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cover
A New South Wales RFS fire-fighter surveys a bushfire burning close to homes in Springwood in the Blue Mountains, west of Sydney, in October 2013.

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URBAN WATER SYSTEM SAFETY: A HUMAN FACTORS INVESTIGATION

An investigation of the human element issues of control room operations for water treatment and distribution

S Cloete, T Horberry, B Head

HEALTH & SAFETY

ABSTRACT

Water systems in first-world countries such as Australia are still vulnerable to critical incidents that can result in health and safety disturbances. This research investigated the human element issues of control room operations for both water treatment and distribution. Data collection was by means of semi-structured management interviews, observations of routine work, operator interviews and questionnaires, and the application of a best practice checklist for alarms.

The main findings were that there is considerable room for improvement in human factor issues such as alarm-handling, interface design and human-technology integration. For example, at one site visited alarm flooding was common, operator interfaces suffered from a lack of consistency and integration, and tasks were not appropriately delegated to human operators and system automation. The key message emerging is that the water sector does not give adequate consideration to the dynamic interactions between equipment, work tasks and operators. There is a need for user-centred design and evaluation in this domain so that technology and humans can be appropriately integrated in a work system.

Keywords: Human factors, control rooms, water treatment, water distribution, alarms, user-centred design.

INTRODUCTION

RISKS FACING THE WATER INDUSTRY

Recognition is growing among stakeholders that water treatment and supply systems in first-world countries such as Australia are not immune to critical incidents resulting in compromises to public health and safety. The case of *E. coli* contamination in Walkerton, Ontario, is the most widely publicised and discussed example of a disease outbreak in a developed country (Hrudey and Hrudey, 2004), and is also an excellent demonstration of how factors across a broad range of stakeholders interact to result in a public health disaster (Vicente and Christoffersen, 2006).

A stance the water sector should be anxious to avoid is to implicitly assume that technological components of supervisory control systems always provide sufficient, meaningful and credible information to the operators. Clearly, in the case of the incident just described, they did not.

THE HUMAN ELEMENT IN WATER SYSTEMS: A RISK MANAGEMENT APPROACH

A water treatment and supply system can be thought of as a complex 'socio-technical' system in which operators, procedures and technology need to interact safely and efficiently. The human element in such complex socio-technical systems is being increasingly studied using a risk management framework (Horberry et *al.*, 2010). The process starts with establishing an understanding of the broader context in which work tasks take place, before undertaking hazard identification and risk assessment.

From a Human Factors risk control perspective, the emphasis 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 (Simpson et *al.*, 2009). The underlying assumption is that the people involved are the 'experts' and must be involved at each stage of the risk management cycle if the process is to be executed successfully.

Contemporary thinking in Human Factors and related disciplines characterises human error as a consequence, rather than a cause, of system failures (Simpson et *al.*, 2009; Reason, 1990). Detailed analyses of industrial accidents with human error contributions show that it is always the case that multiple safety barriers at organisational, technical and operational levels are breached before aberrant human behaviour – labelled as 'error' – can take place.

In systems responsible for the provision of drinking water, this recognition remains under-developed and, with the exception of one recent review article (Wu et *al.*, 2009), human element risks in water treatment and delivery have received scant attention in the academic literature. With consideration also given to the potentially serious nature of incidents and accidents involving water treatment and distribution infrastructure, including threats to public health and large-scale destruction of property, the water sector should be playing a more active role in understanding and managing human element risks.

THE PRESENT RESEARCH

The Wu et *al.* article was an important step in publicising the role of human factors in drinking water contamination, but had a focus on assessments of previous incidents rather than examining current operations. The present research investigated the human element issues in operations of both water treatment and distribution.

Participation was sought from the bulk water transport authority and from a newly commissioned advanced water treatment plant (AWTP). These were selected to represent a broad range of technological sophistication and operational activities. On the one hand, the AWTP plant was commissioned and built relatively recently (2007–2008); it was highly automated and designed to run with minimal input from human operators. At the other end of the spectrum, bulk water distribution relied on a complex network with major components being 40–50 years old.

METHOD

SCOPE

To give the research clear scope, it was restricted to problem-specification tasks, including an appraisal of supervisory control and alarm systems using a best-practice audit tool, questionnaires and work observations, and interviews with operators and management.

