Australian Water Recycling
Centre of Excellence

Project Report

Resilience of Advanced Water Treatment Plants for Potable Reuse

A report of a study funded by the
Australian Water Recycling Centre of Excellence

University of New South Wales, May 2015

Resilience of Advanced Water Treatment Plants for Potable Reuse

This report has been prepared as part of the National Demonstration, Education and Engagement Program (NDEEP). This Program has developed a suite of high quality, evidence-based information, tools and engagement strategies that can be used by the water industry throughout the stages of potable recycling, from early technical feasibility to design, construction and commissioning. Sub-stream 1.3 focused on determining the resilience of advanced water recycling systems by using Monte Carlo-based resilience modelling software. Equipment reliability data from Advanced Water Treatment (AWT) plants were used to model the performance of a reference plant over 10 years to provide insight into the nature of plant failures as well as strategies to reduce the incidence and duration of failure events. Results from the resilience modelling will be used in evidence-based materials to address stakeholder concerns on the practice of potable reuse.

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About the Australian Water Recycling Centre of Excellence

The mission of the Australian Water Recycling Centre of Excellence is to enhance management and use of water recycling through industry partnerships, build capacity and capability within the recycled water industry, and promote water recycling as a socially, environmentally and economically sustainable option for future water security.

The Australian Government has provided $20 million to the Centre through its National Urban Water and Desalination Plan to support applied research and development projects which meet water recycling challenges for Australia’s irrigation, urban development, food processing, heavy industry and water utility sectors. This funding has levered an additional $40 million investment from more than 80 private and public organisations, in Australia and overseas.

ISBN: 978-1-922202-34-5

Citation:

Tng, K.H., Currie, J., Roberts, C., Koh, S.H., Audley, M. and Leslie, G.L. (2015). *Resilience of Advanced Water Treatment Plants for Potable Reuse*, Australian Water Recycling Centre of Excellence, Brisbane, Australia.

Date of publication: May 2015

Publisher:
Australian Water Recycling Centre of Excellence
Level 5, 200 Creek St, Brisbane, Queensland 4000
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This report was funded by the Australian Water Recycling Centre of Excellence through the Australian Government's National Urban Water and Desalination Plan.

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1. EXECUTIVE SUMMARY

Scope	1. The National Demonstration Education and Engagement Program (NDEEP) was created to assemble evidence and materials to enable the broad community to view potable reuse as an acceptable practice to augment potable water supplies in Australia. 2. Sub-stream 1.3 of the NDEEP focused on investigating the resilience of Advance Water Treatment (AWT) plants using mathematical modelling techniques employed in petrochemical industries to predict the likelihood of equipment and instrument failures. A model was built using data from AWT plants operating in Australia and overseas and tested against scenarios informed by analysis of equipment and human failures in water treatment systems.
Use of this product	3. Outputs of this research may be used in the development of evidence-based materials for community stakeholders, particularly technical and medical professionals, with concerns on the performance of treatment processes used in potable reuse (PR) projects.
Stakeholder Concerns	4. Some prominent water industry and medical professionals have expressed concerns that health risks presented by potable reuse cannot be adequately addressed by treatment technologies. The concerns are based on the occurrence of outbreaks of water borne infections in communities in developed countries served by conventional drinking water systems. 5. Their perception is that treatment failures in these conventional systems are more likely in plants where equipment is not adequately maintained. 6. It is their position that potable reuse should be discouraged because of the high concentration of pathogens in the source water (compared to conventional systems) coupled with the lack of long term data on the reliability of AWT plants.
Aims & Objectives	7. The overall aim of this sub-stream is to assess the mechanical resilience of the AWT process. This is achieved by estimating the probability and consequence of equipment and instrument failures in AWT plants over an extended period of operation using numerical modelling techniques. The four objectives associated with this overall aim include: Objective 1. Collect data on equipment and instrument reliability from full scale AWT plants with multiple years of operation; and, develop an expandable database of standard reliability metrics for process mechanical and instrument assets used in AWT plants. Objective 2. Develop a mechanical resilience model for a large scale AWT plant using numerical methods employed in process industries with established procedures for managing critical

	equipment and instrument assets. Objective 3. Review and analyse data on incidents in conventional drinking water systems to determine the contribution of equipment failure, operator error, maintenance practices and scheme management to the occurrence of confirmed cases of water-borne disease outbreaks. Objective 4. Use the resilience model to predict the frequency and duration of failure events impacting plant production *capacity* or product water *quality* over a ten-year period, and; evaluate strategies to improve the resilience of the AWT plants, including the investment in additional redundant equipment and instrumentation and improvement in management/maintenance practices.
Lessons from Failures in Drinking Water Systems	8. Background information was collected on 60 documented cases involving confirmed pathogen outbreaks in public drinking water systems in developed countries between 2003 and 2013 (Case data was derived from the GIDEON Public Health Database; information on the drinking water system was derived from information in the public domain). 9. An alpha-numeric classification system was developed to categorise the failure events based on the cause (alpha) and the location (numeric) of the failure from catchment to tap (Figure 1). 10. Concurrent failures occurring at multiple locations were the main cause behind pathogen outbreaks in drinking water systems in the developed world (Figures 4 & 5). 11. Only 8% of recorded incidents in conventional drinking water systems were attributable exclusively to equipment failure. The majority of pathogen outbreaks were caused by the plant operating outside the design capacity/capability and poor management practices during unexpected conditions such as storm or other events in the catchment. Under these conditions the systems continued to deliver water that resulted in public exposure to water-borne pathogens. 12. The analysis teaches that it is important to model the effects of multiple, simultaneous failures in treatment systems and to delineate between failure events that impact both production capacity and product quality over extended periods of operation covering normal and unexpected conditions.
Equipment Reliability Database	13. An Equipment Reliability Database for AWT plants was developed using design documentation and maintenance records for seven large scale (>10 MLD) AWT plants located in Australia, Asia and the United States with a cumulative operating history of 64 years (Figure 6). Participating water utilities provided 691 Piping and Instrumentation Diagrams (P&ID's) and 9,566 maintenance records (Figure 7 & Table 3). Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) data was consolidated in an asset register for 139 critical components used in a typical dual membrane/advanced oxidation treatment plant (Table 4).

Resilience Modelling	14. Resilience is defined as a system's ability to maintain routine function under normal and unexpected circumstances. Resilience Modelling using numerical techniques has been used in the oil and gas industries to model system availability over a range of conditions involving multiple failures in complex systems, and to assess equipment and instrument redundancy and criticality. These resilience models provide insight into long-term performance, the benefits of additional capital equipment (redundancy), and the impact of improved maintenance response times. 15. A P&ID was developed for an AWT plant based on dual membrane filtration and advanced oxidation (Figure 9). The resilience of this hypothetical Reference Plant was modelled using data for the 139 separate equipment items listed in the reliability asset register (Figure 8). 16. A resilience model developed by DNVL Ltd (UK) using OPTAGON software (Figure 10) was used to undertake Monte Carlo simulation of system failure events that could impact plant treatment *capacity* or *quality* over a ten-year period (87,600 hours). The resilience model was also used to investigate strategies, such as increasing equipment redundancy or improving maintenance response times. 17. The resilience model included a capacity component to estimate plant production availability, (expressed as percent time on-line at design capacity) and operational availability (expressed as the percent time on-line at full capacity). A quality component was used to quantify: the incidence (number) and duration (hours) of failures that impact loss of process control (Category 1); failure of non-critical instruments (Category 2); failure of critical control points (Category 3); and loss of product quality (Category 4) (Table 5).
Production Capacity Resilience Model	18. The production availability of the Reference Plant was 76%. That means the plant was capable of meeting target production capacity requirements for 66,600 out of 87,600 hours in its ten-year operational lifespan. 19. The operational availability was 41%, indicating the plant was able to operate at full design capacity, with availability of all redundancies, for 35,900 hours. 20. The highest proportion (61%) of equipment failures that impacted production and operational availability were associated with product water delivery pumps (PU5), followed by chemical dosing pumps (12%), reverse osmosis feed pumps (8%) and membrane cleaning systems (5%). (Figure 11a). 21. The predicted shortfalls in production capacity were comparable to historical plant data, including RO system production availability, for an indirect potable reuse (IPR) plant for the period 1984 to 1996 (Figure 11b). Maintenance records for this plant were not used in the development of the resilience model. Unlike drinking water treatment plants, IPR plants produce water that is used to augment raw water supplies. A higher demand is placed on these plants in times of drought compared with wetter years. Consequently, production capacity for IPR AWT plants is subject to

	discretionary operation procedures that under some circumstances (eg. wet years) will extend maintenance response times. 22. For DPR schemes, more efficient maintenance strategies and additional redundancies for shortfall contributors would decrease production capacity shortfalls experienced by the AWT plant.
Product Quality Resilience Model	23. The quality model estimated that the AWT plant would experience 427 failure events over 10 years. The majority (95%) of these failure events involved non-critical equipment (Category 1) and instruments and did not have an adverse effect on final product water quality (Category 2) (Figure 12). 24. The quality modelling shows that the traditional approach of having multiple redundancies is relatively ineffective in improving a plant's resilience from a product water quality perspective. 25. Implementation of more efficient maintenance protocols decreased the number of failure events by 58% and had an 88% decrease in total failure duration. 26. Environmental buffers were effective in improving product quality resilience of the AWT plant and preventing the discharge of non-compliant water. A sensitivity analysis indicated that a 12-hour treated water storage buffer time reduced the number of failure events by 21% and their associated failure duration by 19%. 27. Minor improvements to the plant's resilience was observed when the buffer time was increased past 12 hours, however, such measures would be more capital intensive and have greater land requirements and therefore, the cost would most probably outweigh its benefits.
Findings and Recommendations	28. Results were reviewed by an industry panel convened by the Australian Water Recycling Centre of Excellence. The consensus was the data was consistent with experiences from operating IPR projects and reflected the anecdotal data that when AWT plants fail they do so on capacity and not on water quality for the majority of the plant's operational lifespan. 29. Findings show that AWT plants are mechanically resilient and allow for recycled water to be a potential source of potable water. 30. Results from this study would indicate that the best approach to improving a plant's resilience is not by having multiple redundancies, but rather, via implementing more efficient maintenance protocols with an adequate amount of treated water storage. The results indicated there is scope for reducing capital costs through value engineering and review of criteria for redundant equipment. The results also suggest that the amount of buffer storage capacity should be carefully evaluated in direct potable reuse schemes. 31. The database used in this study only covers 64 years of cumulative plant operation. Comparable databases in the oil and gas sector cover 50,000 to 100,000 years of cumulative plant operation.

	Consequently, the water industry is encouraged to contribute to the expansion of the database to create an industry resource for AWT plant designers, operators and maintenance managers.
What is the Take Home Message?	32. Equipment and instruments used in Advanced Water Treatment plants are expected to fail over multiple years of operation. This study used numerical modelling techniques, informed by data taken from seven AWT plants, to simulate failure events that potentially impact water production and/or water quality over a 10-year period. The resilience model indicated that AWT plant events that lead to failures in production capacity are eight times more likely than failures that potentially could impact product quality. Moreover, the probability of equipment or instrument failure that could impact water quality can be reduced to less than one event per year through more efficient maintenance strategies. In practice, however, under the Australian Guidelines for Recycled Water, operators of potable reuse schemes are required to implement plans and procedures that use multiple continuous on-line monitoring points that interrupt water production in the event that water at any critical control point in the process drifts outside tolerable limits. Consequently, although the probability of a failure event is low (less than once per year), systems and procedures are in place to prevent the failure event leading to the production and distribution of water that does not meet quality requirements beyond the boundaries of the AWT plant.

FREQUENTLY ASKED QUESTIONS (FAQ)

1. What does failure mean?

In this study, failure is defined as an event that leads to a critical outage to throughput and/or quality of process equipment. It does NOT imply that the event would result in a non-compliant incident where pathogens are released into the drinking water system.

2. What is meant by the probability of a failure event?

The probability of a failure event is the likelihood of an occurrence that could result in a failure of an item of process equipment.

3. What is resilience modelling?

Resilience modelling is a technique that can be used to quantify and predict equipment failure. Mitigation strategies can then be developed and tested to improve the overall resilience of the Advanced Water Treatment plant.

4. How is resilience modelling different to HACCP?

Resilience modelling takes into account both quality and quantity failures. These aspects are critical factors for AWT plants that reclaim water for augmentation of drinking water sources through Indirect Potable Reuse (IPR) and Direct Potable Reuse (DPR) schemes. These schemes place a high emphasis on both quality and quantity which is unlike HACCP techniques that are focused only on the quality of the product water.

5. How was the model built?

A model, “Reference Plant” was developed to simulate a typical large-scale AWT plant (>10 MLD). Equipment reliability data from source plants were mapped to an asset register of the model plant before being configured into a Reliability Block Diagram (RBD) in the OPTAGON software. The model is a complex system that comprises a combination of 139 advanced water treatment assets, with each component being critical to either production capacity and/or quality of the product water. The OPTAGON resilience model consisted of two separate models; a “Capacity” model that analysed the throughput of the plant and a “Quality” model that assessed the number and duration of the failure events experienced by the plant in a span of 10 operational years.

6. What was the source of the data?

The data was collected from seven AWT plants used in high quality reuse including IPR, with a total of 64 years of cumulative operating history. The adopted approach collected historical flow data, equipment failure rates, Piping and Instrumentation Diagrams (P&IDs) and Operation and Maintenance (O&M) records from the seven source AWT plants and used them as input variables to the resilience model. A total of 691 P&ID drawings and 9,566 maintenance records were analysed and quantitative information on the Mean Time Between Failure (MTBF) and the Mean Time To Repair (MTTR) values were established for the critical components of the Reference Plant.

7. How were the sensitivity scenarios developed?

Based on the preliminary results obtained from the resilience model, five sensitivity scenarios were subsequently developed around the most critical processes identified by the model. This allowed for further interrogation of the results and the efficacy of the suggested strategies. The scenarios tested ranged from the traditional approach of adding extra redundancy for critical equipment to improving maintenance response times via implementation of better asset management strategies.

2. INTRODUCTION AND APPROACH

Key Points:

- The likelihood of equipment and instrument failures in Advance Water Treatment (AWT) plants was assessed using mathematical modelling techniques.
- Results are presented in the context of failures in conventional drinking water systems as well as the procedures in the Australian Guidelines for Water Recycling.

2.1 CONTEXT FOR RESILIENCE MODELLING

The National Demonstration Education and Engagement Program (NDEEP) was created to assemble evidence and materials to enable the community to view potable reuse as an acceptable practice to augment potable water supplies in Australia. Sub-stream 1.3 of the NDEEP focused on investigating the resilience of the Advance Water Treatment (AWT) plants using mathematical modelling techniques employed in petrochemical industries to predict the likelihood of equipment and instrument failures.

The motivation for Sub-stream 1.3 was to assemble quantitative information on the possibility of failure of the treatment process and the consequence of this failure on product water supply and quality. The information from Sub-stream 1.3 could be used by proponents of potable reuse schemes to respond to concerns from some water industry and medical professionals on the possibility of the spread of pathogens through the drinking water supply as a result of treatment plant failure. These concerns were founded on examples where communities in developed countries experienced incidents of pathogen infections due to failures in conventional drinking water systems.

Components of Sub-stream 1.3 included a review of confirmed cases of pathogen infections resulting from system failures in conventional drinking water systems in developed countries for the period 2003 to 2013. The objective was to establish the extent to which equipment failure was a factor in the pathogen outbreak events compared to deficiencies in system design, water system management and plant operational and maintenance practices. The data collected compliments previous work on drinking water system failure published in 2003 by Hrudey and Hrudey.

The work used numerical modelling techniques adopted by the oil and gas industries to manage equipment assets and predict equipment failure. This involved the collection and curation of a database on equipment and instrument failures in operating AWT facilities producing water for either potable or industrial reuse requiring water quality that exceeds potable standards. Results from the study are placed in the context of the procedures described in the Australian Guidelines for Water Recycling (AGWR) (Phase 2) that guide the management of water quality risks in potable reuse schemes including the use of Hazard Analysis and Critical Control Points (HACCP).

2.1.1 Industry Concerns & Knowledge Gaps

Key Points:

- Some water professionals and medical practitioners have concerns that pathogen breakthrough in potable reuse schemes will undermine public health systems designed to segregate wastewater and drinking water.
- These concerns are based on outbreaks of water-borne illness in conventional drinking water systems where the risk of infection is perceived to be amplified by equipment failure due to poor maintenance. The high concentration of pathogens in the source water for AWT plants, coupled with a lack of long-term data from operating plants, reinforces their position that potable reuse should be discouraged.

2.1.1.1 Perception on Process and Equipment Risk in Potable Reuse

Some elements of the Australian water industry and medical community have concerns that the development of potable reuse schemes will undermine long-standing practices to protect public health through the segregation of wastewater and drinking water supplies. Moreover, international and local experience teaches us that pathogen exposure in drinking water systems is not confined to developing countries and occurs in Europe, the United States and Australia. Failures in drinking water systems have resulted in widespread infections (Milwaukee, USA) and death (Walkerton, Canada). In these cases, the provision of adequate treatment was not sufficient to prevent exposure to pathogens. Equipment failure, poor operational or maintenance procedures or, in some cases, negligent behaviour are possible causes and undermine the efficacy of the best designed filtration and disinfection processes.

Extrapolating these experiences and observations to the planned use of recycled water to augment drinking water supplies is perceived by some as an unacceptable risk and should be discouraged. Emphasis on the high level of treatment provided in AWT plants to remove pathogens, organics and salts before the wastewater is blended with surface water impoundments or recharged into aquifers does not provide satisfactory evidence that the risk of pathogen exposure through the drinking water has been mitigated. The argument for a cautious approach to potable reuse is reinforced by the high concentration of pathogens in the source water for AWT plants, coupled with a lack of long-term data from operating plants.

Collecting and quantifying information on the probability and consequence of failure in AWT plants is the first step in assembling evidence that can be compared with data on the risk (probability and consequence) of failures in conventional drinking water systems. Water utilities that produce recycled water for supply augmentation of drinking water systems or potable water substitution for industrial systems have data on pathogen and chemical removal across AWT schemes. However, this data has limited utility for assessing the likelihood of failure and if the failure impacts water supply or water quality, with the later having the potential to result in an increased risk of exposure through the drinking water system. Consequently, an alternative approach was required to assess risks associated with the failure of equipment and instruments used in AWT plants as part of a potable reuse scheme.

2.1.1.2 Knowledge Gaps on AWT Plant Performance

The technical literature on AWT processes and the performance of potable reuse schemes contains data on final water quality and removal efficiency of the treatment processes for a range of contaminants. However, there is little information on how the AWT systems fail.

Failure events can be defined in terms of both failure to meet treatment quality objectives and failure to meet treatment capacity objectives. For example, many AWT plants rely on pressure driven separation processes such as membrane filtration and reverse osmosis followed by UV disinfection and chlorination. If a chlorine dosing pump prior to distribution fails, the AWT plant will fail to meet the treatment quality objectives for correct chlorine residual in the final product water. Similarly, if a UV lamp fails in a UV disinfection reactor, the treatment system will not provide the necessary log reduction removal for viruses. However, in each case, it is possible for the plant to continue to meet the treatment capacity objective because the failure of the dosing pump or UV lamp does not impact the hydraulic capacity of the process. However, if a mechanical device such as a backwash valve, pump, bearing or other component of a membrane process fails, it may not be possible to continue to produce water because plant production is dependent on pressure to move water across the membranes and between the unit processes in the AWT plant. Consequently, the nature of the failure event will determine if there is a risk to treatment capacity or quality or both. In the absence of published data on the nature of failure in AWT plants, it is difficult to provide objective evidence on this aspect of the risk posed by the implementation of potable reuse schemes.

The water industry, like the petrochemical, airline and food processing industries, performs failure analysis as part of routine asset management. The asset management procedures involve the development of an asset register and the collection and analysis of a suite of data for each component describing the availability (operational time) and the maintenance requirements. The same procedure can be adapted to the equipment and instruments used in an AWT plant.

