probably not followed up by effective integration into existing plant technology, and operated in a manner that was at odds with the expectations of operators. These conditions contributed to an operator's decision not to act upon a critical alarm, which resulted in the contamination of treated water in a delivery main. Although there were other contributory factors at play, this incident probably would not have occurred if the new infrastructure was integrated more soundly.

3.2. Limitations of Stage 1 Investigations

Stage 1 of this project was always intended as an exploratory exercise. Time constraints meant that the research team was unable to interview a wider representative body of water grid personnel, particularly operations and maintenance workers. The knowledge base, skill sets and experience of these individuals may provide valuable insights into human-centred risk, and they may have very different opinions to senior management as to the general health of the system and priorities for improvement. We did not have the opportunity to inspect and analyse all of the relevant internal documents and data, such as risk registers, standard operating procedures and incident reporting forms. Our proposals for Stage 2 (see below) include a detailed review of this information for the purposes of a cross-industry benchmarking exercise. Physical site inspections were limited to the Eastbank Mt Crosby Treatment Plant which, despite using older infrastructure and treatment technology, was regarded by our interviewees as one of the best functioning plants in the network. Inspection of poorer-quality assets, as well as examples of more sophisticated plants, would certainly have uncovered more opportunities for exploration. These shortcomings will be addressed in Stage 2, which will be considerably broader in scope.

3.3. Proposed Scope and Outcomes of Stage 2 Research Program

3.3.1 Elements of Stage 2 Proposal

The next phase of this project has been proposed as an integrated series of succinct, highly focussed research exercises, which have been conceived to address the issues raised in this report. Specific details of each exercise are described below.

3.3.1.1 Review of Best Practice for Interface Design and Integration for Automation and New Technologies

In particular, this would look at how such issues have been managed from a human element perspective in other high reliability industries (eg, power generation or food manufacturing). The issues of older and younger workers and the potential problems with information overload from multiple alarms and warnings will also be reviewed.

3.3.1.2 Ergonomics Audits/Checklists of New Technology/Automation

This would focus on reviewing the SCADA systems from an operator-centred perspective. Again, the issues of different aged workers and information overload from multiple displays, warnings and alarms will be areas of more detailed investigation.

3.3.1.3 Observations and Interviews with Operators

This would include both undertaking a broad task analysis of the operators' main tasks, and discussions with operators of any incidents/errors/critical events to help identify any design deficiencies.

3.3.1.4 Participatory Ergonomics Design

Using the knowledge obtained in the above stages (especially where deficiencies have been noted), the researchers would work with operators to propose new/modified designs of technologies/automation.

3.3.1.5 Testing and Evaluation

The final stage would be the completion of user trials to review the benefits and limitations of the automated technology. This stage would include operator acceptance testing, perceived trust in the technology and the perceived issues in switching from automated to manual control.

Given the inherent flexibility of SCADA systems in general, the implementation, empirical user testing and feedback of system improvements should be a relatively uncomplicated research undertaking. In the short term, the results of this investigation would be suitable for publication, particularly if there are opportunities for extensive empirical testing and design iteration. In the longer term, the adoption of a SCADA system which is better integrated with plant technology and the needs and preferences of operators will have benefits, especially for abnormal operating conditions and to assist in future procurement of systems and new technologies.

APPENDIX 1

List of Journals Accessed for the Targeted Literature Review

- Accident Analysis and Prevention
- Applied Ergonomics
- Australian Journal of Water Resources
- Cognition, Technology and Work
- Ergonomics
- Human Factors
- International Journal of Human Factors in Manufacturing
- International Journal of Industrial Ergonomics
- International Journal of Technology and Human Interaction
- Journal of Cognitive Engineering and Decision Making
- Journal of Hydroinformatics
- Journal of Safety Research
- Journal of Water and Health
- Risk Management
- Safety Science
- Water, Air and Soil Pollution
- Water Research
- Water Science and Technology

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