The focus was on control rooms for water treatment and supply plants. These control rooms house the desktop interfaces for distributed control systems, and are where the majority of network operations in the water grid are initiated and governed.

The key topics addressed in the research activities were:

- **Alarm systems:** An operator's inappropriate response to a critical alarm was identified as a contributory factor in a recent industrial accident.
- **Human-system integration:** Recent changes in the organisational structure and ownership in the water grid precipitated, for some entities, a need to decommission aging plant equipment and upgrade existing facilities with newer technology.

DATA COLLECTION METHODS

Several human factor research methods were used: these comprised semi-structured management interviews, observations of routine work, operator interviews and questionnaires, and the application of a best practice checklist for alarms/warnings. Before data collection began, clearance to conduct the research was obtained from the University of Queensland (Australia) Human Ethics Review Committee.

To better understand the organisational context and the actual technology deployed, semi-structured interviews were held with six representatives from senior management, including Service Delivery Managers, Network Managers, and Systems Engineers of the Supervisory Control and Data Acquisition (SCADA) systems.

Research activities for both water grid participants consisted primarily of site visits, during which the research team was given an overview of the control network and site tour (AWTP only). Operators were then interviewed and asked to complete a standardised questionnaire. The questionnaire assessed the operator's level of interaction and experience with the SCADA system (particularly the alarm components), and perceptions of its effectiveness. It was adapted from the Engineering Equipment and Materials Users' Association (EEMUA) guidelines (EEMUA, 2007).

Figure 1. The water distribution control room.

In addition, approximately 21 hours of naturalistic 'fly-on-the-wall' observations of operators in the control rooms were conducted. Non-intrusive observation coincided naturally with periods of higher operator workload, while in quieter periods (and with the operator's consent) the experimenters asked questions about relevant human factor issues.

RESULTS

WATER DISTRIBUTION

<u>Control room operator observations</u>

Operators were observed over five three-hour control room visits, which were conducted at various shift/roster combinations. The main function of such observations was to obtain a broad task description. The operator's duty can be summarised as ensuring efficient bulk water supply to the SEQ water grid, which entailed:

- Monitoring the system for abnormalities;
- Performing routine transport operations;
- Issuing instructions to third parties and other water grid participants;
- Coordinating an active maintenance schedule.

As such, duties varied considerably, notably when only one operator was on duty. Regardless of time of day, phone communication appeared to be a dominant activity, and operators were often observed manipulating the SCADA system and performing other tasks while talking on the phone. The absence of appropriate hands-free telephone headsets increased task difficulty.

Maintaining the operator log also stood out as a major component of their task load, although it was not treated with the same priority as other duties. Operators frequently took notes by hand, which were later transcribed into the operator log. Distraction and interference by other personnel was frequently observed. Figure 1 shows the water distribution control room.

<u>Operator experience questionnaires and interviews</u> From a workforce of seven operators, we interviewed four and obtained the consent of three to complete our questionnaire instruments. Unfortunately, the particularly small sample size did not allow us to quantitatively analyse questionnaire data, but did provide insights that were consistent with the observations and interviews.