The information required to assess the probability and nature of failures in AWT plants includes:

- Historical Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for AWT plant equipment and instruments;
- Classification of asset criticality based on the number of duty and stand-by components;
- Estimates for the operational availability (A_o) of the equipment and instruments based on criticality, MTBF and MTTR; and
- Assessment of impact of availability on treatment capacity, quality or both.

In other industries, such as the airline and petrochemical industries, data sets for MTBF and MTTR would have been collected for hundreds of plants with decades of operation time corresponding to thousands of years of cumulative data. For AWT plants, the lack of this information prevents a detailed quantitative analysis of the probability and consequence of equipment and instrument failure in potable reuse schemes.

2.1.1.3 AGWR Risk Management Framework and Role of HACCP

The Australian Guidelines for Water Recycling (AGWR) (Phase 2) cover the use of recycled water for the augmentation of drinking water supplies. The AGWR risk management framework is very comprehensive and defines the practices and procedures necessary to manage the risks associated with the use of recycled water to augment drinking water supplies. Under the AGWR, potable reuse scheme operators are required to implement a Recycled Water Management Plan (RWMP). One element of the RWMP is the use of Hazard Analysis and Critical Control Points (HACCP) techniques to continuously monitor the performance, particularly the reduction in concentration in pathogens at different barriers in the AWT plant. HACCP was adapted from the food industry to manage product quality and provides a system that shifts the emphasis for quality and safety from endpoint product testing to continuous monitoring at every step of the treatment process.

HACCP uses on-line instrumentation to monitor key parameters at different stages of the AWT process. A Supervisory Control and Data Acquisition (SCADA) system is programmed to implement corrective action, including plant shut-down, should the values recorded at any critical control point drift outside a range (critical limits) for acceptable operation. The purpose of HACCP is to prevent the types of events that could result in the movement of microbial pathogens from the source water through to the final product water. To this end, the use of a HACCP process, rather than a detailed understanding of the probability and consequence of equipment or instrument failure, addresses the concerns identified in Section 2.1.1.1. The purpose of using numerical techniques to model the probability and consequence of asset failure is not to critique or improve on the HACCP process. The motivation for this study is to generate information on the types of failures in equipment and instruments that are likely to occur and assess if these failures potentially result in reduced treatment capacity or compromise quality. In the event that the failure would compromise quality, the implementation of HACPP methods would result in corrective action that prevents the distribution of water that does not comply with the water quality requirements.

2.1.1.4 Role of AWT Plants in Potable Reuse Schemes

A potable reuse scheme uses multiple barriers to prevent the biological and chemical contaminants present in the municipal wastewater from moving into the drinking water supply. Multiple barriers in an Indirect Potable Reuse (IPR) scheme consist of: a source control or tradewaste program to limit the discharge of hazardous chemicals into municipal wastewater; a wastewater treatment plant that treats the water to a standard suitable for discharge to the environment; an AWT plant that provides additional treatment that allows the water to be returned to a reservoir or aquifer; and a conventional water treatment plant that produces the drinking water reticulated through a distribution system. An AWT plant also consists of multiple barriers for the removal of biological and chemical contaminants, which can include filtration, membrane separation, oxidation, adsorption, ultraviolet irradiation and chlorination. Every barrier in the potable reuse process, including the multiple barriers within an AWT plant, is managed using the procedures defined in the Recycled Water Quality Management Plan (RWQMP). Again, the implementation and regular review of the RWQMP, rather than a detailed understanding of the probability and consequence of equipment or instrument failure in the AWT, is the process that protects public health and addresses the concerns associated with the use of recycled water to augment drinking water supplies.

2.2 SCOPE AND LIMITATION OF CURRENT MODELLING STUDY

2.2.1 Guidance on Interpretation of Modelling Results

The standard reliability engineering terminology and nomenclature are used extensively throughout this study; however, given the scope of this report, some terms do deviate from the standard definitions. Therefore, the terms and nomenclature used in this report are listed in the table below.

2.2.1.1 Nomenclature and Terminology

Terms	Definitions
Production Availability	The proportion of time that a plant is meeting the required demand.
Operational Availability	The proportion of time that a plant is at its maximum throughput.
Failure Event	Failure is defined as an event that leads to a critical outage to throughput and/or quality process equipment. It does NOT imply that the failure event would result in a non-compliant incident where pathogens are released into the drinking water system.
Failure Duration	Duration of plant equipment unavailability due to the failure event.
Mean Time Between Failure (MTBF)	The average elapsed time between recorded failures. Equipment taken off-line for servicing are not considered within the definition of failure.
Mean Time To Repair (MTTR)	The average duration required to repair failed equipment and return it back into service.
Logistic Delays	Downtime due to logistical interruptions during the repair or replacement of equipment.
Deferred Effect Time	Time required for the effects of the failure event to occur. In water recycling schemes, a buffer storage system is created to verify product water quality prior to direct or indirect distribution. Therefore, a larger Deferred Effect Time would translate into a greater buffer capacity and a reduced likelihood of plant failure.
Critical Number	Number of units that have to be unavailable for a process to fail. For an example, the product water pumps are in a 4x33% configuration (3 duty, 1 standby) and process throughput would be affected if 2 or more pumps failed, therefore, a critical number of 2 would be assigned for this process equipment.

2.3 AIMS AND OBJECTIVES

The overall aim of this project was to assess the probability and consequence of equipment and instrument failures in AWT plants using resilience modelling techniques employed in petrochemical industries. The four objectives associated with this overall aim included:

Database Development

The first objective was to collect data on equipment and instrument reliability from full-scale IPR AWT plants with multiple years of operation and to develop an expandable database of standard reliability metrics for process mechanical and instrument assets used in AWT plants.

Development of Resilience Model

The second objective was to develop a mechanical resilience model for a large-scale AWT plant using numerical methods employed by process industries with established procedures for managing critical equipment and instrument assets. The resilience model was populated with data sourced from existing AWT plants. The model was used to identify the frequency and duration of failure events impacting plant production *capacity* or product water *quality* or both.

Lessons Learnt from Documented Failures

The third objective was to review and analyse data on the incidents in conventional drinking water systems to determine the contribution that management practices, operator error, equipment failures and maintenance practices contributed to water borne disease outbreaks.

Evaluation of Strategies to Improve Asset/Equipment Resilience

The final objective was to use the resilience model to predict the frequency and duration of failure events impacting plant production capacity and product water quality over a ten-year period. Sensitivity analysis was used to evaluate strategies to improve the resilience of AWT plants, including the investment in additional redundant equipment and instrumentation and improvement in management/maintenance practices. Special considerations appropriate for Direct Potable Reuse (DPR) applications based on product water storage capacity were also considered.

2.4 ADOPTION OF ANALYTICAL METHODS USED BY OTHER INDUSTRIES

Resilience is defined as a system's ability to maintain routine function even under unexpected circumstances, therefore, it is an essential factor to ensure that an advanced water treatment plant has continuous process throughput whilst remaining compliant with strict treated water quality standards.

Although resilience modelling tools have been widely used in the petrochemical, oil and gas, and aviation industries to model process reliability and safety, there has been no standard resilience modelling method developed for the water treatment industry. Techniques developed for the oil and gas industry to assess equipment and instrument redundancy and criticality have been used to model system availability over a range of conditions involving multiple failures in complex systems. These resilience models provide insight into long-term performance and allocation of addition capital equipment (redundancy) and the impact of improved maintenance response times.

Therefore, in order to accurately simulate and predict a plant's resilience, this study utilised DNVGL's Monte Carlo-based Reliability, Availability and Maintainability (RAM) simulation software, OPTAGON, to determine and quantify the resilience of a representative Reference Plant. OPTAGON has been tried, tested and proven in the oil and gas industry over the last 15 years, and is capable of assessing process equipment availability, criticality and the plant's overall resilience.

The proposed approach also used actual reliability data for all process equipment and instruments collected from seven AWT source plants to establish a complete asset register of both conventional and advanced water treatment processes. Thus, this approach is unlike previous reliability studies of water and wastewater systems that only employed manufacturer-provided failure rates and simulated plant performance under a range of conditions by applying statistical methods.

3. FAILURES IN DRINKING WATER SYSTEMS IN DEVELOPED COUNTRIES

Key Points

- In the developed world, 60 documented cases of pathogenic outbreaks in drinking water systems were recorded in the Global Infectious Disease and Epidemiology Network (GIDEON) database from 2003 to 2013.
- An alpha-numeric classification system was developed to categorise types of failures in drinking water systems.
- The most common type of failure was one that stemmed from the distribution system with a combination of inadequate management framework, poor infrastructure design and failure in human operation.
- Further analysis concluded that it is important to model the effects of multiple, simultaneous failures as well as to understand failures that impact both production capacity and product quality.

In order to study the consequences of failures in AWT systems, failure occurrences in drinking water systems in developed countries were reviewed. Drinking water system failures and their public health impacts were investigated to develop an interrelation between the type of failure and the outbreak of disease. These incidents were sourced from the Global Infectious Disease and Epidemiology Network (GIDEON) database which records the occurrence of outbreaks worldwide.

The incidents recorded in the GIDEON database were classified using aspects of the Australian Drinking Water Guidelines (ADWG) to determine possible failure points. Five possible failure points (1-5) from raw water catchment to tap (Table 1) were determined in combination with the type of failure (assigned an alphabet code, A-E) (Table 2) to yield an alpha-numeric coding system to categorise these drinking water failure events.

Table 1: Failure Point Numbering System

Number	Represents
1	Catchment management and source water protection failure
2	Extraction from water source failure
3	Treatment system failure
4	Disinfection system failure
5	Distribution system failure

Table 2: Failure Alphabet Classification System

Letter	Represents
A	Denotes a failure in the upper management framework. This concerns operational and maintenance procedures and risk mitigation and assessment.
B	Denotes that the cause of the failure was due to a breakage of equipment.
C	Denotes that the failure occurred due to a poor engineering design and that the system would not suitably treat the capacity or quality of the raw water coming into the plant.
D	Denotes a failure in a system that was due to poor maintenance and monitoring of the plant.
E	Denotes an operational failure that involves a team without appropriate knowledge and expertise, resulting in human error.

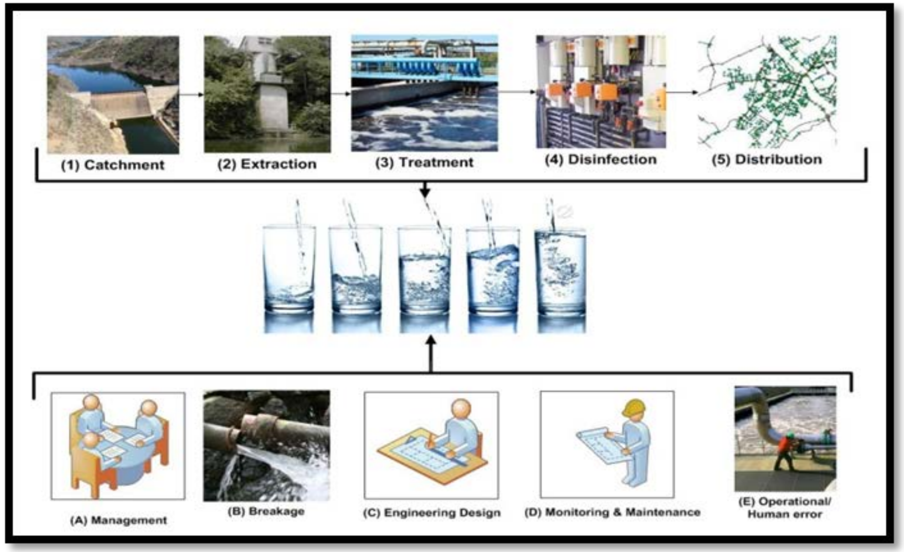


Figure 1: Alpha-numeric Coding System for Failure Events

According to the GIDEON database, 2,500 laboratory-confirmed pathogen outbreaks were catalogued and reported in the developed world from 2003 to 2013. Of all the confirmed cases, only 60 cases were able to provide well-documented information regarding the failure modes resulting in the subsequent pathogen outbreaks.

Using the alpha-numeric classification system (Figure 1), failure events were categorised according to location and the cause of the failure. For example, a failure that led to an outbreak during raw water extraction due to a combination of equipment failure, poor engineering design and inadequate maintenance would be classified as a “2BCD” failure (Figure 2).

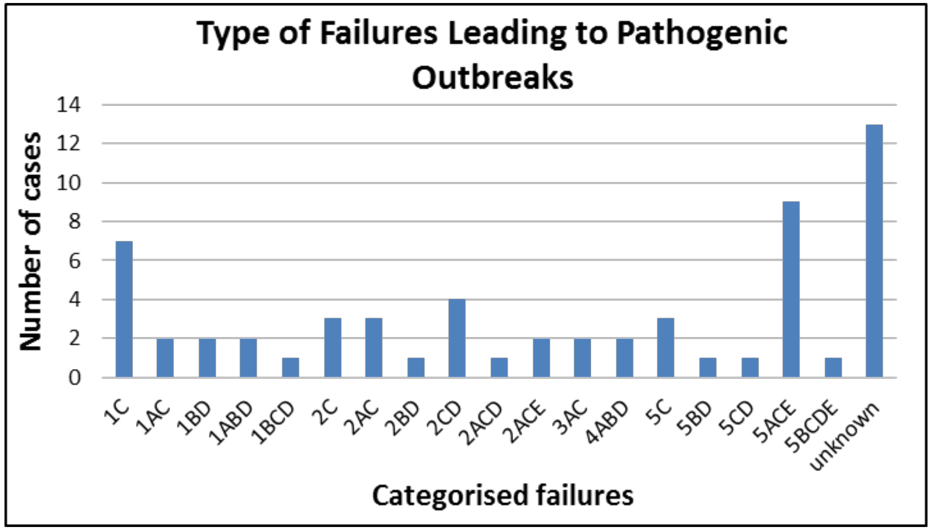


Figure 2: Categorised Failures that Led to Pathogen Outbreaks

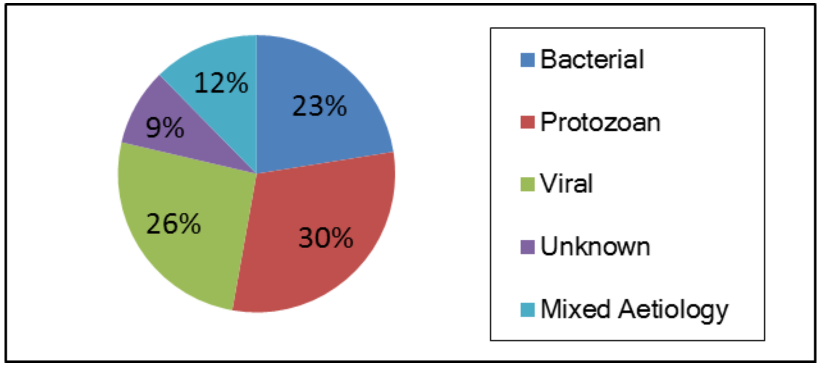


Figure 3: Type of Pathogens Detected in Outbreaks

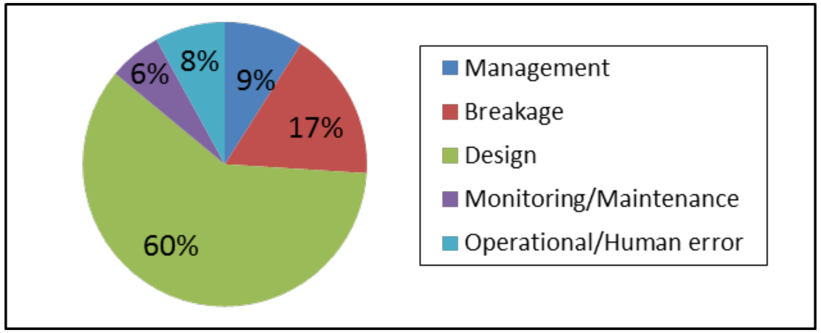


Figure 4: Recorded Causes of Failures

From Figure 2, the most common type of failure was 5ACE (15%), which involved a failure that stemmed from the distribution system with a combination of inadequate management practices, poor infrastructure design and failure in human operation. The second most prominent case (11%) was a 1C failure that involved a failure in the raw water catchment area in combination with an engineering design failure. Only 8% of recorded incidents in conventional drinking water systems were attributable exclusively to equipment failure. Further analysis concluded that the majority of the pathogen outbreaks were protozoan and viral (Figure 3), with the most common cause of failure due to an inadequate process design (Figure 4).

To determine the magnitude of the outbreak relative to the number of barriers that failed, the number of laboratory confirmed cases for a given outbreak was compared. The mean value of the confirmed cases was taken relative to how many barrier failures were observed.

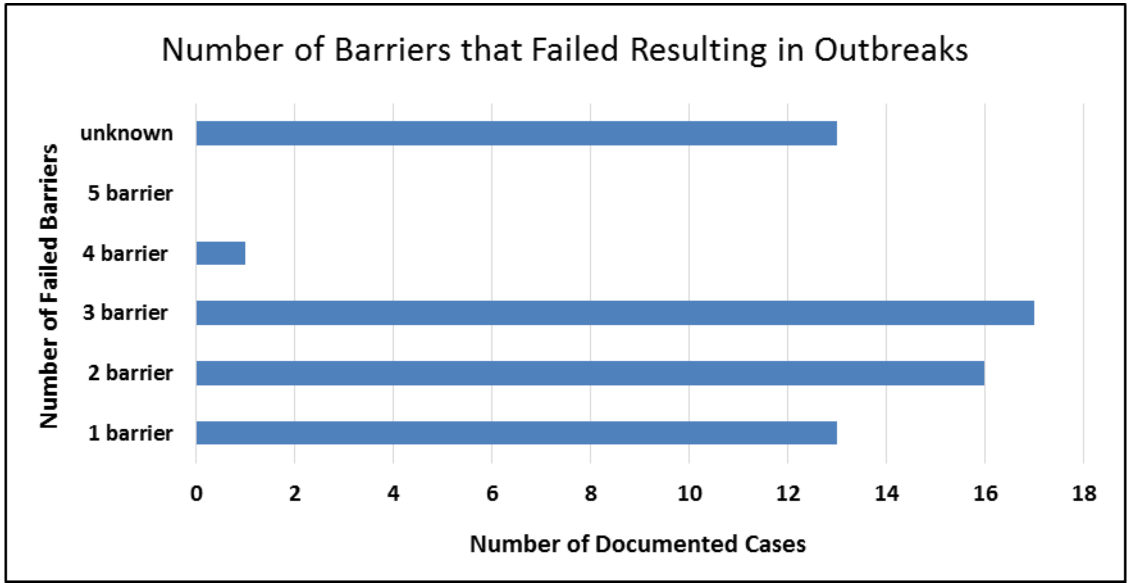


Figure 5: Documented Cases of Multi-barrier System Failures

Figure 5 shows the documented cases of failures in multi-barrier systems that led to an outbreak. The majority of the failures occurred in 1, 2 and 3 barrier systems with most common being a 3-barrier failure.

These failure modes due to poor asset management and inadequate process design highlight the need and importance of resilience modelling in the water industry. The traditional method of resilience analysis uses manufacturer's warranty and vendor data which is not representative of the actual process equipment or instrument's reliability and performance, thus, introduces uncertainty and subsequently adds to the complexity of resilience modelling in the water industry.

4. RESILIENCE MODELLING

Key Points:

- Data collection from seven AWT plants worldwide with a total of 64 cumulative years of historical reliability data.
- A Reference Plant model was developed to simulate the resilience of a typical large scale (>10MLD) AWT plant.
- Model results were expressed in terms of plant availability and were informed by using historical reliability data for system components including Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR).
- The Reference Plant model was separated into two distinct models to investigate the effects of equipment failures on the plant's production capacity (throughput) and product water quality metrics based on collected historical data.

4.1 SOURCE DATA COLLECTION

The adopted approach collected historical flow data, equipment failure rates, Piping and Instrumentation Diagrams (P&IDs) and Operation and Maintenance (O&M) records from seven source AWT plants, with a total of 64 years of cumulative operating history, and used them as input variables to the resilience model.

Figure 6: Source AWT Plants

Data Element	Element Description	Source Documentation
Process configuration/Design	Overall process design diagram/information of plant.	Engineering drawings and operational documents (P&ID, PFD, O&M Manua
Equipment name	The common name for the equipment set.	Asset Register, equipment data sheets, Engineering drawings.
Equipment ID	The unique identifier for the equipment.	Asset Register, equipment data sheets, Engineering drawings.
Number of duty and spares	Number and operating mode of the equipment set.	Operational documents, O&M Manuals, layout drawings.
Equipment Design Capacity	Design capacity of the equipment in terms of primary flow.	Equipment data sheets, Historic flow monitoring data (avg), and PFDs.
Mean Time Between Failure (MTBF)	Mean Time Between Fail (MTBF) for each failure mode.	Equipment failure rates, site maintenance records from CMMS.
Mean Time To Repair (MTTR)	Mean Time To Repair (MTTR) for each failure mode.	Site maintenance records from CMMS, O&M Manuals.
Maintenance Frequency	Number of planned maintenance activities per year.	O&M Manuals.

Figure 7: Types of Data Collected from Source AWT Plants

Table 3: Operational Features of Source AWT Plants

	Treatment Capacity (MLD)	Reuse Purpose	Operating Years	Assets Mapped to Model	Maintenance Records Analysed
Plant 1	9	Industrial	8	62	1,168
Plant 2	16	Industrial	11	128	836
Plant 3	45	Industrial	9	55	203
Plant 4	64	Industrial/IPR	11	59	-*
Plant 5	68	Industrial/IPR	11	56	-*
Plant 6	70	Industrial/IPR	7	58	2,625
Plant 7	278	IPR	7	280	4,734

* Utility did not release maintenance records

The P&IDs and O&M records were collected and consolidated into a reliability database. An asset register listing the main components of the treatment process was then developed for each plant based on information obtained from the P&IDs. Individual plant asset registers were populated with reliability information of individual components based on data obtained from the plant's maintenance records. Table 4 shows an example of how each source plant's data inputs were organised into an asset register before being mapped to the corresponding process equipment of the Reference Plant.

The maintenance records were analysed and converted into quantitative information on Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) to establish the reliability of the components in the treatment process. The MTBF and MTTR data were then entered into the asset register to create a database of cumulative reliability data of individual components from the seven operating plants.

Table 4: Example of a Source Plant's Asset Register

Equipment Tag ID	Equipment Name	Config.	Failure Description	MTBF (hrs)	MTTR (hrs)	Logistic Delays (hrs)	Impact on Quality		Impacts on Throughput
							Deferred Time (hrs)	Critical Number	
PU1	Feed Water Pumps	4x33%	Throughput	238	64	12	N/A	2	As per config.
ME3	RO Membrane	12x11%	Quality	4231	136	12	Immediate	2	As per config.
L1	Chemical Dosing Pump	2x100%	Quality	782	28	12	24	1	As per config.

4.2 REFERENCE PLANT MODEL

A process flow diagram was developed for an AWT Reference Plant based on dual membrane filtration with advanced oxidation (Figure 9) and a model was developed to simulate and determine the resilience of the plant when faced with typical failure events experienced by large scale (>10 MLD) AWT plants. The reliability database established from the source plants was mapped to the asset register of the Reference Plant and used as input variables for the resilience model. Figure 8 shows an example of how equipment from each source plant was mapped to the reference plant's asset register. The full asset register for the Reference Plant can be found in Appendix A.

Through OPTAGON, the Reference Plant was configured into a Reliability Block Diagram (RBD), with each block representing a corresponding asset in the model plant (Figure 10). The model is a complex system that comprises a combination of 139 conventional and advanced water treatment assets, with each component being critical to either production capacity (throughput) and/or quality of the product water.

REFERENCE PLANT (100 MLD)						SOURCE RECYCLING PLANT 1													
Master Equipment						Master Equipment			Operating Mode					Equipment Capacity, ea	Total Capacity	Unit	Critical No.	Data source	Additional comments
CCI	Equipment Name	Equipment ID	Process Descriptio	N + R	Flow Sequen	Equipment Name	Equipment ID	Functional Location	Duty No. (N)	Standby No. (R)	Assis t N	Spare No	Boxed Spare						
	WWTP Effluent Storage Tank	TA1	Main Process	N+1 or N/2	a01	NA	NA	NA	0	0	0	0	0						
	WWTP Effluent Water forwarding pumps	PU1	Main Process	N+1	a02	Feed Water Pumps	PU03001, PU03002, PU03003 PU03004	s1003425, s1003428, s1003431, s1003434,	3	1				170	510	L/s			Max = 170 L/s @ 18 m
#	Water Quality 1_Turb	WQ1_Turb	Main Process		a03	Sample Panel #1 (Raw Water)_Turbidity Analyser	AE04005	s1003452	1	0									
#	Water Quality 1_pH	WQ1_pH	Main Process		a03	Sample Panel #1 (Raw Water)_pH Analyser	AE04001	s1003453	1	0									
#	Water Quality 1_Temp	WQ1_Temp	Main Process		a03	NA	NA	NA	0	0	0	0	0						
#	Water Quality 1_Cond	WQ1_Cond	Main Process		a03	Sample Panel #1 (Raw Water)_Conductivity Analyser	AE04002	s1003454	1	0									
	Water Quality 1_User defined	WQ1_?	Main Process		a03	Sample Panel #1 (Raw Water)_Ammonia Analyser	AE04003	s1003351	1	0									
	Flow Instrument 1	FI01	Main Process		a04	Magflow_Pump Station Outlet	FE04006	s1003442	1	0									
	Ammonium Sulphate Dosing Point	A1	Chloramine Dosing System/Main Process		a05	Ammonia Injection Point	-	s1003458	1	0									Located on main stream
	Sodium Hypochlorite dosing point	B1	Chloramine Dosing System/Main Process		a05	Sodium Hypo Injection Point	-	s1003459	1	0									Located on main stream
#	Water Quality 2_Cl2	WQ2_Cl2	Main Process		a06	Sample Panel #4_Contact Tank Inlet Total Chlorine Analyser	AE04007	s1003349	1	0									
	Water Quality 2_User defined	WQ2_?	Main Process		a06	Sample Panel #4_Contact Tank Inlet ORP Analyser	AE04013	s1003826	1	0									
	Flow Instrument 2	FI2	Main Process		a07	NA	NA	NA	0	0	0	0	0						
	Flow Instrument 3	FI3	Main Process		a08	NA	NA	NA	0	0	0	0	0						
	Water Quality 3_pH	WQ3_pH	Main Process		a09	NA	NA	NA	0	0	0	0	0						
	Water Quality 3_User defined	WQ3_?	Main Process		a09	NA	NA	NA	0	0	0	0	0						
	pH Adjustment dosing point	C or D	Main Process		a10	Sulphuric Acid Injection Point	-	s1003480	1	0									
	Flow Instrument 4	FI4	Main Process		a11	NA	NA	NA	0	0	0	0	0						
	Water Quality 4_pH	WQ4_pH	Main Process		a12	NA	NA	NA	0	0	0	0	0						
	Water Quality 4_Turb	WQ4_Turb	Main Process		a12	NA	NA	NA	0	0	0	0	0						
	Water Quality 4_User defined	WQ4_?	Main Process		a12	NA	NA	NA	0	0	0	0	0						

Figure 8: Example of Mapping of Asset Register to Reference Plant

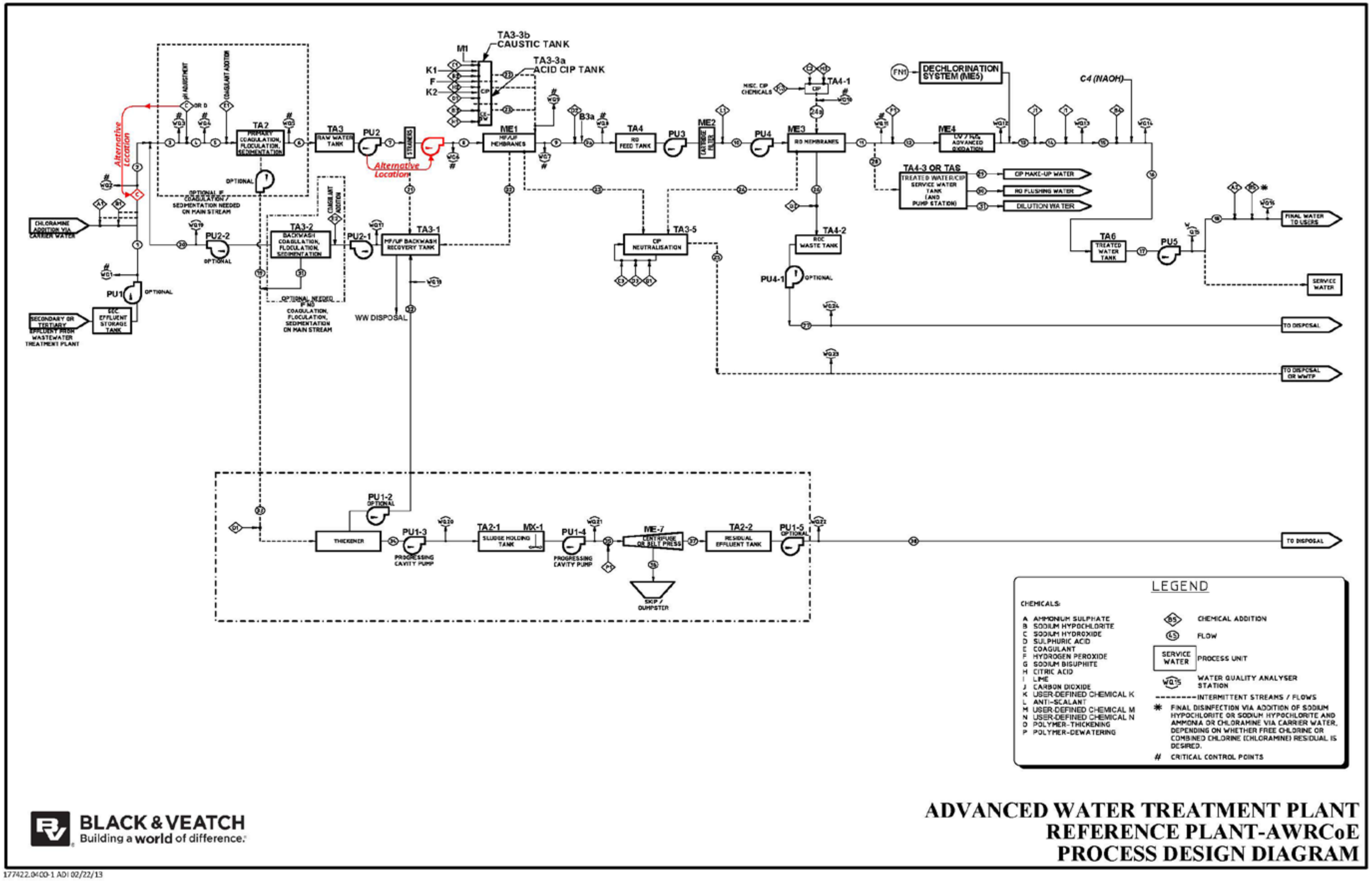


Figure 9: Process Flow Diagram of the Reference Plant

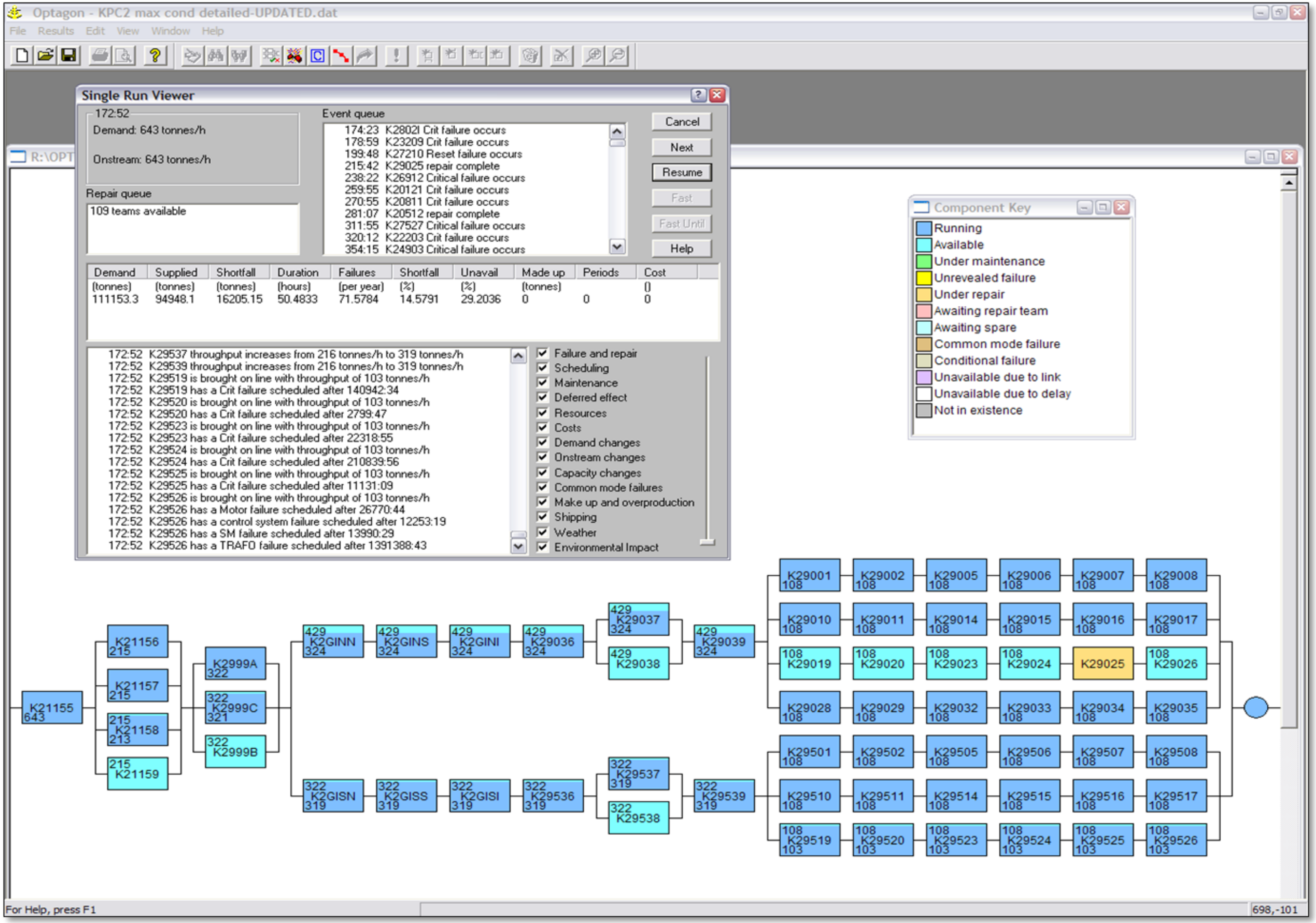


Figure 10: Reliability Block Diagram Representation of the Reference Plant in OPTAGON

4.3 MODEL DEVELOPMENT

The Reference Plant model was then subjected to typical failure and maintenance events that could occur during the lifetime of a typical AWT plant. System performance and reliability data were the key inputs to the model with logistic delays also accounted for so as to accurately and realistically simulate equipment unavailability. The OPTAGON resilience model consisted of two separate models; a “Capacity” model that analysed the throughput of the plant and a “Quality” model that assessed the number and duration of the failure events experienced by the plant in a span of 10 operational years.

4.3.1 Capacity Model

The resilience model’s Capacity model assessed the production and operational availability of components that influence throughput in a 10-year operation period. The components that are significant contributors to shortfalls in throughput were highlighted by the model. The shortfall due to these contributors can be mitigated via the introduction of additional redundancies.

4.3.2 Quality Model

The Quality model quantified the frequency and duration of process failure events. The failure events were divided into four categories, however, only two were critical to the final water quality. Table 5 shows the four different failure categories and unlike process control losses and non-critical instrument failures (Category I and Category II), only Critical Control Point (CCP) and product quality losses (Category III and Category IV) have direct adverse effects on water quality and would have potential impacts on the final product water quality. Therefore, results from the quality model were focused on failure events due to Categories III and IV.

The Deferred Effect Time (DET) and critical number play important roles in the determination of the consequences of a failure event. If the number of equipment failures meets or exceeds the critical number, and should the equipment have a DET (greater than 0 hours), the duration of the DET would have to be exceeded for a failure event to occur.

Table 5: Definitions of the Various Types of Consent Breaches

Type of Consent Breach	Failure Category	Definition
Process Control Loss	I	Failure of equipment or instrument that results in a loss of the ability to control the process.
Non-critical Instrument Failure	II	Failure of equipment or instrument that impacts data collection and not used for process control or a Critical Control Point (CCP).
Critical Control Point Loss	III	Failure of instrument that is used to detect a loss of water quality and/or disinfection capability.
Product Quality Loss	IV	Failure of equipment that results in a loss of water quality and/or disinfection capability.

For example, the chemical dosing pump has a critical number of 1 and a DET of 24 hours, thus, if one of the two dosing pumps is not repaired within 24 hours, a failure event would occur. The failure duration would be the MTTR (including logistical delay time) minus the DET. Unlike the chemical dosing pumps, the RO membranes have a zero DET; therefore, a failure event would occur immediately as there is no DET buffer and would thus lead to longer failure durations.

4.3.3 Sensitivity Analysis

Five sensitivity scenarios were developed to further interrogate the results and test the effects of the strategies used to improve plant resilience.

- **Scenario 1**: Adding redundancy to critical instruments at various CCPs.
- **Scenario 2**: Adding redundancy to critical process equipment.
- **Scenario 3**: Implementing better maintenance protocols by reducing MTTR to eight hours for critical instruments and 72 hours for critical equipment.
- **Scenario 4**: Increasing Deferred Effect Times to 12 hours.
- **Scenario 5**: Combination of both improved maintenance strategies and different Deferred Effect Times. DET was increased and the MTTR for critical instruments and critical equipment were reduced to eight hours and 72 hours respectively. The Deferred Effect Time was increased to 12 hours to simulate a typical storage buffer time where non-compliant water can be rejected before being released into the distribution system.

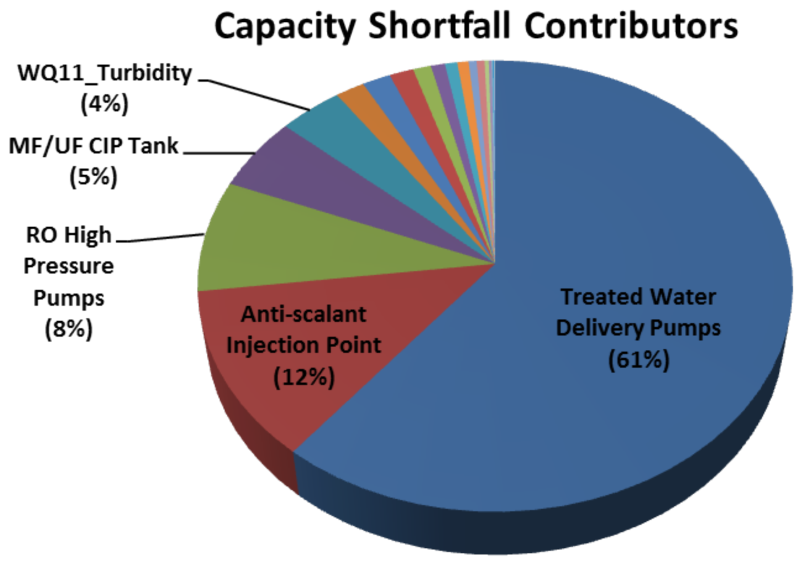
5. RESILIENCE MODELLING SIMULATION RESULTS

5.1 SIMULATION RESULTS: CAPACITY

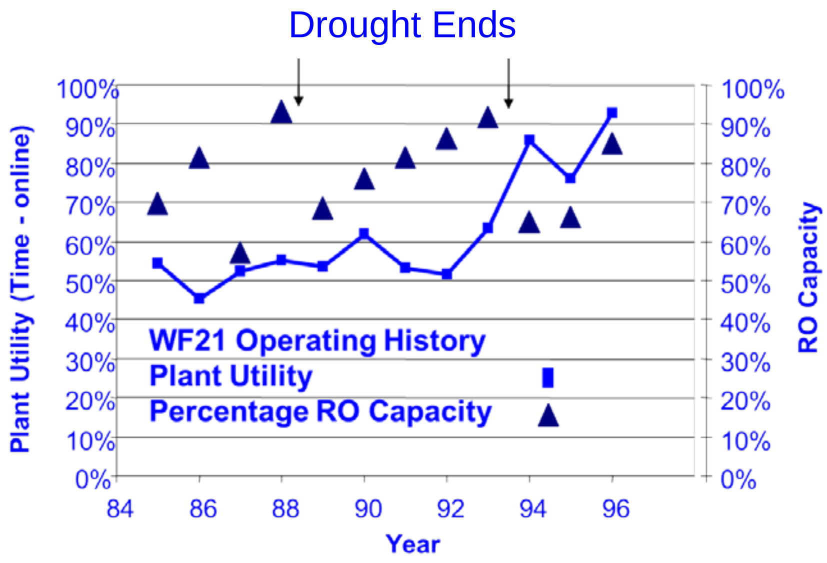
Key Points:

- The capacity model showed that the Reference Plant met target production capacity for 66,600 out of 87,600 hours (76%) in its ten-year operational period.
- The Reference Plant could operate at full design capacity, with all redundancies available, for 35,900 hours (41% of the time).
- Shortfalls are acceptable and common for IPR AWT plants that exercise discretionary discharge protocols.
- For DPR schemes, more efficient maintenance strategies and additional redundancies for shortfall contributors would decrease process unavailability experienced by the AWT plant.