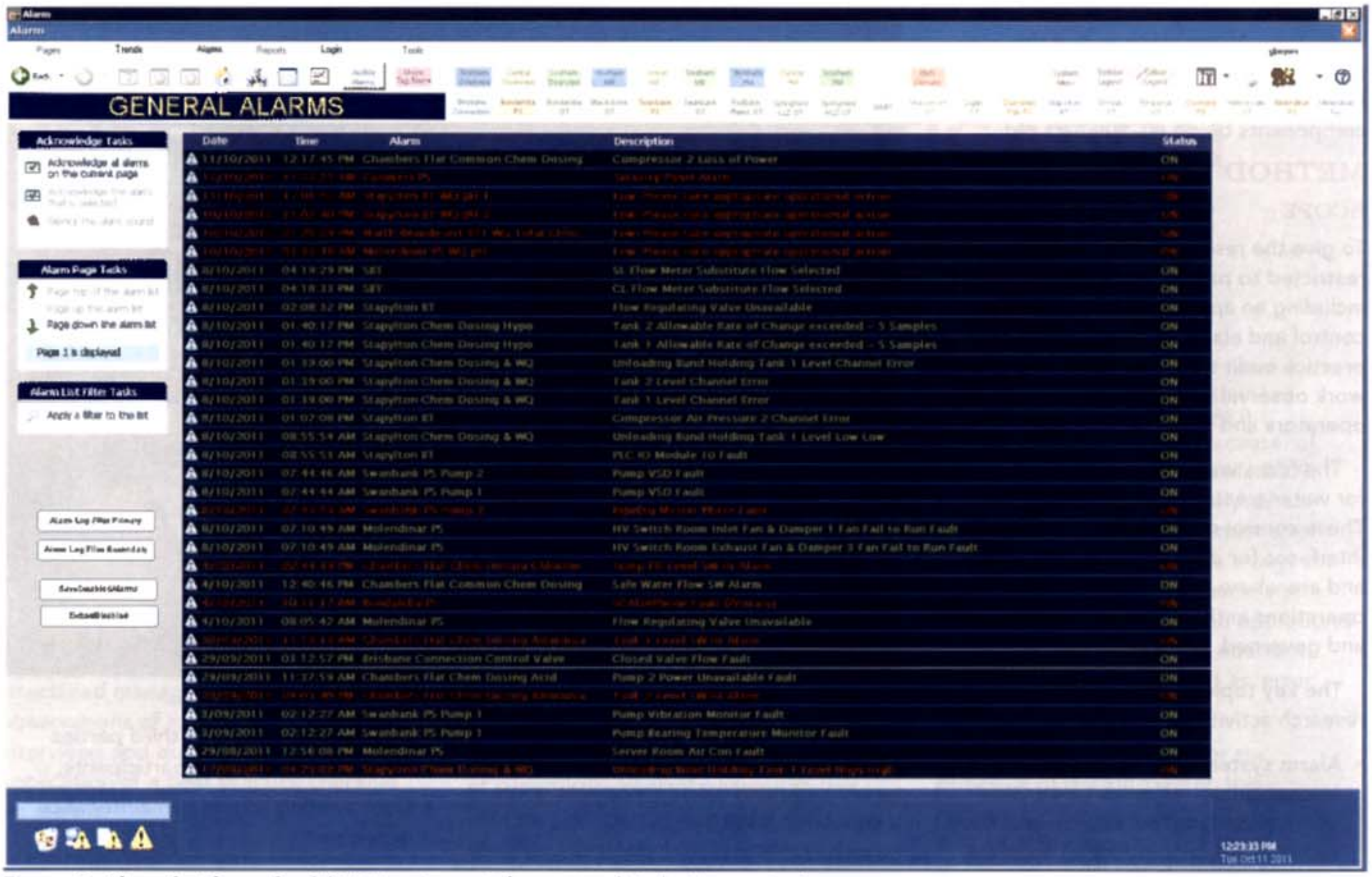

Figure 2. Alarm list from the SCADA system at the water distribution control room.

Responses to questionnaire items were quite variable, which indicates that individuals may develop a unique operating style. This was reflected in some observations, particularly the idiosyncratic ways in which operators arranged their screens and managed the operator log. Operators were fairly consistent in their assessment of the alarm system, but again differed in their preferences for the way SCADA system information was displayed and manipulated.

Operator log Operators reported numerous problems with the operator log – primarily that it was maintained in an Excel spreadsheet, which was burgeoning in size and processed on an ageing laptop. One operator claimed that the volume of log entries required, and delays due to inadequate computing power, accounted for up to 50% of their time in the control room, and this was subsequently confirmed with other operators. Given that the most trivial situations require multiple log entries, such as a cleaner requiring access to a secure facility, this is of considerable concern. They were unanimous in their desire for improvements to information logging, and argued that this may be best implemented at the level of discrete operations – for instance, if a valve is opened or a pump disabled, the system would automatically log the date and time of the operation.

Alarms Two lines of alarm information were displayed at the bottom of each screen. A dedicated alarm screen was accessible by clicking, but most operators reported that they did not allocate an entire screen to this function full-time. Alarms were categorised according to priority, but alarm priority was not clearly distinguished in the system, and neither priority was signalled by an auditory alarm. Figure 2 shows a screenshot of the alarm list. Note that the use of red text on a dark blue background is difficult to read.

Alarm flooding was reported to be common during a major upset such as power failure to a pump station. Operators reported that 'pages' of mostly redundant alarm messages are triggered in the first 10 minutes of an event. Operators agreed that functionality to detect and integrate related alarm signals would reduce cases of alarm flooding, but, given the size and complexity of the network, implementation of alarm rationalisation would not be trivial.