The Reference Plant's production availability was determined to be 76%. This meant that the plant was capable of meeting target production capacity requirements for 66,600 out of 87,600 hours in its ten-year operational lifespan. The operational availability indicated that the plant was able to operate at full design capacity, with availability of all redundancies, for 35,900 hours (41% of the time).



(a)



(b)

Figure 11(a): Breakdown of Reference Plant's capacity shortfall contributors; **(b)** Graph of fluctuations of Plant Utility and RO Capacity in an IPR scheme

The main contributor to the production capacity shortfall was due to failures in the Treated Water Delivery Pumps (PU5), with 61% of the total number of failure events (Figure 11(a)). The pumps had a relatively low MTBF of 1,837 hours and a long MTTR of 973 hours, suggesting that it was likely that a pump would fail whilst another was under maintenance or being repaired, therefore, resulting in system downtime.

It should be noted that the importance of meeting the throughput requirements is highly dependent on the intended use of the treated water. Comparing a Direct Potable Recycling (DPR) scheme to an Indirect Potable Recycling (IPR) scheme, the former would place a greater importance on achieving production requirements than the latter that exercises discretionary production protocols. An example of acceptable shortfalls in production can be seen in Figure 11(b), where an IPR plant's Reverse Osmosis (RO) production capacity and plant utility experienced fluctuations based on the changing treated water demands due to the onset and breaking of a drought.

Process bottlenecks of final downstream processes would have the greatest impact on the plant's production capacity and thus, reduction of their MTTR via a more efficient maintenance schedule or adding a redundant standby unit would be beneficial to the plant's overall availability.

5.2 SIMULATION RESULTS: QUALITY

Key Points:

- Dual membrane AWT plants fail on capacity rather than quality.
- The majority of failure events were non-critical and did not have an adverse effect on final product water quality.
- Traditional approach of adding multiple redundancies does not significantly improve an AWT plant's resilience from a product water quality perspective.
- Implementation of more efficient maintenance protocols decreased the number of failure events by 58%.
- Better maintenance strategies in tandem with an adequate amount of treated water storage buffer time were the most effective at improving the plant's resilience (67% decrease in number of failure events).

5.2.1 Base Case Scenario

The base case scenario modelling results showed that the reference plant experienced approximately 427 failure events in a span of 10 years (42.7/year) with an associated total duration of approximately 24,600 hours (2,460 hours/year). Figure 12 shows the breakdown of the contributors to the number of failure events experienced by the plant throughout its operation.

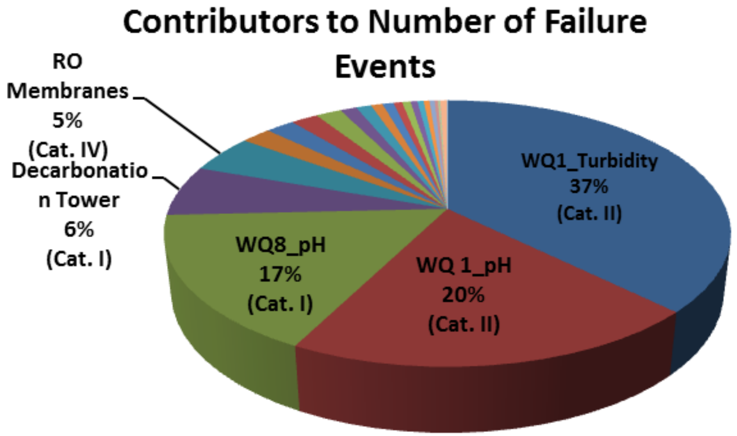


Figure 12: Breakdown of Contributors to the Number of Failures Events

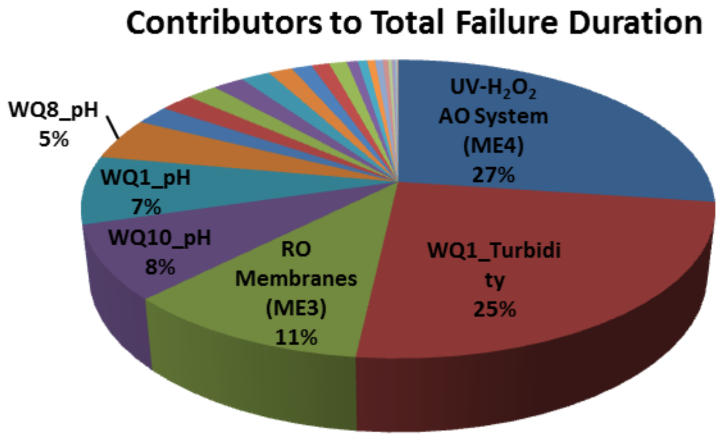


Figure 13: Breakdown of Contributors to the Total Failure Duration

The top four contributors were Category I and Category II failures and these would not have any impact on the final product water quality. The RO membranes, on the other hand, were the only critical failures that would lead to a loss in product quality (Category IV), but attributed to only 21 out of 427 events (5%) in a ten-year operation span (Figure 12).

The two contributors that had a significant impact on the final product water quality were the UV-H_2O_2 Advanced Oxidation System (ME4) and the RO membranes (ME3) (Figure 13), being responsible for 27% and 11% of the total failure time respectively.

Given that these processes have a zero DET and a long MTTR duration, these processes made larger contributions to the total failure duration. The other contributors were non-critical instrument failures and would not affect the final product water quality, but a reduction of the resulting downtime due to these failures would have a positive effect on the plant's availability and overall efficiency.

5.2.2 Sensitivity Scenarios

The reduction in number of failure events and the total failure duration would suggest that the recommended mitigation strategy was capable of improving the plant's resilience and thus would provide an insight into which strategy was more effective.

From the sensitivity scenario analysis, it was clear that the most significant decrease in the average number of failure events and the average total failure duration were observed in scenarios 3 and 5a (Table 6). The results showed that the most important parameter that improved the plant's resilience was the combination of MTTR values and the Deferred Effect Times. This meant that the having a shorter maintenance response/action time together with a treated water storage buffer time of 12 hours would have a significant improvement on a plant's resilience.

Table 6: Summary of Results for Base Case and Scenarios 1 to 5a*

Scenarios	Average Number of Failure Events	Total Failure Duration (Hours)
Base Case	427	24,555
Scenario 1	418	23,286
Scenario 2	419	16,927
Scenario 3	180	2,874
Scenario 4	402	23,697
Scenario 5a	142	2,340

* **Note**: See Section 4.3.3 for a brief description of each Scenario.

Sensitivity Scenario 5 was further investigated to determine if increasing the DET would have a significant impact on the plant's resilience. Five DETs were modelled ranging from 12 to 144 hours (Scenarios 5a to 5e) to simulate increases in storage buffer times prior to distribution. Results were compared to Scenario 3 to better highlight the effect of increasing DET with the MTTR kept constant.

Of the five DETs simulated, the largest relative change was observed in Scenario 5a, when the DET was increased from 0 to 12 hours, with a 21% and 19% reduction in the average number of failure events and failure duration respectively (Table 7). Therefore, it can be concluded that having 12 hours of treated water storage buffer time effectively reduced failure events and was significant in improving a plant's resilience.

Increasing the DET past 12 hours did further improve the plant's resilience, however, would be more capital intensive and have greater land requirements given the large footprint required for treated water storage in a 100 MLD plant.

Table 7: Comparison of Results for Sensitivity Scenarios 3 and 5

Scenarios	Number of Failure Events	Change (%)	Total Failure Duration (Hours)	Change (%)
Scenario 3 – 0 Hrs	180	-	2,874	-
Scenario 5a – 12 Hrs	142	21.1	2,340	18.6
Scenario 5b – 24 Hrs	131	7.8	1,966	16.0
Scenario 5c – 48 Hrs	122	6.9	1,617	17.8
Scenario 5d – 72 Hrs	117	4.1	1,451	10.3
Scenario 5e – 144 Hrs	113	3.4	1,264	12.9

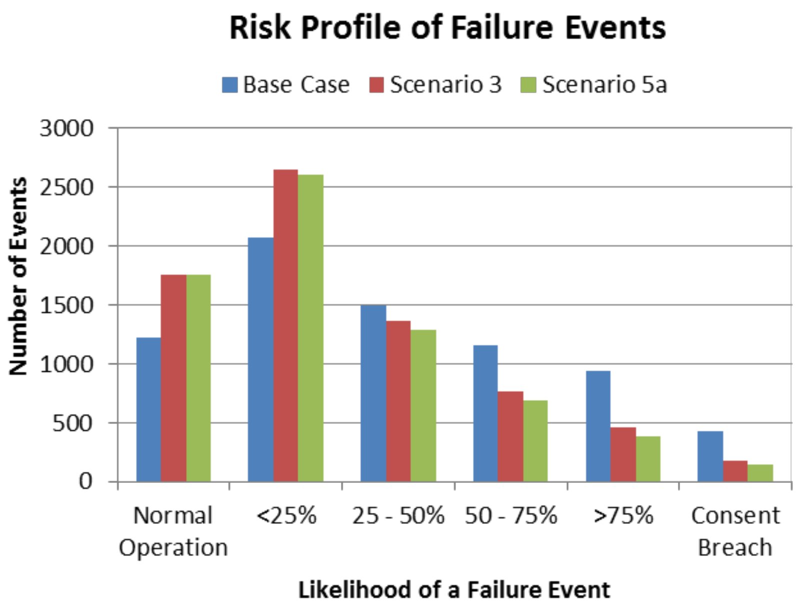


Figure 14: Risk Profile Comparison of Number of Failure Events

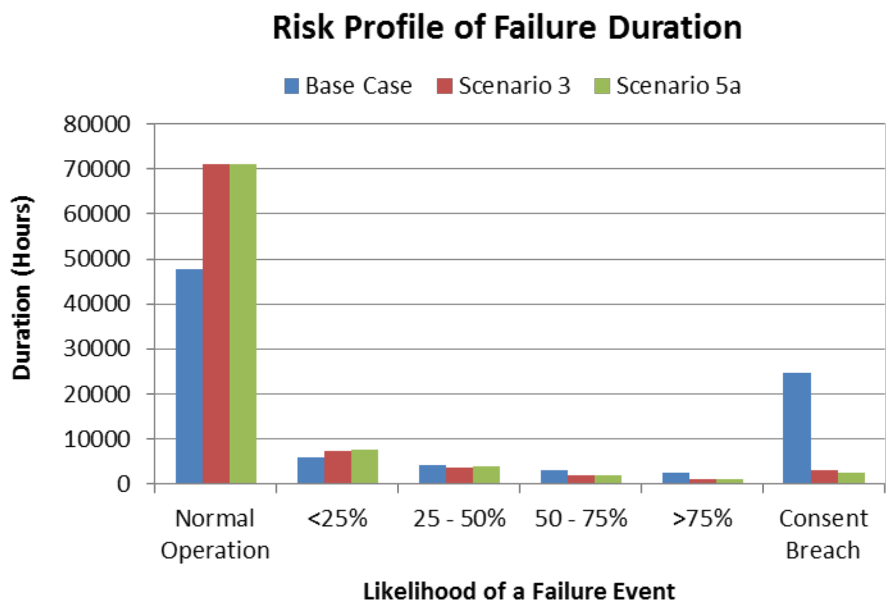


Figure 15: Risk Profile Comparison of Total Failure Duration

Scenarios 3 and 5a were compared against the base case. From Figure 14, the likelihood of a failure event was left-skewed with the majority of the failure events being in the <25% likelihood and normal operating (0% likelihood) conditions.

Implementation of Scenarios 3 and 5a increased the number of “Normal Operation” and “<25% likelihood” events whilst reducing events with moderate likelihood (>25%) and the number of “Consent Breach” failure events. This indicated that the plant was already operating with low to no risk of a failure event and having better maintenance and adequate storage further improved its resilience and reduced the risk of final product water excursions.

Likewise, with the number of failure events being reduced and the plant’s resilience improved, the amount of time that the plant was running with 0% likelihood of a failure event increased by 48% to 71,015 hours in a 10-year span (Figure 15). This showed that the introduction of more efficient maintenance measures as well as a 12-hour increase in treated water storage duration resulted in a decrease in the likelihood of a failure event and also a reduction in the total failure time experienced by the plant.

6. SUMMARY OF KEY FINDINGS AND PROJECT LEGACY

6.1 KEY FINDINGS

- Failures in **conventional drinking water** treatment systems resulting in pathogen outbreaks are most often caused by multiple failures occurring simultaneously. Most of these outbreaks occur when the drinking water plant attempts to treat water that exceeds the design limits of the process. Consequently, many of the outbreaks that occur in drinking water systems result from a combination of management and operational failures.
- Failures of equipment in the treatment plant only accounted for 8% of 60 documented cases of pathogen outbreak in drinking water systems from 2003 to 2013. Notwithstanding this, equipment failure and the lack of long-term operating data for potable reuse schemes are perceived by some to be valid reasons to restrict the use of recycled water to non-potable uses.
- This report acknowledges that failure of equipment and instruments can occur in Advanced Water Treatment systems used in potable reuse projects. However, the occurrence of these events should not prevent the acceptance of recycled water as a viable source for augmenting water supplies for the following reasons:
  1. Numerical simulation of AWT resilience over a ten-year period indicated that equipment and instrument failure events had a greater impact on production capacity than on water quality. That is, most failure events prevent the production of recycled water at the full capacity of the plant. Simulated data for plant availability were consistent with historical records of potable reuse schemes.
  2. Less than 5% of failure events over a 10-year period (equivalent to 2.1 events per year) that could impact the quality of water were associated with failure of critical equipment or instruments (specifically, the RO membranes and UV/advanced oxidation system).
  3. Decreasing the maintenance response time (i.e. decreasing MTTR) reduced the number of these critical water quality failure events by 58% (to 0.9 events/year) and the duration of the failure events by 88%.
  4. The use of a 12-hour treated water storage buffer reduced the number of water quality failure events by a further 21% (to 0.7 events/year) and the duration of the failure event by a further 19%.
  5. The numerical simulation only considered the impact of equipment failure. In Australia, an AWT plant would comply with the requirements of the Australian Guidelines for Water Recycling, which include the use of Hazard Analysis and Critical Control Points (HACCP) and a description of maintenance and response plans as part of an overall Recycled Water Quality Management Plan (RWQMP). In the event that the performance of the RO or UV/advanced oxidation drifted outside of the critical control limits, the RWQMP would require that immediate action be taken to stop the production of recycled water (usually achieved via alarms and interlocks in the Supervisory Control and Data Acquisition System). These procedures prevent the distribution of water that fails to meet water quality specifications.

6.2 INDUSTRY USE AND DISSEMINATION OF FINDINGS

6.2.1 Public Consultation

The results of this study could be communicated to general audience as follows.

Equipment and instruments used in Advanced Water Treatment plants are expected to fail over multiple years of operation. This study used numerical modelling techniques, informed by data taken from seven AWT plants with a cumulative operating history of 64 years, to simulate failure events that potentially impact water production and/or water quality over a 10-year period. The resilience model indicated that for AWT plants, events that lead to failures in production capacity are eight times more likely than failures that potentially could impact product quality. Moreover, the probability of equipment or instrument failure that could impact water quality can be reduced to less than one event per year through more efficient maintenance strategies. In practice, under the Australian Guidelines for Recycled Water, operators of potable reuse schemes are required to implement plans and procedures that use multiple continuous on-line monitoring points that interrupt water production in the event that water quality drifts outside tolerable limits at critical control points in the process. Consequently, although the probability of a failure event is low (less than once per year), systems and procedures are in place to prevent the failure event leading to the production and distribution of water that does not meet quality requirements beyond the boundaries of the AWT plant.

6.2.2 Industry Consultation

The implications of this study for designers and operators of advanced water treatment plants include the following.

This research shows that AWT plants are mechanically resilient and allow for recycled water to be a potential source of potable water. The resilience modelling showed that AWT plant equipment failures are eight times more likely to impact on production and operational availability than the quality of the product water. More efficient maintenance strategies and additional redundancies for shortfall contributors would decrease production shortfalls experienced by the AWT plant.

The water quality resilience model estimated that the AWT plant would experience 427 failure events over 10 years, with the majority (95%) of these failure events involving non-critical equipment and instruments and not having an adverse effect on final product water quality. The best approach to improving a plant's water quality resilience is not by having multiple redundancies, but rather, by implementation of more efficient maintenance protocols with an adequate amount of treated water storage. The results indicate that there is scope for reducing capital costs through value engineering and review of criteria for redundant equipment. The results also suggest that the amount of buffer storage capacity should be carefully evaluated in direct potable reuse schemes.

Compared to databases in the oil and gas sector that cover 5,000 to 10,000 years of cumulative plant operation, the database used in this study only covers 64 years of cumulative plant operation. Consequently, the water industry is encouraged to contribute to the expansion of the database to create an industry resource for AWT plant designers, operators and maintenance managers.

7. LESSONS AND RECOMMENDATIONS

7.1 RESPONDING TO INDUSTRY CONCERNS ON EQUIPMENT FAILURE

The study addressed the concerns of using recycled water as a potential source of potable water. Results from this study were consistent with most long-term experiences of operating IPR projects and reflect the anecdotal data that these plants fail on capacity and not on water quality for the majority of the plant’s operational lifespan and therefore, pose little risk to public health and safety. The resilience model also concluded that AWT plants were mechanically resilient and capable of reliably producing high quality water for IPR applications.

7.2 LESSONS FOR DESIGN AND MAINTENANCE OF IPR AND DPR SCHEMES

DPR schemes, unlike IPR schemes that can exercise discretionary discharge protocols, would have to place greater emphasis on equipment maintenance and reliability to ensure that both production availability and product water quality compliance are maintained at all times. Given that the current resilience database established was sourced from IPR schemes, the reliability data cannot be directly applied to DPR systems.

7.3 FUTURE WORK AND ACTIVITIES

7.3.1 Development of Potable Reuse Utility Network

Development of Data Collection Standards

Benefits from analysing reliability data range from optimisation of operating and maintenance procedures to life cycle costing as well as upgrading programmes of existing operational assets. Other potential benefits include improved decision-making, reductions in failures, and improved performance. However, improvement of equipment reliability is largely informed by experiences from real-time operation, therefore, in order to merge reliability data obtained from plants/utilities in the industry, the data would have to be collected and exchanged in a standardised and compatible format. The database established in this work (see Appendix A) could serve as a template for the type of failure data required for resilience modelling, although more granularity on the failure modes of the equipment would make the database more comprehensive and beneficial to other reliability studies.

Options of Data Sharing

Data collected and the resulting database developed could be shared with operators and utilities through Research Data Australia’s “Australian Urban Water” collection which has been established to compile appropriate data collections held by various research partner organisations and government bodies. Access to data would allow operators and utilities to develop “best practices” that could be customised to their specific needs and requirements.