Information Support The manner in which the SCADA information was accessed and displayed, particularly for routine activities, was overly cumbersome. As an example, current practices required operators to check reservoir level trends at the beginning and end of each shift, to detect potential problems with reservoir input and output. The operator must go through a series of operations involving several mouse-clicks to obtain the information, and must pay particular attention to the date and time range over which the information was requested. There were fixed options for selecting a period, ranging from 1 minute to 13 weeks. It is inconceivable that any meaningful change in reservoir levels could occur over less than one hour (taking into account the flow rate set-point of 300L/s), so many of these fixed options were essentially useless. The options cluttered the drop-down menu display and increased the likelihood that an operator could select an incorrect period.

Compliance with Best Practice As previously noted, the SCADA design checklist was derived from EEMUA guidelines *(EEMUA, 2007)*. The checklist comprised 40 items assessing various aspects of display and alarm design and general control room ergonomics. It was

Table 1. Deviations from EEMUA (2007) Best Practice Guidelines.

Best Practice Violation	Comments
Lack of consistency in the use of colour, graphic design elements and schematics between the different SCADA software platforms.	In some instances, colours are used to convey diametrically opposite meanings (e.g., on/off). This is a plainly unacceptable situation.
No spatially/geographically organised network overview screen and no protocols to constrain the way in which operators organise the screens.	Operators do not always organise their displays in an efficient way. Organisation according to the geographical distribution of the network, potentially utilising the GIS system, is recommended.
No dedicated screens for intranet, email and ad-hoc tasks.	The lack of a dedicated non-SCADA terminal means that operators need to use screens that should be dedicated to system monitoring and network activities.
No dedicated screen for alarm lists.	Best Practice recommends that active alarms are displayed schematically. However, with a complex network, an alarm list is generally the only way that all active alarms can be depicted simultaneously. A dedicated alarm screen should be provided, with functionality to navigate directly to the relevant screen.
No auditory alarms, with unacknowledged alarms progressing to a phone alert after three minutes.	Recommendations are that Category 1 alarms (requiring immediate operator action) have an auditory signal.
No one-click integration of alarms to relevant screens/schematics, and no online alarm documentation.	Click-to-navigate functionality reduces the operator's reliance on memory and saves time navigating to the appropriate screen to deal with the problem. Alarm documentation, including information on fault diagnosis and step-by-step instructions for remedying the situation, should be available at a mouse-click.
Alarm flooding during incidents is common.	Alarm flooding defeats the purpose of alarms, which is to support operators in fault detection and diagnosis. Alarm flooding has been implicated in several major industrial catastrophes, including Three-Mile Island.

completed independently by a SCADA system engineer and the operators. Compliance with best practice was rated on only 13 of the 40 items. Examples of the major deviations are shown in Table 1.

Water distribution summary The control system for water distribution was inefficient and struggling to support operators in their duties. Short-term gains could be made by addressing problems in a piecemeal fashion, but the only way to ensure a robust solution would be through a thorough operator-centred evaluation and overhaul of instrumentation, alarm rationalisation and interface design. Fortunately, both management and operators were receptive to the findings of this research, which confirmed their proposed changes. Steps were being taken to deploy a new and more stable system.

ADVANCED WATER TREATMENT

The advanced water treatment plant visited by the team was a relatively new acquisition in the water grid. It uses cutting-edge water treatment technology to recycle treated wastewater, which was sold via dual-reticulation systems. The plant uses a process of sedimentation, microfiltration, reverse osmosis and ultraviolet disinfection, and is capable of producing 70ML of water in a 24-hour period.

Control room and operator observations Operators in the control room (and on site) were observed in their duties over a six-hour site visit. Observations were conducted in between more rigorously scheduled data collection activities. The staff recruitment model differed significantly to that employed at the water distribution facility. The plant was only staffed between 6am and 2.30pm, after which it ran automatically with an operator on call. The majority of control operators spent less than 25% of their time at the SCADA terminals, and performed extensive site maintenance activities as well as supervisory control.

During the research visit, operators reported that there was a degree of redundancy in staffing levels. Apart from a lead operator who staffed the control room on a full-time basis (subject to a rolling roster), operators engaged themselves between control room and site maintenance duties on an as-needed basis. A view of the primary operator console at the control room is shown in Figure 3; this console is 100% attended during shift hours.