Guidance on Resilience Modelling Options

The OPTAGON resilience model could be used to analyse both the likely throughput of the plant and the probable number and duration of failure events that could be expected to be experienced by a plant over a period of 10 operational years. The modelled plant could then be subjected to typical failure events and maintenance strategies to test and validate the system's performance and reliability. This would allow for a wide range of models to be built to simulate and predict the resilience of a new or existing asset under different physical configurations and management approaches.

Development of Standard Codes for Failure

In the petroleum, natural gas and petrochemical industries, great emphasis is placed on safety, reliability and maintainability of process equipment. Through the establishment of International Standard 14224 (ISO 14224:2006)[1], these industries have benefitted from the development of best practices. The use of standard codes of failure allowed for improved understanding and more cost-effective design and maintenance of new and existing assets. Likewise, the water industry would greatly benefit from a similar standard for collecting and analysing data on water treatment process equipment failures. Development of standard codes would also enable open sharing of experiences and practices from various operators and utilities.

7.3.2 Application of Methods to Conventional Water Treatment Schemes

Apart from the membrane processes, non-membrane plants are mechanically similar to typical AWT membrane plants given that they both utilise similar process pumps, meters and storage tanks. Thus, resilience modelling can also be applied to non-membrane plants. Resilience modelling of conventional water treatment plants would allow for optimisation of maintenance and inspection protocols to help improve the efficiency of treatment processes. It would also assist the operator or utility to identify potential sources of failure and to implement appropriate preventative measures.

[1] ISO 14224:2006: Petroleum, petrochemical and natural gas industries – Collection and exchange of reliability and maintenance data for equipment

8. APPENDICES

AUSTRALIAN WATER RECYCLING CENTRE OF EXCELLENCE GOAL 3

NATIONAL DEMONSTRATION, EDUCATION AND ENGAGEMENT PROGRAM
STREAM 1.3: RESILIENCE OF ADVANCED WATER RECYCLING SYSTEMS

Appendix A: Asset Register
Mechanical Reliability Data

Australian Water Recycling
Centre of Excellence

RIF-CS Element	Guidance
Class	Data Collection
Type	Mechanical Reliability Dataset
Key	TBA
Source	Seven source Advanced Water Treatment Plants (AWTPs) from Asia-Pacific and America
Originating Source	Plant process equipment data from AWTPs
Group	The University of New South Wales (UNSW), Black & Veatch Australia (BV), DNV GL United Kingdom (DNVGL UK)
Names	Mechanical reliability data for typical process equipment in the Water industry
Identifiers	TBA
Location	The Australian Water Recycling Centre of Excellence (National Demonstration Education and Engagement Program)
Coverage	64 cumulative years of reliability data
Related Objects	TBA
Subjects	Australian Water Recycling Centre of Excellence, National Demonstration Education and Engagement Program, Mechanical Reliability, Asset Register
Description	This study was supported by the Australian Water Recycling Centre of Excellence and was prepared as part of the National Demonstration, Education and Engagement Program (NDEEP) Stream 1.3. Stream 1.3 focused on determining the resilience of advanced water recycling systems by using a Monte Carlo-based resilience modelling software. Equipment reliability data from Advanced Water Treatment (AWT) plants with a cumulative operating history of 64 years was used to model the performance of a reference plant over 10 years to provide insight into nature of plant failure as well as strategies to reduce the incidence and duration of failure events. Results from the resilience modelling will be used in evidence based materials to address stakeholder concerns on the practice of potable reuse.
Citation	TBA
Related Info	Tng, KH, Currie, J, Leslie G, 2015, 'Resilience of advanced water recycling systems' Australia Water Recycling Centre of Excellence (Australia). 2015:1. Link to the AWRCoE web site: http://www.australianwaterrecycling.com.au/
Rights	AWRCoE holds all rights and ownership of this data.
Sensitive Data	Approval from AWRCoE is required prior to access, use and redistribution of data.

Asset Register of Equipment Mapped to Reference Plant

CCP	Equipment Name	Equipment Tag ID	Configuration	N + R	MTBF (hrs)	MTTR (hrs)	Impacts on Quality		Impacts on throughput
							Critical Number	Deferred Time	
#	Water Quality 1_Turb	WQ1_Turb	1 x 100%	1 + 0	195	33.5	1	24	Not critical to throughput
#	Water Quality 1_pH	WQ1_pH	1 x 100%	1 + 0	195	16.8	1	24	Not critical to throughput
#	Water Quality 1_Temp	WQ1_Temp	1 x 100%	1 + 0	N/A	N/A	1	24	Not critical to throughput
#	Water Quality 1_Cond	WQ1_Cond	1 x 100%	1 + 0	778	4.5	1	24	Not critical to throughput
#	Water Quality 1_TOC	WQ5_TOC	1 x 100%	1 + 0	0	0	1	24	Not critical to throughput
#	Water Quality 2_Cl2	WQ2_Cl2	1 x 100%	1 + 0	4246	24.8	1	24	Not critical to throughput
#	Water Quality 5_Turb	WQ5_Turb	1 x 100%	1 + 0	11676	33.5	1	24	Not critical to throughput
#	Water Quality 5_UV254	WQ5_UV	1 x 100%	1 + 0	N/A	N/A	1	24	Not critical to throughput
	MF/UF Membrane	ME1	12 x 10%	10 + 2	3839	133.4	2	Immediate	As per configuration
#	Water Quality 7_Turb	WQ7_turb	1 x 100%	1 + 0	2943	33.3	1	24	Not critical to throughput
#	Water Quality 7_Cond	WQ7_Cond	1 x 100%	1 + 0	46706	4.5	1	24	Not critical to throughput
#	Water Quality 7_pH	WQ7_pH	1 x 100%	1 + 0	0	0	1	24	Not critical to throughput
#	Water Quality 7_PartCount	WQ7_PC	1 x 100%	1 + 0	0	0	1	24	Not critical to throughput
#	Water Quality 7_Total Cl	WQ7_TCL	1 x 100%	1 + 0	14401	3	1	24	Not critical to throughput
#	Water Quality 7_User defined ORP	WQ7_ORP	1 x 100%	1 + 0	6780	72	1	24	Not critical to throughput
#	Water Quality 8_pH	WQ8_pH	1 x 100%	1 + 0	26	10.2	1	24	Not critical to throughput
	Anti-scalent Injection Point	L1	1 x 100%	1 + 0	782	28.4	1	24	As per configuration
	RO Membranes	ME3	12 x 11%	9 + 3	4231	135.9	2	Immediate	As per configuration
#	Water Quality 11_Cond	WQ11_Cond	1 x 100%	1 + 0	46706	4.5	1	24	As per configuration

CCP	Equipment Name	Equipment Tag ID	Configuration	N + R	MTBF (hrs)	MTTR	Impacts on Quality		Impacts on throughput
						hr	Critical Number	Deferred Time	
#	Water Quality 11_TOC	WQ11_TOC	1 x 100%	1 + 0	0	0	1	24	As per configuration
#	Water Quality 11_pH	WQ11_pH	1 x 100%	1 + 0	11676	16.8	1	24	As per configuration
#	Water Quality 11_Turbidity	WQ11_Turb	1 x 100%	1 + 0	2943	33.3	1	24	As per configuration
	Hydrogen Peroxide Injection point	F1	1 x 100%	1 + 0	0	234	1	Immediate	As per configuration
	UV-H2O2 Advanced Oxidation System	ME4	4 x 33%	3 + 1	1890	291.3	2	Immediate	Not critical to throughput
#	Water Quality 12_ORP	WQ12_ORP	1 x 100%	1 + 0	6780	72	1	24	Not critical to throughput
#	Water Quality 12_UV Transmittance Analyser	WQ12_UVT	1 x 100%	1 + 0	0	0	1	24	Not critical to throughput
	Decarbonation Tower	ME5	1 x 100%	1 + 0	389	1.3	1	Immediate	Not critical to throughput
	Decarbonation fans	FN1	3 x 50%	2 + 1	1398	35.4	2	Immediate	Not critical to throughput
	Carbon Dioxide Injection Point	J1	1 x 100%	1 + 0	N/A	N/A	1	Immediate	Not critical
	Lime Injection Point	I1	1 x 100%	1 + 0	0	0	1	Immediate	Not critical
	Sodium Hypochlorite dosing point	B4	1 x 100%	1 + 0	0	0	1	Immediate	As per configuration
	Sodium Hydroxide dosing point	C4	1 x 100%	1 + 0	0	0	1	Immediate	As per configuration
#	Water Quality 15_Turbidity	WQ15_Turb	1 x 100%	1 + 0	2943	33.3	1	24	Not critical
#	Water Quality 15_Free Chlorine	WQ15_FCL	1 x 100%	1 + 0	8266	44	1	24	Not critical
#	Water Quality 15_pH	WQ15_pH	1 x 100%	1 + 0	11676	16.8	1	24	Not critical
	Ammonium Sulphate Injection Point	A2	2 x 100%	1 + 1	N/A	N/A	2	Immediate	Not critical
	Sodium Hypochlorite dosing point	B5	2 x 100%	1 + 1	0	0	2	Immediate	Not critical
#	Water Quality 10_pH	WQ10_pH	1 x 100%	1 + 0	2998	103	1	24	Not critical
#	Water Quality 10_Cond	WQ10_Cond	1 x 100%	1 + 0	0	0	1	24	Not critical

Collection and Mapping of MTBF Values to Equipment

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
WWTP Effluent Storage Tank	TA1	1	0	No impact on quality but has direct impact on throughput.	N/A	0	N/A	N/A	N/A	N/A	N/A	**0**
WWTP Effluent Water forwarding pumps	PU1	1	0	No impact on quality but has direct impact on throughput.	713.56	0	N/A	N/A	N/A	N/A	0	**237.85**
Water Quality 1_Turb	WQ1_Turb	1	0	No impact on quality but can lead to indirect impact on throughput (increased membrane fouling).	194.6	N/A	N/A	N/A	N/A	N/A	N/A	**194.60**
Water Quality 1_pH	WQ1_pH	0	0		194.6	N/A	N/A	N/A	N/A	N/A	N/A	**194.60**
Water Quality 1_Cond	WQ1_Cond	0	0		778.43	N/A	N/A	N/A	N/A	N/A	N/A	**778.43**
Ammonium Sulphate Dosing Point	A1	1	0	Chloramine dosing would be unavailable, biofouling would increase but effluent quality would not be affected.	1156.85	N/A	N/A	0	N/A	N/A	N/A	**578.43**
Sodium Hypochlorite dosing point	B1	1	0	Chloramine dosing would be unavailable, biofouling would increase but effluent quality would not be affected.	222.4	N/A	N/A	694	5800	N/A	N/A	**2238.80**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 2_Cl2	WQ2_Cl2	0	1	Free Chlorine meter would not have any impact on throughput but could lead to chlorine degradation of MF/RO membranes' integrity.	8492	N/A	N/A	0	N/A	N/A	N/A	**4246**
pH Adjustment dosing point	C or D	0	0		778.43	N/A	N/A	0	N/A	N/A	N/A	**389.22**
Water Quality 4_pH	WQ4_pH	0	0		N/A	N/A	N/A	0	0	N/A	N/A	**0**
Water Quality 4_Turb	WQ4_Turb	0	0		N/A	N/A	N/A	N/A	0	N/A	N/A	**0**
Raw Water Tank(s)	TA3	0	0		1557	N/A	N/A	0	0	N/A	N/A	**519**
MF/UF Feed Pumps	PU2	1	0	No impact on quality but has direct impact on throughput.	N/A	7056	0	4458	4066	0	51	**2605.17**
Flow Instrument 7	FI7	0	0		N/A	N/A	11928	0	N/A	N/A	N/A	**5964**
Strainers	ST1	0	0	Failure of strainer could lead to breaches in integrity and premature failure of MF membranes.	306	4280	0	0	1714	N/A	N/A	**1260**
Water Quality 6_Turb	WQ6_Turb	0	1	Failure would affect detection of breaches in the strainer.	N/A	0	0	N/A	N/A	N/A	N/A	**0**
MF/UF Membrane	ME1	1	1	Breaches can lead to impacts on both quantity and quality.	241	4764	10930	6483	546	N/A	67	**3838.50**
Water Quality 7_Turb	WQ7_turb	0	0		N/A	9900	0	0	1873	N/A	N/A	**2943.25**
Acid Dosing Point	D2	0	0		N/A	0	N/A	N/A	2188	N/A	N/A	**1094**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Hypochlorite Dosing Point	B3a	0	0		778	N/A	0	N/A	N/A	N/A	N/A	**389**
Flow Instrument 9 A	FI9A	0	0		1557	N/A	N/A	N/A	0	N/A	N/A	**778.50**
Water Quality 8_pH	WQ8_pH	0	0		104	0	0	N/A	0	N/A	N/A	**26**
RO Feed Tank	TA4	0	0		519	0	0	0	0	N/A	N/A	**103.80**
RO Low Pressure Pumps	PU3	1	0	No impact on quality but has direct impact on throughput.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Cartridge Filters	ME2	0	0	Failure of cartridge filter could lead to breach in integrity and premature failure of RO membranes.	N/A	N/A	0	N/A	0	N/A	N/A	**0**
Anti-scalent Injection Point	Anti-scalent Injection Point	1	1	If antiscalant dosing fails then scaling may occur in ROs which will eventually lead to higher salt passage which might affect the quality of the product water.	N/A	3126	0	0	0	N/A	N/A	**781.50**
RO High Pressure Pumps	PU4	1	0	If 2 or more pumps are unavailable then production will be reduced but no affect on quality	0	656	771	1462	6042	240	71	**1320.29**
RO Membranes	ME3	1	1	Breaches can lead to impacts on both quantity and quality.	275	10956	2748	6997	4383	26	N/A	**4230.83**
Flow Instrument 11	FI11	0	0		0	0	N/A	26	0	N/A	N/A	**6.50**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 11_Cond	WQ11_Cond	0	1	Failure of conductivity meter would affect detection of breaches/salt passage of RO membranes.	0	0	0	N/A	9873	N/A	N/A	**2468.25**
Hydrogen Peroxide Injection point	F1	0	1	No Hydrogen Peroxide dosing could lead to inadequate disinfection of product water.	N/A	N/A	N/A	N/A	0	N/A	N/A	**0**
UV-H2O2 Advanced Oxidation System	ME4	0	1	Failure of UV system inadequate disinfection of product water.	N/A	N/A	N/A	N/A	5390	121	158	**1889.67**
Decarbonation	ME5	0	1	Failure of decarbonation system could lead to high amounts of CO2 in product water.	1557	0	N/A	0	0	N/A	N/A	**389.25**
Decarbonation fans	FN1	0	1	Failure of decarbonation system could lead to high amounts of CO2 in product water.	545	3823	N/A	0	1224	N/A	N/A	**1398**
Sodium Hypochlorite dosing point	B4	1	1	If dosing point fails then product water would be out of spec in 1 hour (which is the detention time in the chlorine contact tank)	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Sodium Hydroxide dosing point	C4	1	1	If dosing point fails then product water would be out of spec in 1 hour (which is the detention time in the chlorine contact tank)	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Flow Instrument 16	FI16	0	0		389	N/A	N/A	N/A	N/A	N/A	N/A	**389**
Treated Water Storage Tanks	TA6	1	0	Failure of pumps would result in no water throughput to final users.	350	0	0	N/A	0	N/A	N/A	**87.50**
Treated Water Delivery Pumps	PU5	1	0	Failure of pumps would result in no water throughput to final users.	259	1207	0	11119	222	51	0	**1836.86**
Ammonium Sulphate Injection Point	A2	0	1	Failure of Choloramine final disinfection would directly impact water quality.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sodium Hypochlorite dosing point	B5	0	1	Failure of Choloramine final disinfection would directly impact water quality.	N/A	0	0	N/A	N/A	N/A	N/A	**0**
Sodium Hydroxide Injection Point	C1	1	0	If this is unavailable then CIPs can not be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Sodium Hypochlorite Injection Point	B2	1	0	If this is unavailable then CIPs can not be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Peroxide Injection Point	F	1	0	If this is unavailable then CIPs can not be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
MF/UF CIP Tank	TA3-3b	1	0	If this is unavailable then CIPs can not be done, this may cause CMF units to fail after a few weeks and may result in reduced production, but no affect on quality	1557	0	0	0	N/A	N/A	N/A	**389.25**
Citric Acid Injection Point	H2	1	0	If this is unavailable then CIPs can not be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	4176	0	N/A	N/A	N/A	**2088**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Sulphuric Acid Injection Point	D1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
MF/UF CIP Tank	TA3-3a	1	0	If this is unavailable then CIPs cannot be done, this may cause CMF units to fail after a few weeks and may result in reduced production, but no effect on quality	778	N/A	N/A	N/A	0	N/A	N/A	**389**
Sodium Hypochlorite Injection Point	B3	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Citric Acid Injection Point	H1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	4176	N/A	N/A	N/A	N/A	**4176**
Water Quality 9_pH	WQ9_pH	0	0		519	N/A	N/A	N/A	N/A	N/A	N/A	**519**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 9_Cond	WQ9_Cond	0	0		1557	N/A	N/A	N/A	N/A	N/A	N/A	**1557**
Sodium Hydroxide Injection Point	C2	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	129	N/A	N/A	**64.50**
Citric Acid Injection Point	H3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	0	N/A	N/A	**0**
RO CIP TANK	TA4-1	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	6624	12132	46668	12949	N/A	N/A	**19593.25**
Water Quality 10_pH	WQ10_pH	0	0		N/A	N/A	N/A	1610	4386	N/A	N/A	**2998**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
CIP Neutralisation Tank	TA3-5	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Sodium Hydroxide Injection Point	C3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sulphuric Acid Injection Point	D3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sodium Bisulphite Injection Point	G1	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