Operator experience questionnaires and interviews As with water distribution, the limited number of operators on duty meant that quantitative analysis of the research questionnaire instruments was not possible. Therefore, observation at this site and responses on these instruments and operator interviews provided the bulk of the qualitative data presented here.

Alarms The alarm system was more sophisticated and functional than the one examined at the water distribution facility. This was not surprising given that the plant was new and quite constrained in size. However, the utilisation of advanced water treatment technologies (microfiltration, reverse osmosis, UV disinfection) and the higher degree of automation mean that the control network was no less complex.

Grouping of correlated alarms was in place to prevent alarm flooding and operators reported that it worked well. However, an unintended consequence of alarm groupings was the occasional situation in which fault diagnosis was impeded, because parts of the process control logic and corresponding interface were highly detailed and sequential. Operators suggested that improvements to drill-down functionality, and one-click

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Table 2. Departures from 2007 EEMUA Best Practice Guidelines.	
Best Practice Departure	Comments
Use of colour not restricted to alarm functions.	Colour is used to designate functional properties in schematics, such as operational status. Recommendations are that displays are primarily monochrome, with the excellent alerting properties of colour assigned to alarm functions only.
No one-click integration of alarms to relevant screens/schematics.	Click-to-navigate functionality reduces the operators' reliance on memory and saves time navigating to the appropriate screen to deal with the problem. This is particularly problematic if the operator's mental model of the network is inconsistent with the SCADA system. Alarm documentation including information on fault diagnoses and step-by-step instructions for remedying the situation should be available at a mouse click.
Rectangles used in overview screen to designate functionally different plant components.	Major system components should be differentiated symbolically. This was a major omission in an otherwise good human-machine interface.

localisation of alarms to the relevant SCADA screen, could solve these problems.

A recent change to the system, universally appreciated by the operators, was the ability to inhibit nuisance alarms on the basis of criteria such as priority, type and physical location.

Opportunities for operator feedback It was reported that getting changes made to the system was overly restrictive. Particularly, there was no simple mechanism for capturing user feedback about system design.

Information Support Operators reported that the system generally met their information support needs. Criticism of the SCADA displays and navigation hierarchy was minor and largely piecemeal. However, operators stated that some aspects of general system function, particularly those pertaining to network security, required extensive workarounds, which increased the time required to perform routine tasks. For example, previously operators would insert trending information directly into Microsoft Excel and produce a report in approximately 15 minutes, but the introduction of strict network security protocols meant that a complicated data transfer procedure had to be followed, which often took over two hours.

Compliance with Best Practice In general, the system demonstrated better compliance to 2007 EEMUA best practice guidelines than the earlier described system analysed at the bulk water distribution facility. A senior operator/maintainer completed the SCADA design checklist and rated 21 of the 40 items as compliant. Minor departures included the items in Table 2.

DISCUSSION

SUMMARY OF MAIN FINDINGS

The key findings are that there is considerable room for improvement in human factor issues such as alarm handling and interface design. Consistent with the broader risk management philosophy in human factors, our research focus was on the anticipation of future system failures, rather than the retrospective analysis of failures. This complements the work of previous commentators (eg, Wu *et al.*) whose approach was concerned principally with the retrospective analysis of system failures.

At the water distribution control room, many avenues for improving system stability and reducing operator workload were found. The complex monitoring and communication role of the operator in this context requires extensive support from the supervisory control system, and this was found to be inadequate in several ways. Alarm flooding was common,