Collection and Mapping of MTTR Values to Equipment

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
WWTP Effluent Storage Tank	TA1	1	0	No impact on quality but has direct impact on throughput.	N/A	0	N/A	N/A	N/A	N/A	N/A	**0**
WWTP Effluent Water forwarding pumps	PU1	1	0	No impact on quality but has direct impact on throughput.	9.25	0	N/A	N/A	N/A	N/A	184	**64.42**
Water Quality 1_Turb	WQ1_Turb	1	0	No impact on quality but can lead to indirect impact on throughput (increased membrane fouling).	33.5	N/A	N/A	N/A	N/A	N/A	N/A	**33.50**
Water Quality 1_pH	WQ1_pH	0	0		16.75	N/A	N/A	N/A	N/A	N/A	N/A	**16.75**
Water Quality 1_Cond	WQ1_Cond	0	0		4.5	N/A	N/A	N/A	N/A	N/A	N/A	**4.50**
Ammonium Sulphate Dosing Point	A1	1	0	Chloramine dosing would be unavailable, biofouling would increase but effluent quality would not be affected.	3	N/A	N/A	0	N/A	N/A	N/A	**1.50**
Sodium Hypochlorite dosing point	B1	1	0	Chloramine dosing would be unavailable, biofouling would increase but effluent quality would not be affected.	25.25	N/A	N/A	5	627	N/A	N/A	**219.08**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 2_Cl2	WQ2_Cl2	0	1	Free Chlorine meter would not have any impact on throughput but could lead to chlorine degradation of MF/RO membranes' integrity.	49.5	N/A	N/A	0	N/A	N/A	N/A	**24.75**
pH Adjustment dosing point	C or D	0	0		28.75	N/A	N/A	0	N/A	N/A	N/A	**14.38**
Water Quality 4_pH	WQ4_pH	0	0		N/A	N/A	N/A	0	0	N/A	N/A	**0**
Water Quality 4_Turb	WQ4_Turb	0	0		N/A	N/A	N/A	N/A	0	N/A	N/A	**0**
Raw Water Tank(s)	TA3	0	0		4.5	N/A	N/A	0	0	N/A	N/A	**1.50**
MF/UF Feed Pumps	PU2	1	0	No impact on quality but has direct impact on throughput.	N/A	172	168	53	64	368	72	**149.50**
Flow Instrument 7	FI7	0	0		N/A	N/A	84	0	N/A	N/A	N/A	**42**
Strainers	ST1	0	0	Failure of strainer could lead to breaches in integrity and premature failure of MF membranes.	29.5	42	0	0	254	N/A	N/A	**65.10**
Water Quality 6_Turb	WQ6_Turb	0	1	Failure of turbidity meter would affect detection of breaches in the strainer.	N/A	N/A	0	N/A	N/A	N/A	N/A	**0**
MF/UF Membrane	ME1	1	1	Breaches can lead to impacts on both quantity and quality.	86.38	39	172	0	48	N/A	455	**133.40**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 7_Turb	WQ7_turb	0	0		N/A	24	24	0	85	N/A	N/A	**33.25**
Acid Dosing Point	D2	0	0		N/A	0	N/A	N/A	60	N/A	N/A	**30**
Hypochlorite Dosing Point	B3a	0	0		8	N/A	0	N/A	N/A	N/A	N/A	**4**
Flow Instrument 9 A	FI9A	0	0		42.5	N/A	N/A	N/A	0	N/A	N/A	**21.25**
Water Quality 8_pH	WQ8_pH	0	0		40.75	0	0	N/A	0	N/A	N/A	**10.19**
RO Feed Tank	TA4	0	0		28	0	0	0	0	N/A	N/A	**5.60**
RO Low Pressure Pumps	PU3	1	0	No impact on quality but has direct impact on throughput.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Cartridge Filters	ME2	0	0	Failure of cartridge filter could lead to breach in integrity and premature failure of RO membranes.	N/A	N/A	0	N/A	0	N/A	N/A	**0**
Anti-scalent Injection Point	Anti-scalent Injection Point	1	1	If antiscalant dosing fails then scaling may occur in ROs which will eventually lead to higher salt passage which might affect the quality of the product water.	N/A	17.6	0	0	96	N/A	N/A	**28.40**
RO High Pressure Pumps	PU4	1	0	If 2 or more pumps are unavailable then production will be reduced but no effect on quality	0	64	54	19	193	156	1287	**253.29**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
RO Membranes	ME3	1	1	Breaches can lead to impacts on both quantity and quality.	22.63	42	239	40	324	284	0	**135.95**
Flow Instrument 11	FI11	0	0		0	0	N/A	7	0	N/A	N/A	**1.75**
Water Quality 11_Cond	WQ11_Cond	0	1	Failure of conductivity meter would affect detection of breaches/salt passage of RO membranes.	0	0	0	N/A	218	N/A	N/A	**54.50**
Hydrogen Peroxide Injection point	F1	0	1	No Hydrogen Peroxide dosing could lead to inadequate disinfection of product water.	N/A	N/A	N/A	N/A	234	N/A	N/A	**234**
UV-H2O2 Advanced Oxidation System	ME4	0	1	Failure of UV system inadequate disinfection of product water.	N/A	N/A	N/A	N/A	60	721	93	**291.33**
Decarbonation	ME5	0	1	Failure of decarbonation system could lead to high amounts of CO2 in product water.	5	0	N/A	0	0	N/A	N/A	**1.25**
Decarbonation fans	FN1	0	1	Failure of decarbonation system could lead to high amounts of CO2 in product water.	26.25	45.5	N/A	0	70	N/A	N/A	**35.44**
Product Water/ CIP Service Water Tank	TA5	0	0		0	N/A	216	N/A	N/A	N/A	N/A	**108**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Flow Instrument 15	FI15	0	0		N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sodium Hypochlorite dosing point	B4	1	1	If dosing point fails then product water would be out of spec in 1 hour (which is the detention time in the chlorine contact tank)	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Sodium Hydroxide dosing point	C4	1	1	If dosing point fails then product water would be out of spec in 1 hour (which is the detention time in the chlorine contact tank)	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Flow Instrument 16	FI16	0	0		48	N/A	N/A	N/A	N/A	N/A	N/A	**48**
Treated Water Storage Tanks	TA6	1	0	Failure of pumps would result in no water throughput to final users.	37	0	0	N/A	0	N/A	N/A	**9.25**
Treated Water Delivery Pumps	PU5	1	0	Failure of pumps would result in no water throughput to final users.	17.63	26	2520	1	94	1025	3128	**973.09**
Flow Instrument 18	FI18	0	0		N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Ammonium Sulphate Injection Point	A2	0	1	Failure of Choloramine final disinfection would directly impact water quality.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Sodium Hypochlorite dosing point	B5	0	1	Failure of Choloramine final disinfection would directly impact water quality.	N/A	0	0	N/A	N/A	N/A	N/A	**0**
Sodium Hydroxide Injection Point	C1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Sodium Hypochlorite Injection Point	B2	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
User-desfined chemical M Injection Point	M1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Peroxide Injection Point	F	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
MF/UF CIP Tank	TA3-3b	1	0	If this is unavailable then CIPs cannot be done, this may cause CMF units to fail after a few weeks and may result in reduced production, but no effect on quality	3.5	0	0	0	N/A	N/A	N/A	**0.89**
Citric Acid Injection Point	H2	1	0	If unavailable then CIPs cannot be done, may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	1200	0	N/A	N/A	N/A	**600**
Sulphuric Acid Injection Point	D1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
User-desfined chemical K Injection Point	K2	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
MF/UF CIP Tank	TA3-3a	1	0	If this is unavailable then CIPs cannot be done, this may cause CMF units to fail after a few weeks and may result in reduced production, but no effect on quality	12.5	N/A	N/A	N/A	0	N/A	N/A	**6.25**
Sodium Hypochlorite Injection Point	B3	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Citric Acid Injection Point	H1	1	0	If this is unavailable then CIPs cannot be done, this may cause MF units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	1200	N/A	N/A	N/A	N/A	**1200**
Water Quality 9_pH	WQ9_pH	0	0		14.25	N/A	N/A	N/A	N/A	N/A	N/A	**14.25**
Water Quality 9_Cond	WQ9_Cond	0	0		1	N/A	N/A	N/A	N/A	N/A	N/A	**1**
Water Quality 9_User defined	WQ9_?	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
Water Quality 9_User defined	WQ9_?	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sodium Hydroxide Injection Point	C2	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	153	N/A	N/A	**76.50**
Citric Acid Injection Point	H3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	0	N/A	N/A	**0**
RO CIP TANK	TA4-1	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	54	120	0	20	N/A	N/A	**48.50**
Water Quality 10_pH	WQ10_pH	0	0		N/A	N/A	N/A	15	191	N/A	N/A	**103**

Equipment Name	Equipment ID	Throughput	Quality	Notes / Remarks	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Average
CIP Neutralisation Tank	TA3-5	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	0	N/A	N/A	N/A	**0**
Sodium Hydroxide Injection Point	C3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sulphuric Acid Injection Point	D3	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**
Sodium Bisulphite Injection Point	G1	1	0	If this is unavailable then CIPs cannot be done, this may cause RO units to fail after a few months and may result in reduced production, but no effect on quality	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**N/A**

AUSTRALIAN WATER RECYCLING CENTRE OF EXCELLENCE GOAL 3

NATIONAL DEMONSTRATION, EDUCATION AND ENGAGEMENT PROGRAM

STREAM 1.3: RESILIENCE OF ADVANCED WATER RECYCLING SYSTEMS

8.2 Appendix B: Global Infectious Disease and Epidemiology Network (GIDEON) database - Collection and classification of failures in drinking water systems

Australian Water Recycling Centre of Excellence

RIF-CS Element	Guidance
Class	Data Collection
Type	Collection and classification of failures in drinking water systems
Key	TBA
Source	Global Infectious Disease and Epidemiology Network (GIDEON) database
Originating Source	http://www.gideononline.com/
Group	The University of New South Wales (UNSW), Black & Veatch Australia (BV), DNV GL United Kingdom (DNV GL UK)
Names	Failures and outbreaks in drinking water systems from 2003 to 2013
Identifiers	TBA
Location	The Australian Water Recycling Centre of Excellence (National Demonstration Education and Engagement Program)
Coverage	From 2003 to 2013
Related Objects	TBA
Subjects	Australian Water Recycling Centre of Excellence, National Demonstration Education and Engagement Program 1.3, Failures in drinking water systems from 2003 to 2013, GIDEON, Alpha-numeric classification
Description	Consequences of failures in drinking water systems were reviewed. Drinking water system failures and their public health impacts were investigated to develop an interrelation between the type of failure and outbreak occurrences. These incidents were sourced from the Global Infectious Disease and Epidemiology Network (GIDEON) database which records the occurrence of outbreaks worldwide between 2003 and 2013. Using aspects of the Australian Drinking Water Guidelines (ADWG) to determine possible failure points, an alpha-numeric classification system was developed to categorise each failure event. This study was supported by the Australian Water Recycling Centre of Excellence.
Citation	TBA
Related Info	Tng, KH, Currie, J, Leslie G, 2015, 'Resilience of advanced water recycling systems' Australia Water Recycling Centre of Excellence (Australia). 2015:1. Link to the AWRCoE web site: http://www.australianwaterrecycling.com.au/
Rights	AWRCoE holds all rights and ownership of this data.
Sensitive Data	Approval from AWRCoE is required prior to access, use and redistribution of data.

Documented Cases from GIDEON Public Health Database

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
1	02/2000 to 04/2001	North Ireland	Belfast	Surface water	Random sampling biological treatment, clarification, filtration, disenfection	•Seepage of raw sewage and wastewater into drinking water system •Blocked wastewater drain	laboratory confirmed cases	Cryptosporidium spp
2	2001	France	Dracy Le Fort	Surface water	Unknown	•Oocycsts identified in public drinking water supply - suspected human sewage • contamination was neither the alluvial water table supply nor the water treatment plant but ather the distribution network upstream of the city.	Health authorities notified	Cryptosporidium hominis
3	2001	Netherlands	Central	Ground water	Unknown	•Failure to disconnect main drinking water system from grey water system following maintenance work	laboratory confirmed cases	Norovirus
4	2002	North Ireland		Surface water	Chlorination	•Water source contaminated with manure from nearby cattle shed •Lack of filtration	laboratory confirmed cases	Cryptosporidium spp
5	2003	Finland		Ground water		•Broken pipe		Norovirus
6	2003	Ireland	Ennis	Ground Water (spring)	filtration chlorination	• Assessed has a high risk for Cryptosporidium • Spring source influenced by surface water and was not fully filtered although it was disenfected using chlorine.	Health authorities notified	Cryptosporidium spp
7	2004	Finland	East	Ground water	•No disinfection •pH adjusted before distribution	•Heavy precipitation prior to outbreak •Cleaning and maintenance work incorrectly positioned roof gutter into drinking water storage • Rainwater runoff from the roof leached bird droppings into the drinking water storage tower	n/a	Campylobacter jejuni

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
8	2004	USA	South Bass Island, Ohio	Ground water (well water)	Chlorination	•Extreme precipitation transported faecal wastewater from the Lake into subsurface water •Porous, fractured aquifer provided little to no filtration and may have allowed passage of microorganisms •Poorly installed sewage systems	n/a	Multiple aetiologies ; Camplylobacter jejuni Giardia intestanalis Norovirus Arcobacter Adenovirus DNA
9	2004	USA	Ohio	Ground water (well water)		Information not available	n/a	Multiple aetiologies ; Campylobacter spp. Cryptosporidium spp., Helicobacter canadensis
10	2004	Norway	Bergen	Surface water	Chlorination	•Old and leaking sewage pipes •Heavy rainfall caused sewage overflow into the lake •Chlorine disinfection doses not sufficient against protozoa	Increase in laboratory confirmed cases	Giardia lamblia
11	2005	Austria	Salzburg			•Heavy rainfall flooded the hotel the tourists were staying at •Tourists exposed to flood water contaminated with raw sewage	n/a	Unidentified aetiology

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
12	2005	Ireland	Carlow	Surface water (River; two sources Slaney and Burren Rivers)	Rathvilly treatment: Chemical coagulation, sludge blanket clarifiers, rapid gravity sand filtration, chlorination, fluoridation and pH correction. Sand filters backwashed daily. Circular flocculation tank and horizontal flow sedimentation tank. Sion Cross Treatment: Chemical coagulation, rapid gravity filters, chlorination and fluoridation. Hopper bottom sedimentation tanks, chemical coagulation with flash mixing.	• Sion Cross plant abstracted water from the river Burren which drained a highly agricultural basin with traditional stock watering points along the river valley and a number of sewage treatment plants upstream of extraction point. • Replacement of Sand filters in 2004 at Sion Cross reuced the turbidity of the treatment water. • Treated water from both Rathvilly and Sion Cross was mixed at Brownshilly reservoir before supplying Carlow town. Monitoring did not pick up levels of pathogenic contamination (0.04 oocysts/10L found in treated water).	n/a	C.Parvum, C. andersoni, C. Muris. Cryptosporidium
13	2005	England	Portsmouth (South East)	Surface water (River Itchen)	Coagulation, clarification, rapid gravity filtration, disenfection.	• No monitoring for exceedence in treatment standard of 1 oocyst per 10 litres.	n/a	Cryptosporidium hominis
14	2005	Turkey	West	Ground water	Chlorination	•Contamination of drinking water supply by sewage or animal waste following heavy rainfall •Ineffective chlorination (no chlorine in the water despite claims it was chlorinated) •Lack of a routine detection method for Cryptosporidium	n/a	Cryptosporidium with Cyclospora co-infection
15	2005	Turkey	Malatya City	Ground water (well water)	Chlorination	•Water interruptions due to substructure work in the city •supply of untreated water to residents	n/a	group A rotavirus

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
16	2005	Wales	Llyn Cwellyn	Surface water	Microstraining, pressurised sand filtration and chlorination.	• Works was vulnerable to turbidity and Cryptosporidium breakthrough under lack of a coagulation stage. The catchment for the impounding reservoir had a mixture of land uses including grazing of sheep and cattle. The catchmet also contained a village which discharged treated sewage to the reservoir, together with a number of houses with septic tank systems. • Turbidity spikes occured following filter washing because there was no ability to run to waste.	n/a	Cryptosporidium spp
17	2006	England	South West	Ground water (well water)	Chlorination	•Faecal contamination of surface water after heavy rainfall •Contaminated surface water used for activities •Cracks in the well wall and evidence of faeces nearby •Lack of sufficient fencing off of well from livestock	n/a	Unidentified aetiology
18	2006	New Zealand		Surface water		•Drinking water contaminated with human sewage		Norovirus
19	2006	Italy	Apulia	Unknown		•Possible technical problems at the local chlorination facilities	Reported by A&E department	Norovirus Rotavirus
20	2006	Ireland	Portlaw	Surface water (spring)	chlorination, fluoridation, pH control.	• Spring source at Laherden supplying storage reservoir was supplemented by a borehole. Spring was collected in a concrete tank buried in boggy ground.	n/a	Cryptosporidium spp
21	2006	Austria		Surface water (reservoir)		•Faecal contamination of untreated drinking water •Heavy rainfall led to possible surface runoff Filtration of water was lacking	Reported by local physician Absentees recorded	Unidentified aetiology

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
22	2006	Australia	Queensland	Tank water		Information not available	n/a	Campylobacter jejuni
23	2007	USA	New Hampshire	Ground water (well water)	No treatment whatsoever	•Total and faecal coliform in distribution water samples possibly from surface water runoff into the well •No treatment prior to distribution •Failure to meet regulatory approval of distance between a well and surface water (15m)	n/a	Giardia intestinalis
24	2007	Australia	Victoria	Surface water	No treatment whatsoever	•Contaminated rain water probably due to animal droppings •Lack of treatment of the collected rain water •No disinfection of the rainwater collection tanks	n/a	Salmonella typhimurium
25	2007	England	Hull	Surface Water	not available	• Deterioration in raw water quality. Increased load on filters due to increase in turbidity	n/a	Cryptosporidium spp.
26	2007	England	North Walsham	Ground water (aquifer)	not available	• raw water contamination. Investigatory boreholes.	n/a	Cryptosporidium spp.
27	2007	England	Fairford, Gloucestershire	Surface water	not available	• Sudden rise in turbidity causes by heavy rain and a landslide.	n/a	Cryptosporidium spp.
28	2007	USA	Florida	Surface water (reservoir)		Information not available	n/a	Unidentified etiology
29	2007	Ireland	Galway, West	Surface water	•coagulation, rapid gravity filtration and disenfection (new plant) •No filtration in the other plant adequate for removing cryptosporidium	•Heavy rainfall led to farmland runoff into the lake increasing turbidity •Mixing filtered water with non-filtered water prior to distribution • upstream sewage treatment plant designed to service 250 households was receiving sewage from 800 properties.	n/a	Cryptosporidium spp.

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
30	2007	Norway	Oslo	Groundwater		• Contamination linked to distribution system, bacteria detected in tap water samples. Post treatment contamination with faecal matter, associated with maintenance work.	laboratory confirmed cases.	Multiple aetiologies; cryptosporidium, giardia
31	2007	Norway	Roros	Groundwater	No treatment whatsoever	•Lack of treatment of source water •Old and leaking water pipes •Failure of personnel to follow chlorination recommendation after maintenance work •Fall in water pressure due to maintenance work	n/a	Campylobacter spp.
32	2007	Finland	Nokia	Groundwater	Chlorination and pH adjustment	•Cross connection between wastewater effluent and drinking water supplies left open during and after maintenance work	n/a	Multiple aetiologies; Campylobacter spp, Norovirus, Giardia spp, Clostridium difficile, Rotavirus, Enterovirus, Astrovirus, Shigella boydii, and Salmonella spp
33	2007	Denmark		Ground water (well water)	No treatment whatsoever	•Backflow of partially filtered wastewater into drinking water supply	n/a	Multiple aetiologies; Campylobacter *jejuni*, Enteropathogenic E.coli, *Salmonella,* Norovirus, Rotavirus.
34	2007	Belgium		Ground water (well water)	not available	•Faecal contamination	Reported by hospital	Norovirus
35	2007	China	Shenzen (South)	unknown		•Broken water pipes at source •Negative pressure may have allowed contaminated groundwater to penetrate broken pipes	n/a	Norovirus
36	2008	France	Ardeche	Ground water (well water)			n/a	Unidentified aetiology

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
37	2008	Sweden	Lilla Edet	Surface water	Prechlorination, coagulation/direct filtration and post-chlorination	Heavy rainfall Sewer overflows Discharge of untreated wastewater into an upstream tributary	Nurse at primary healthcare centre reported cases to County Medical Officer	Norovirus
38	2008	USA	Alamosa, Colorado	Ground water (well water)	No treatment whatsoever	•Lack of chlorination	Culture confirmed cases	Salmonella typhimurium
39	2008	Switzerland	Zurich			Faecal contamination of drinking water due to cross-contamination error Indistinguishable pipes (not labelled to differentiate sewage from drinking water)	Consumer complaints	Multiple aetiologies; norovirus and campylobacter jejuni
40	2008	England	Berkshire	Ground water	traditional treatment	• Action not taken on an uncharacteristic raw water turbidity alarm, site was not assessed as being vulnerable to flooding and cryptosporidium at a time of heavy rainfall and high river levels.	n/a	Cryptosporidium spp
41	2008	England	Pitsford, North Hampton	Surface water (reservoir)	clarification, filtration, ozonation, granular activated carbon filtration, and disenfection.	•Contaminated tap water • Dead rabbit found in the treated water tank • Water was drawn from a large surface reservoir open to public for recreational purposes. • lack of maintenance of tank hatches/vents allowed animal to gain access.	n/a	Cryptosporidium spp
42	2009	Greece	Crete		Chlorination	Information not available	Patients (children) presenting with symptoms in the ED	Campylobacter jejuni

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
43	2009	Sweden	West	Ground water (well water)	Rapid sand filtration and UV disinfection	Faecal contamination at water source due to seasonal snow melt Leakage in the water pipe system Inadequate physical barrier protection of source water No WQ monitoring performed in over a year (since last use) Reservoir tank not fitted with brim	n/a	Norovirus
44	2009	Italy	Lombardy	Surface water	treated with chlorine dioxide and hypochlorite and passes through sand filters	The water company had undertaken work on the collection reservoir which might have limited the effect of chlorination; Two filters were 10 years old (cleaned weekly but not disinfected); The chlorine concentration in the water before it passed through the filters was 0.4 mg/l; in filtered water it was only 0.08 mg/l.	A general practitioner from the municipality of San Felice del Benaco notified to the local health authority of Brescia; laboratory confirmed cases.	Viral gastroenteritis; norovirus, rotavirus, enterovirus or astrovirus
45	2009	Australia	North Pine treatment facility	Municipal drinking water		•Treatment plant offline for maintenance •Malfunctioning flow control meter led to automated fluoride dosing •Backup switch disabled due to maintenance •Alarm noted but no action was taken •Miscommunication between operational staff and maintenance staff regarding disabled controls	n/a	Unidentified aetiology
46	2009	Australia	Pimpama-Coomera	Surface water (river)		•Failure to remove cross-link between drinking water and recycled water	n/a	Unidentified aetiology
47	2009	China				Information not available	n/a	Norovirus

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
48	2009	France		Surface Water (River)	traditional treatment	• Flood water contaminated drinking water	n/a	Cryptosporidium spp.
49	2010	Australia	Pimpama-Coomera	Surface water (river)		•On-lot cross connections between recycled water and potable water done by plumbers	n/a	Unidentified aetiology
50	2010	China	South		Coagulation sedimentation Filtration Disinfection	Sewage contamination at source Obsolete disinfectant devices and pipelines Dirt on the disilter walls and filtering ponds Lack of adequate testing systems and personnel Irregular management and shortage of water quality analyses Sewage dischagred directly into the river without prior treatment due to malfunction of the lifting pumping station	Reported by hospital doctors to local CDC	Norovirus
51	2010	Belgium	Antwerp			Faecal contamination	n/a	Multiple aetiologies; Norovirus, Campylobacter and Giardia
52	2010	Denmark	Koge			Information not available	Reported to public health medical officer by GP	Campylobacter jejuni
53	2010	Sweden	Östersund	Surface water	Filtration but no chlorination	•Sewage contamination of drinking water system •Cross-connection between stormwater pipes and sewer pipe	n/a	Cryptosporidium hominis
54	2011	Spain	Gipuzkoa			•Broken hot water system in daycare •Poor sanitation practices	n/a	Cryptospodium spp
55	2011	Sweden	Skelleftea			Information not available	n/a	Cryptosporidium hominis

	Year	Country	Location	Source water	Treatment in place	Major failures	Outbreak detection	Pathogens identified
56	2012	New Zealand	Darfield	Surface water	Chlorination	•Uncalibrated chlorine analyser •Heavy rainfall led to surface flooding and turbidity (animal faecal contamination)	n/a	Multiple aetiologies; Campylobacter spp, escherichia coli
57	2012	China	Jiangxi	Contaminate d bottle water		Information not available	Reported by university to the local CDC	Enteropathogenic E. coli
58	2012	Greece	Elassona	Surface water	Chlorination	•Heavy rainfall a week before outbreak •Animal shed close to water source •Contaminated tap water (possibly from human sewage)	n/a	Rotavirus
59	2012	Greece	Nea Santa Kilkis	Contaminted tap water		Faecal contamination Heavy snowfall Increased microbial load in water supply due to school closure	n/a	Multiple aetiologies; norovirus and adenovirus
60	2013	Ireland	Roscommon	Surface water		Dead cattle found in stream	n/a	Cryptosporidium parvum
61	2013	USA	Oregon			Information not available		Cryptosporidium

GIDEON Outbreak Database

	Year	Country	Location	Source water	Cases confirmed	Total cases estimated	Hospital admission	Deaths	
1	February 2000 - April 2001	North Ireland	Belfast	Surface water	120	476		0	Risebro et al. 2005
2	2001	France	Dracy Le Fort	Surface water	19	563	n/a	0	Dalle et al., 2003
3	2001	Netherlands	Central	Ground water	250	n/a	n/a	0	Fernandes et al., 2007
4	2002	North Ireland		Surface water	29	32	3	0	Jennings P, and Rhatigan A, 2002 (Eurosurveillance, Volume 6, Issue 22, 30 May 2002)
5	2003	Finland		Ground water	40	90	n/a	0	
6	2003	Ireland	Ennis	Ground Water (spring)	n/a	n/a	n/a	0	EPA 2011
7	2004	Finland	East	Ground water	3	n/a	n/a	0	Pitkanen, et al., 2008
8	2004	USA	South Bass Island, Ohio	Ground water (well water)	650	n/a	21	0	Fong et al., 2007; O'Reilly et al., 2007
9	2004	USA	Ohio	Ground water (well water)	n/a	82	n/a	0	Liang et al., 2006
10	2004	Norway	Bergen	Surface water	1268	48000	n/a	0	Nygård et al., 2006
11	2005	Austria	Salzburg		4	n/a	n/a	0	Schmid et al., 2005 (Eurosurveillance, Volume 10, Issue 24, 16 June 2005)
12	2005	Ireland	Carlow	Surface water (River; two sources Slaney and Burren Rivers)	31	n/a	n/a	0	Roch, B, et al. 2005
13	2005	England	Portsmouth (South East)	Surface water (River Itchen)	44	140	n/a	0	Nichols et al., 2006
14	2005	Turkey	West	Ground water	24	191	n/a	0	Askoy et al., 2007 (Eurosurveillance, Volume 12, Issue 7, 15 February 2007)
15	2005	Turkey	Malatya City	Ground water (well water)	1925	20000	276	0	Koroglu et al. 2011

	Year	Country	Location	Source water	Cases confirmed	Total cases estimated	Hospital admission	Deaths	
16	2005	Wales	Llyn Cwellyn	Surface water	231	n/a	n/a	0	Outbreak Control Team, North West Wales. 2006
17	2006	England	South West	Ground water (well water)	n/a	20	2	0	
18	2006	New Zealand		Surface water	n/a	n/a	n/a	0	Hewitt et al., 2007
19	2006	Italy	Apulia	Unknown	n/a	2860	n/a	0	Martinelli et al., 2007
20	2006	Ireland	Portlaw	Surface water (spring)	8	n/a	n/a		Carlow County Council. 2008
21	2006	Austria		Surface water (reservoir)	n/a	160	3	0	Meusburger et al., 2007
22	2006	Australia	Queensland	Tank water	11	46	n/a	0	Dale et al. 2010
23	2007	USA	New Hampshire	Ground water (well water)	27	n/a	n/a	0	Daly et al., 2010
24	2007	Australia	Victoria	Surface water	11	n/a	n/a	0	Franklin et al., 2008
25	2007	England	Hull	Surface Water	n/a	n/a	n/a	n/a	Anon 2009
26	2007	England	North Walsham	Ground water (aquifer)	n/a	n/a	n/a	n/a	Anon 2009
27	2007	England	Fairford, Gloucestershire	Surface water	n/a	n/a	n/a	n/a	Mcdonald, S. EPA online. Accessed 30.8.2013
28	2007	USA	Florida	Surface water (reservoir)	n/a	1663	n/a	0	Centres for Disease Control and Prevention, vol 60
29	2007	Ireland	Galway, West	Surface water	182	240	40	0	Pelley et al., 2007 (Eurosurveillance, Volume 12, Issue 18, 03 May 2007)
30	2007	Norway	Oslo	Groundwater					Robertson, L, et al. 2007
31	2007	Norway	Roros	Groundwater	32	1500	7	0	Jakopanek et al., 2008
32	2007	Finland	Nokia	Groundwater	250	8453	200	0	Laine et al., 2011; Halonel et al., 2012; Meittinen et al, 2012
33	2007	Denmark		Ground water (well water)	77	140	4	0	LS Vestergaard et al. 2007
34	2007	Belgium		Ground water (well water)	51	185	40	0	ter Waarbeek et al., 2010

	Year	Country	Location	Source water	Cases confirmed	Total cases estimated	Hospital admission	Deaths	
35	2007	China	Shenzen (South)	unknown	n/a	43	n/a	0	Ya-Qing et al, 2010
36	2008	France	Ardeche	Ground water (well water)	n/a	n/a	n/a	0	Galey et al., 2012
37	2008	Sweden	Lilla Edet	Surface water	33	2400		0	Larsson et al., 2013
38	2008	USA	Alamosa, Colorado	Ground water (well water)	124	1300	20	1	Centres for Disease Control and Prevention, vol 60 •Associated press online Ailes et al., 2013
39	2008	Switzerla nd	Zurich		12	n/a	n/a	0	Breitenmoser et al., 2011
40	2008	England	Berkshire	Ground water	n/a	n/a	n/a	n/a	Smith et al. 2010
41	2008	England	Pitsford, North Hampton	Surface water (reservoir)	33	250000	n/a	0	Northampton Chronicle & Echo (http://www.northamptonchron.co.uk/news/features/people-in-northampton-and-daventry-warned-not-to-drink-tap-water-1-928232) Smith et al 2010-Eurosurevillance
42	2009	Greece	Crete		60	n/a	n/a	0	Karagiannis et al., 2010
43	2009	Sweden	West	Ground water (well water)	6	n/a	n/a	0	Riera-Montes et al., 2011
44	2009	Italy	Lombardy	Surface water	30	299	n/a	0	http://www.ncbi.nlm.nih.gov/pubmed/19643050, http://www.eurosurveillance.org/viewarticle.aspx?articleid=19274
45	2009	Australia	North Pine treatment facility	Municipal drinking water	n/a	n/a	n/a	0	Cloete el al, 2011
46	2009	Australia	Pimpama-Coomera	Surface water (river)	n/a	n/a	n/a	0	Cloete el al, 2011

	Year	Country	Location	Source water	Cases confirmed	Total cases estimated	Hospital admission	Deaths	
47	2009	China			n/a	n/a	n/a	0	
48	2009	France		Surface Water (River)	150	n/a	n/a	0	Deere, D. et al. 2009
49	2010	Australia	Pimpama-Coomera	Surface water (river)	n/a	n/a	n/a	0	Cloete el al, 2011
50	2010	China	South		6	427		0	Yang et al., 2010
51	2010	Belgium	Antwerp		26	n/a	6	0	
52	2010	Denmark	Koge		61			0	Gubbels et al 2012
53	2010	Sweden	Östersund	Surface water	n/a	27000	65	0	WQRA, issue 65 Local Media (http://op.se/ostersund/1.2575643-kommunens-parasitenkat-avslutas)
54	2011	Spain	Gipuzkoa		26	n/a	n/a	0	Eurosurveillance, Volume 17, Issue 5, 02 February 2012
55	2011	Sweden	Skelleftea		n/a	20000	n/a	0	Andersson et al., 2013
56	2012	New Zealand	Darfield	Surface water	118	n/a	n/a	0	New Zealand Public Health Surveillance Report, vol 10, issue 4
57	2012	China	Jiangxi	Contaminated bottle water	n/a	417	n/a	0	Wang et al., 2012
58	2012	Greece	Elassona	Surface water	38	3600	2	0	HCDCP, 2013
59	2012	Greece	Nea Santa Kilkis	Contaminted tap water	7	n/a	n/a	0	Mellou et al 2013
60	2013	Ireland	Roscommon	Surface water	n/a	10000	n/a	n/a	RTE News Ireland 2013 (http://www.rte.ie/news/2013/0517/450919-water-roscommon/)
61	2013	USA	Oregon		n/a	n/a	n/a	n/a	n/a

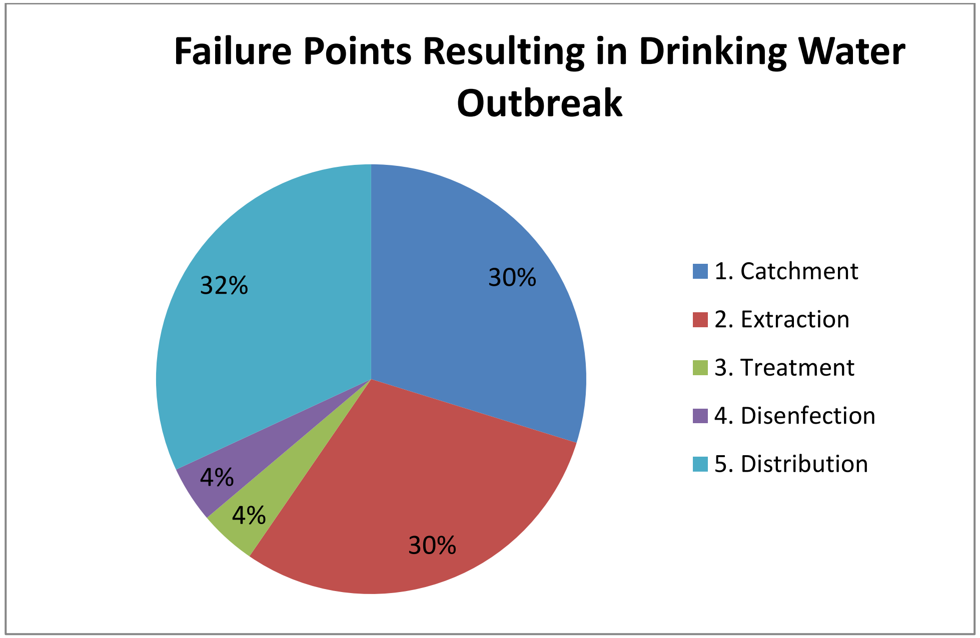
Alpha-Numeric Categorisation System

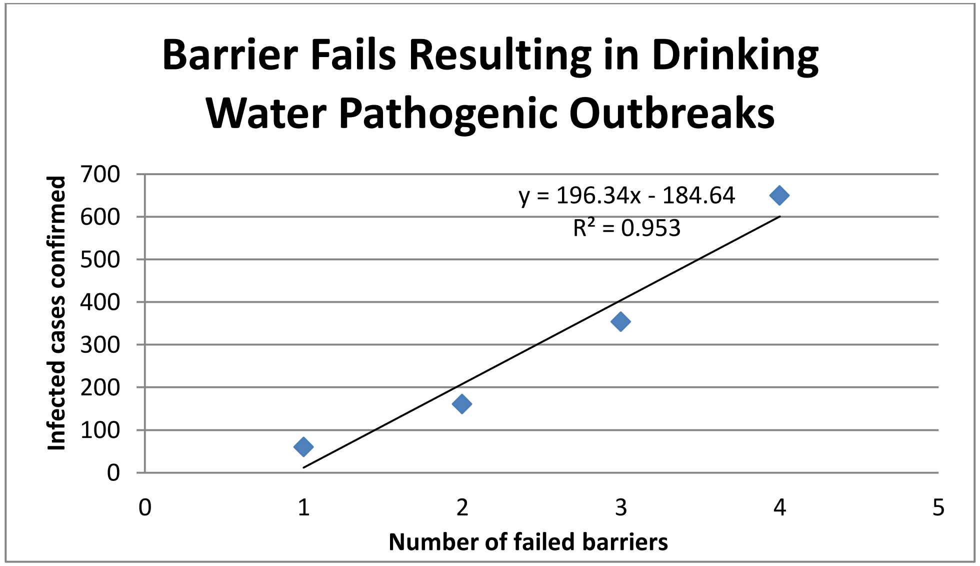
Case	ADWG Failure Point	Type of failure					Category	Confirmed cases
		Management Fail [A]	Infrastructural Breakage Fail [B]	Scheme Design Fail [C]	Monitoring Fail [D]	Operational Fail [E]		
Ireland (2000-2001)	5			C	D		5CD	120
France (2001)	5			C			5C	19
Netherlands (2001)	5	A		C		E	5ACE	250
Ireland (2002)	1			C			1C	29
Finland (2003)	5		B		D		5BD	40
Ireland (2003)	1			C			1C	n/a
Finland (2004)	2	A		C		E	2ACE	3
USA (2004)	2		B	C	D	E	2BCDE	650
USA (2004)	unknown							
Norway (2004)	2			C	D		2CD	1268
Austria (2005)	2			C			2C	4
Ireland (2005)	2	A		C			2AC	31
England (2005)	1	A		C			1AC	44
Turkey, West (2005)	2	A		C			2AC	24
Turkey, Malatya (2005)	5	A		C		E	5ACE	1925
Wales (2005)	1			C			1C	231
England (2006)	1		B	C	D		1BCD	
NZ(2006)	unknown							
Italy(2006)	unknown							
Ireland (2006)	1		B		D		1BD	8
Austria (2006)	2			C			2C	
Australia (2006)	unknown							11
USA; New Hampshire (2007)	1	A		C			1AC	27
Australia (2007)	1			C			1C	11
England;Hull (2007)	2			C	D		2CD	
England; North Walsham (2007)	1		B		D		1BD	
England; Fairford (2007)	2			C	D		2CD	
USA; Florida (2007)	unknown							
Ireland (2007)	2	A		C			2AC	182
Norway; Oslo (2007)	5	A		C		E	5ACE	
Norway;Roros (2007)	1	A	B		D		1ABD	32
Finland (2007)	5	A		C		E	5ACE	250

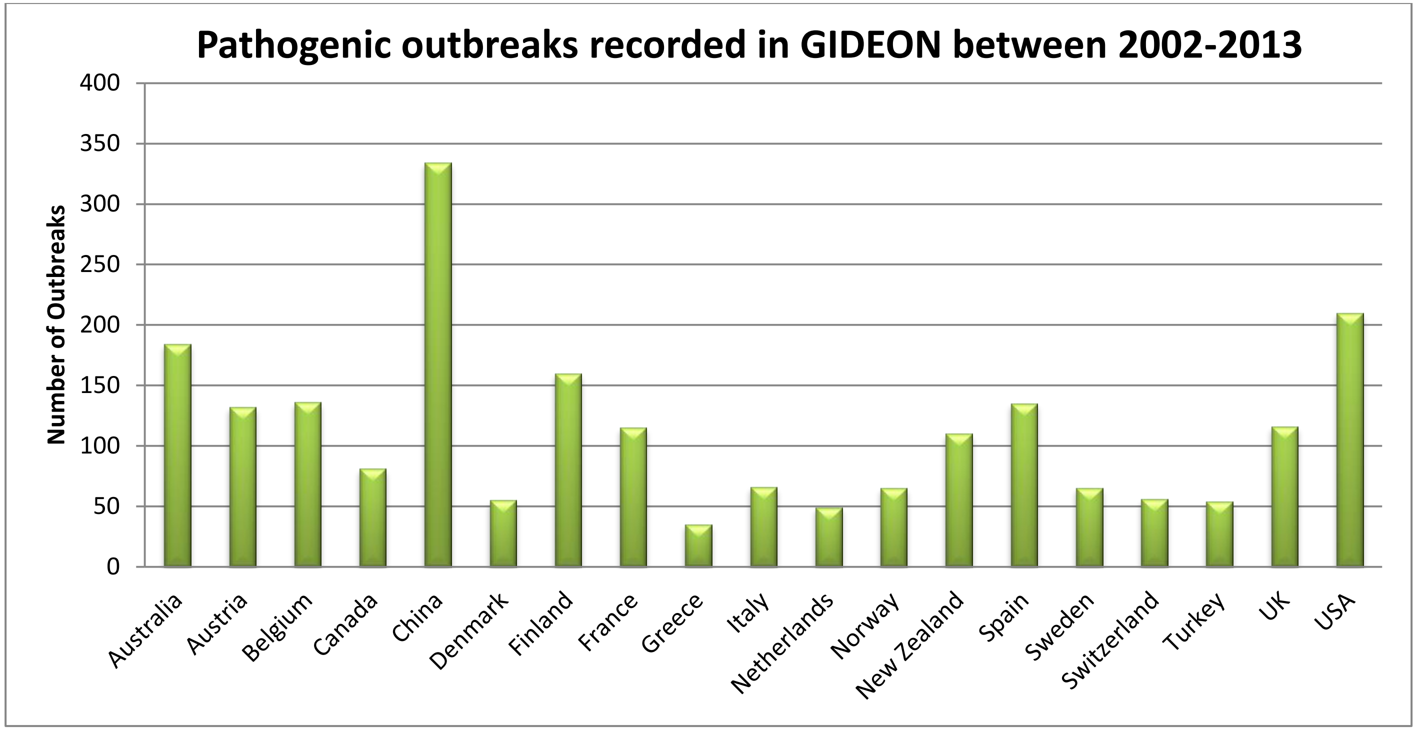
		Type of failure						
Case	ADWG Failure Point	Management Fail [A]	Infrastructural Breakage Fail [B]	Scheme Design Fail [C]	Monitoring Fail [D]	Operational Fail [E]	Category	Confirmed cases
Denmark (2007)	5			C			5C	77
Belgium (2007)	unknown							51
China (2007)	2		B		D		2BD	
France (2008)	unknown							
Sweden (2008)	2			C			2C	33
USA(2008)	3	A		C			3AC	124
Switzerland (2008)	5	A		C		E	5ACE	12
England; Berkshire (2008)	2	A		C		E	2ACE	n/a
England; Pitsford (2008)	2			C	D		2CD	33
Greece (2009)	unknown							60
Sweden (2009)	1	A	B		D		1ABD	6
Italy (2009)	3	A		C			3AC	30
Australia; North Pine (2009)	5	A		C		E	5ACE	
Australia; Pimpama (2009)	5	A		C		E	5ACE	
China (2009)	unknown							
France (20009)	5			C			5C	150
Australia (2010)	5	A		C		E	5ACE	
China (2010)	4	A	B		D		4ABD	6
Belgium (2010)	unknown							26
Denmark (2010)	unknown							61
Sweden (2010)	5	A		C		E	5ACE	
Spain (2011)	4	A	B		D		4ABD	26
Sweden (2011)	unknown							
New Zealand (2012)	2	A		C	D		2ACD	118
China (2012)	unknown							
Greece; Elassona (2012)	1			C			1C	38
Greece; Nea Santa Kilkis (2012)	1			C			1C	7
Ireland (2013)	1			C			1C	