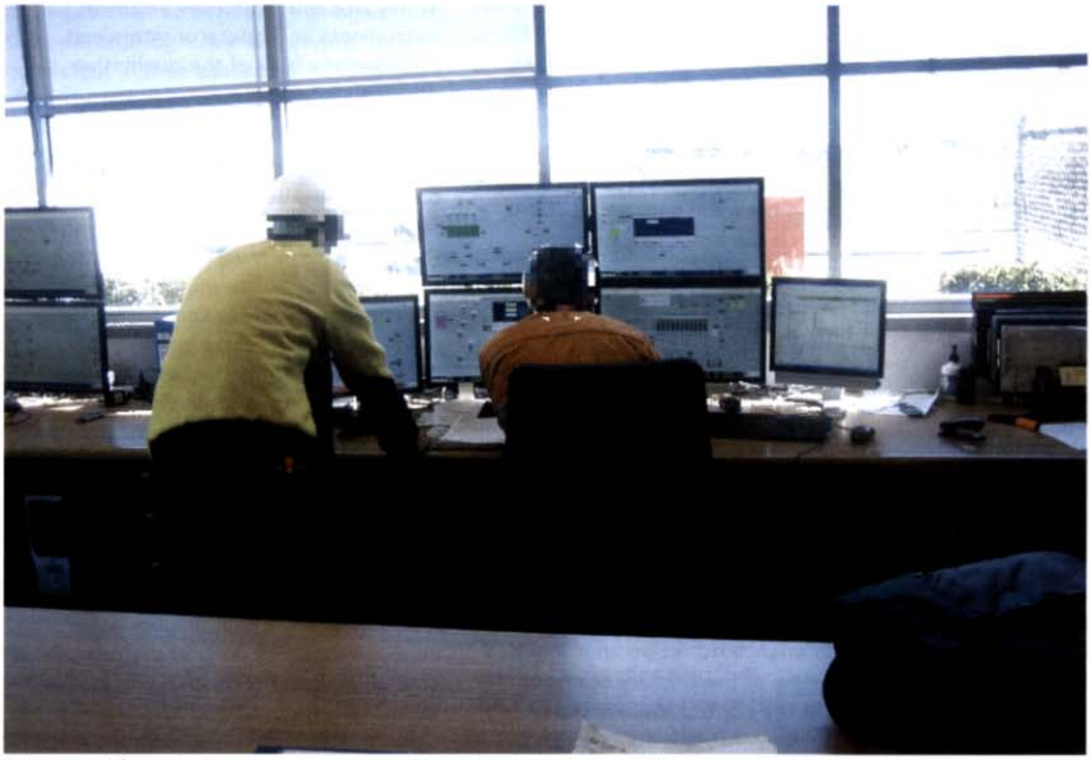

Figure 3. The primary operator console at the AWTP control room.

operator interfaces suffered from a lack of consistency and integration, and tasks were not appropriately delegated to human operators and system automation – for example, up to 50% of the operators' time was spent manually maintaining an inefficient and potentially disordered log. In no small part, the problems identified here were problems of inheritance owing to organisational change in the sector, and ongoing efforts were underway to improve both technical and human aspects of the system.

The AWTP control room, on the other hand, represented state-of-the-art process control. Being newly commissioned, it was a considerably better integrated control system. A sophisticated and highly consistent alarm management philosophy was in place, alarm flooding did not occur, and operator criticisms of the SCADA system were minor. However, the system fell short of the highest standards of industry best practice in regard to the lack of click-to-navigate functionality for alarms and the lack of online alarm documentation.

LINKS TO PREVIOUS RESEARCH

Similar applied research studies in other work domains have found comparable issues. Research using a similar human factors toolkit showed that control rooms in the minerals processing industry (Li et al., 2012) have a similar pattern of poor human technology integration. Portions of the operator experience questionnaire were developed for a cross-industry survey of alarm systems in the chemical and power generation industries (Bransby and Jenkinson, 1998). For the purposes of qualitative comparison it suggests that the operators' perceptions of the alarm systems, while variable, do not differ dramatically from those in the other industries. Given that the systems investigated in the previous survey represent the technology and management practices of 15 years ago, this is cause for some concern (Cloete et al., 2011).

FUTURE RESEARCH

Opportunities for data collection in this project were limited to routine control room operations. This was owing to the extreme logistical difficulty of gaining access to control room facilities during incidents and emergencies, not to mention the risks and attached ethical considerations. Exploration of human factor issues surrounding abnormal situations may have to assume a retrospective approach, and there is no shortage of examples where this approach has been successfully applied in other industries, notably in mining (Horberry and Cooke, 2010).

CONCLUSIONS: THE NEED FOR HUMAN-CENTRED DESIGN

The research presented here is an encouraging start towards a fuller understanding of the role of the human operator in the water sector, which should lead to improvements in efficiency and stability of system function. Further work here should follow a user-centred design and evaluation process. In this current research, discussions with control room operators and observations of work practices revealed several departures from this ideal, and one of the key messages emerging here is that operator expertise was an underutilised resource.

In a wide range of work contexts, the gap between end users and new technology is widening, which introduces problems that did not exist before the widespread introduction of technology (Vicente, 2004). It is only through the application of human-centred methods that technology and humans can be appropriately integrated in a work system.

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