ADWG Failure Points	total
1. Catchment	14
2. Extraction	14
3. Treatment	2
4. Disenfection	2
5. Distribution	15

Type of Failure	total
1C	7
1AC	2
1BD	2
1ABD	2
1BCD	1
2C	3
2AC	3
2BD	1
2CD	4
2ACD	1
2ACE	2
3AC	2
4ABD	2
5C	3
5BD	1
5CD	1
5ACE	9
5BCDE	1






Pathogenic outbreaks recorded in GIDEON between 2002-2013
Number of Outbreaks
400
350
300
250
200
150
100
50
0
Australia
Austria
Belgium
Canada
China
Denmark
Finland
France
Greece
Italy
Netherlands
Norway
New Zealand
Spain
Sweden
Switzerland
Turkey
UK
USA

AUSTRALIAN WATER RECYCLING CENTRE OF EXCELLENCE GOAL 3

NATIONAL DEMONSTRATION, EDUCATION AND ENGAGEMENT PROGRAM

STREAM 1.3: RESILIENCE OF ADVANCED WATER RECYCLING SYSTEMS

8.3 Appendix C: DNV GL Resilience Modelling Report - Resilience Model Results

Australian Water Recycling
Centre of Excellence

RIF-CS Element	**Guidance**
Class	Report
Type	Resilience Modelling Results
Key	TBA
Source	DNV GL (UK) OPTAGON Software
Originating Source	DNV GL (UK)
Group	The University of New South Wales (UNSW), Black & Veatch Australia (BV), DNV GL United Kingdom (DNVGL UK)
Names	Results from OPTAGON Resilience Modelling Software
Identifiers	TBA
Location	The Australian Water Recycling Centre of Excellence (National Demonstration Education and Engagement Program)
Coverage	Reliability data from 64 cumulative years
Related Objects	TBA
Subjects	Australian Water Recycling Centre of Excellence, National Demonstration Education and Engagement Program, Mechanical Reliability
Description	This study was supported by the Australian Water Recycling Centre of Excellence and was prepared as part of the National Demonstration, Education and Engagement Program (NDEEP) Stream 1.3. Stream 1.3 focused on determining the resilience of advanced water recycling systems by using DNV GL's OPTAGON RAM Software. OPTAGON is a Monte Carlo-based resilience modelling software that was used to model the performance of a reference plant over 10 years to provide insight into nature of plant failure as well as develop strategies to reduce the incidence and duration of failure events.
Citation	TBA
Related Info	Tng, KH, Currie, J, Leslie G, 2015, 'Resilience of advanced water recycling systems' Australia Water Recycling Centre of Excellence (Australia). 2015:1. Link to the AWRCoE web site: http://www.australianwaterrecycling.com.au/
Rights	AWRCoE holds all rights and ownership of this data.
Sensitive Data	Approval from AWRCoE is required prior to access, use and redistribution of data.

AWRCOE WATER REUSE PROCESS RESILIENCE MODELLING

Capacity and Quality RAM Modelling

Black & Veatch

Report No.: 15887, Rev. 1
Document No.: 1
Date: 19/11/2014

Project name:	AWRCoE Water Reuse Process Resilience Modelling	
Report title:	Capacity and Quality RAM Modelling	
Customer:	Black & Veatch, 2 Bukit Merah Central #07-01, Singapore 159835	
Contact person:	Sock-Hoon Koh	
Date of issue:	19/11/2014	
Project No.:	4002873	
Organisation unit:	Risk Advisory	
Report No.:	15887, Rev. 1	
Document No.:	1	

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Applicable contract(s) governing the provision of this Report:

Objective:

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Tara Smith Senior Safety Engineer		

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Keywords:
Water Resilience Modelling

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2014-10-31	First issue (Draft Report)	M Audley & T Smith		
1	2014-11-19	Final Report	M Audley & T Smith		

Table of contents

EXECUTIVE SUMMARY

The resilience of a waste water treatment facility is a fundamental factor in maintaining continuous compliance with its environmental discharge consent.

Resilience is defined as the ability of a system to perform and maintain its functions in routine, as well as unexpected circumstances. Or in other words, the overall resilience of a waste water treatment facility combines the performance of the treatment process with the availability of the associated critical equipment.

DNV GL has been engaged to develop a resilience model for a water re-use reference plant, using their OPTAGON software.

OPTAGON is a modelling tool that has been developed in-house by DNV GL, and has been used to deliver Reliability, Availability and Maintainability (RAM) assessments for a variety of major international oil and gas companies for over 15 years.

This reference plant study involves developing a resilience model to reflect the proposed operations, to quantify the risk of Non-Compliance as a result of the unavailability of specific equipment items. In addition, a number of 'what-if' scenarios are also modelled.

Finally, the resilience model consists of two parts; a 'Capacity' model, which looks at throughput, and a 'Quality' model, which assesses the number of Non-Compliance events and total duration of Non-Compliance events expected after a given time period.

Capacity Model

The Production Availability assessment of the components influencing capacity demonstrates a Production Availability of 75.93% and corresponding shortfall of 24.07%, indicating that the system spends around a quarter of time not producing any output.

The Operational Availability assessment of the components influencing capacity demonstrates an Operational Availability/Uptime of 40.54%, indicating that the system spends a high proportion of time not at maximum capacity.

The main contributors to shortfall for the capacity model are the Treated Water Delivery Pumps, equipment ID PU5. These pumps have a relatively high MTTR compared to their MTBF and spend a high proportion of their life in a failed state. Improving the MTTR of these components, or increasing redundancy, would have the greatest impact on reducing the system shortfall.

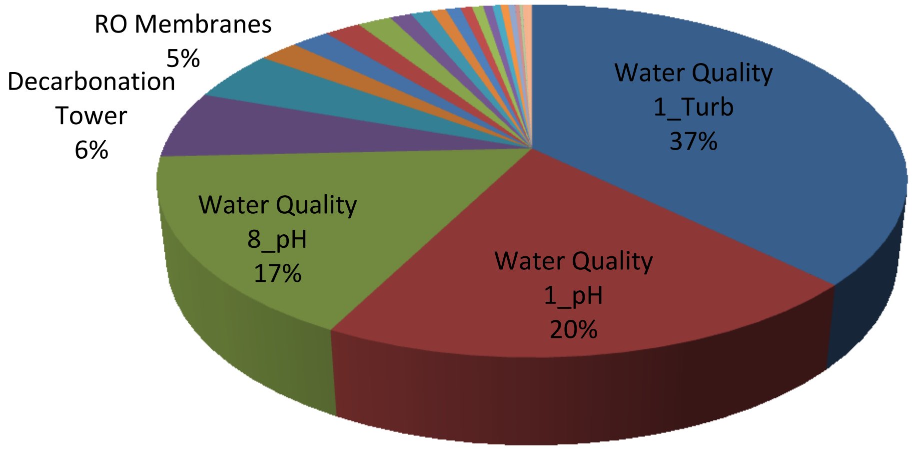
Quality model

The following predictions were made for the Base Case Quality model:

- The mean number of Non-Compliance events expected over a 10 year period is 427.

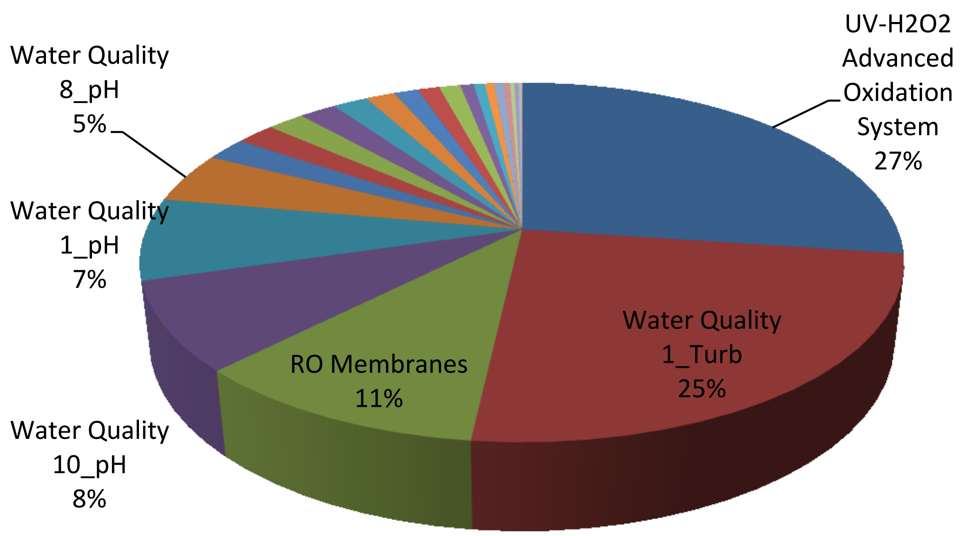
- Approximately 38% of the Non-Compliance events are caused by the inclusion of the component WQ1_Turb (Water Quality 1 Turbidity) in the model.
- The mean total duration of Non-Compliance events, over the 10 year period, is 24,555 hours.
- Approximately 27% of the total duration of Non-Compliance events is caused by the inclusion of ME4 (UV-H2O2 Advanced Oxidation System) in the model.

The top 5 contributors to Non-Compliance events are shown, in their respective proportions of the total 427 Non-Compliance events, as a pie chart in the figure below:



Base Case Non-Compliance events

In addition, the top 6 contributors to the total duration of Non-Compliance are shown, in their respective proportions of the total 24,555 hours, as a pie chart in the figure below:



Base Case Breakdown of Non-Compliance event Time

Following a presentation of the Base Case results, five Sensitivity Cases were modelled. The table below shows a summary of the Base Case and Sensitivity Case results for the quality model. The most significant drop in Non-Compliance events and duration of Non-Compliance events can be seen in Sensitivity Cases 3 and 5. This demonstrates that the most significant input parameters, which impact the number of Non-Compliance events and the duration of Non-Compliance events, are the MTTR and the deferred effect. Hence, adequate storage should be included in the proposed facility to maintain a suitable deferred effect time. In addition, for equipment with long repair times, either storing spare components on site to reduce any logistic delays within the repair times or further sparing of these equipment items could be considered.

Summary of Base Case and Sensitivity Case Results (10 year period)

Case	No. Non-Compliance events	Duration of Non-Compliance events (Hours)
Base Case	427	24,555
Sensitivity Case 1	418	23,286
Sensitivity Case 2	419	16,927
Sensitivity Case 3	180	2,874
Sensitivity Case 4	402	23,697
Sensitivity Case 5a	142	2,340
Sensitivity Case 5b	131	1,966
Sensitivity Case 5c	122	1,617
Sensitivity Case 5d	117	1,451
Sensitivity Case 5e	113	1,264

1 INTRODUCTION

The resilience of a waste water treatment facility is a fundamental factor in maintaining continuous compliance with its environmental discharge consent.

Resilience is defined as the ability of a system to perform and maintain its functions in routine, as well as unexpected circumstances. Or in other words, the overall resilience of a waste water treatment facility combines the performance of the treatment process with the availability of the associated critical equipment.

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Finally, the resilience model consists of two parts; a 'Capacity' model, which looks at throughput, and a 'Quality' model, which assesses the number of Non-Compliance events and total duration of Non-Compliance events expected after a given time period.

2 DATA ASSUMPTIONS

The following assumptions have been made with regard to input data:

- Failure, repair and deferred effect data has been provided by Black & Veatch.
- The Probability of failure to start on demand has been considered as negligible.
- For the following data inputs, mean values with statistical distributions has been used:
    - MTBF (Exponential Distribution);
    - MTTR (Exponential Distribution);
- The throughput is a constant 100ML/d.
- All Models are run for 10,000 simulations over a 10 year period.

3 DEFINITIONS

3.1 Common Definitions

Mean Time Between Failures (MTBF)

The MTBF is, on average, the time between failures for that equipment item and does include the repair time.

Mean Time To Repair (MTTR)

The MTTR is the ‘downtime’. The ‘downtime’ includes the response time and the time to repair the equipment item.

3.2 Capacity Model Specific Definitions

Production Availability

Production Availability is the proportion of required demand that a facility is meeting. As such, it is a measure of a facility’s ability to be used to accomplish its intended function.

Operational Availability/Uptime

Operational Availability is the proportion of time that a facility is at maximum throughput.

3.3 Quality Model Specific Definitions

Deferred Effect

The deferred effect is used by the system to understand when a Non-Compliance event has occurred. The deferred effect is the time between the equipment item(s) failing, where the number of failures meets the critical number, and this failure causing a Non-Compliance event. This includes the amount of storage and the dynamics of the treatment plant.

Critical Number

The critical number is the number of concurrent component failures needed to cause a Non-Compliance event, once the duration of the deferred effect has been exceeded. For example, for equipment items with configuration 3 x 100%, the critical number is 3 and for equipment items with configuration 3 x 50%, the critical number is 2.

4 CAPACITY MODEL

4.1 Input Data

Table 4.1 details the equipment configuration and input data that is used to build the capacity model. Failure of any of the equipment items listed in Table 4.1 will reduce the capacity of the system.

Table 4.1: Capacity Model Input Data

Equipment Name	Equipment Tag ID	Configuration	N + R	MTBF (Hours)	MTTR (Hours)	Impacts on throughput
WWTP Effluent Storage Tank	TA1	2 x 100%	1 + 1	34,566	20.5	As per configuration
WWTP Effluent Water forwarding pumps	PU1	4 x 33%	3 + 1	14,271	64	As per configuration
Water Quality 1_Turb	WQ1_Turb	1 x 100%	1 + 0	11,676	34	Not critical to throughput (Reduce by 10%)
Water Quality 1_pH	WQ1_pH	1 x 100%	1 + 0	11,676	17	Not critical to throughput (Reduce by 10%)
Water Quality 1_Temp	WQ1_Temp	1 x 100%	1 + 0	N/A	N/A	Not critical to throughput (Reduce by 10%)
Water Quality 1_Cond	WQ1_Cond	1 x 100%	1 + 0	46,706	4.5	Not critical to throughput (Reduce by 10%)
Water Quality 1_TOC	WQ5_TOC	1 x 100%	1 + 0	0	0	Not critical to throughput (Reduce by 10%)
Ammonium Sulphate Dosing Point	A1	2 x 100%	1 + 1	46,706	1.5	As per configuration
Sodium Hypochlorite dosing point	B1	2 x 100%	1 + 1	6,613	219	As per configuration
Raw Water Tank(s)	TA3	2 x 100%	1 + 1	519	1.5	As per configuration
MF/UF Feed Pumps	PU2	6 x 20%	5 + 1	2,605	150	As per configuration
Strainers	ST1	6 x 20%	5 + 1	1,260	65.1	As per configuration
MF/UF Membrane	ME1	12 x 10%	10 + 2	3,839	133	As per configuration
RO Feed Tank	TA4	2 x 100%	1 + 1	103.8	5.6	As per configuration
RO Low Pressure Pumps	PU3	4 x 33%	3 + 1	Pump 11,559 Motor 63,694	30 26	As per configuration
Cartridge Filters	ME2	6 x 20%	5 + 1	87,600	24	As per configuration
Anti-scalent Injection Point	L1	1 x 100%	1 + 0	782	28	As per configuration
RO High Pressure Pumps	PU4	12 x 11%	9 + 3	1,320	253	As per configuration
RO Membranes	ME3	12 x 11%	9 + 3	4,231	136	As per configuration
Water Quality 11_Cond	WQ11_Cond	1 x 100%	1 + 0	46,706	5	As per configuration
Water Quality 11_TOC	WQ11_TOC	1 x 100%	1 + 0	0	0	As per configuration
Water Quality 11_pH	WQ11_pH	1 x 100%	1 + 0	11,676	17	As per configuration
Water Quality 11_Turbidity	WQ11_Turb	1 x 100%	1 + 0	2,943	33	As per configuration
Hydrogen Peroxide Injection point	F1	1 x 100%	1 + 0	0	234	As per configuration
CIP Service Water Tank	TA5	1 x 100%	1 + 0	34,566	108	As per configuration
Sodium Hypochlorite dosing point	B4	1 x 100%	1 + 0	0	0	As per configuration
Sodium Hydroxide dosing point	C4	1 x 100%	1 + 0	0	0	As per configuration
Treated Water Storage Tanks	TA6	2x 100%	1 + 1	87.5	9	As per configuration
Treated Water Delivery	PU5	4 x 33%	3 + 1	1,837	973	As per configuration

Equipment Name	Equipment Tag ID	Configuration	N + R	MTBF (Hours)	MTTR (Hours)	Impacts on throughput
Pumps						
MF/UF CIP Acid Tank	TA3-3b	1 x 100%	1 + 0	389	1	As per configuration
MF/UF CIP Caustic Tank	TA3-3a	1 x 100%	1 + 0	389	6	As per configuration
RO CIP TANK	TA4-1	1 x 100%	1 + 0	19,593	49	As per configuration

4.2 Capacity Model Results

The Production Availability assessment of the components influencing capacity demonstrates a Production Availability of 75.93% and corresponding shortfall of 24.07%.

The Operational Availability assessment of the components influencing capacity demonstrates an Operational Availability/Uptime of 40.54%.

The top contributors to the 24.07% shortfall are detailed in Table 4.2 and Figure 4.1.

Table 4.2: Capacity Model Top Shortfall Contributors

Equipment Tag ID	Equipment Name	Contributor to Shortfall (%)	Proportion of Shortfall (%)
PU5	Treated Water Delivery Pumps	14.65	60.85
L1	Anti-scalent Injection Point	2.94	12.21
PU4	RO High Pressure Pumps	1.93	8.01
TA3-3a	MF/UF CIP Caustic Tank	1.28	5.33
WQ11_Turb	Water Quality 11_Turbidity	0.92	3.81
PU2	MF/UF Feed Pumps	0.42	1.74
TA6	Treated Water Storage Tanks	0.41	1.70
ST1	Strainers	0.35	1.45
TA5	CIP Service Water Tank	0.26	1.08
TA4-1	RO CIP TANK	0.20	0.84
TA3-3b	MF/UF CIP Acid Tank	0.18	0.74
ME1	MF/UF Membrane	0.16	0.67
WQ11_pH	Water Quality 11_pH	0.12	0.48
TA4	RO Feed Tank	0.11	0.47
ME3	RO Membranes	0.06	0.25
B1	Sodium Hypochlorite dosing point	0.04	0.18
WQ1_Turb	Water Quality 1_Turb	0.02	0.09
WQ1_pH	Water Quality 1_pH	0.01	0.05
WQ11_Cond	Water Quality 1_Cond	0.01	0.03
PU3	RO Low Pressure Pumps	0.00	0.02
	Others	0.00	0.01
	Total	24.07	100

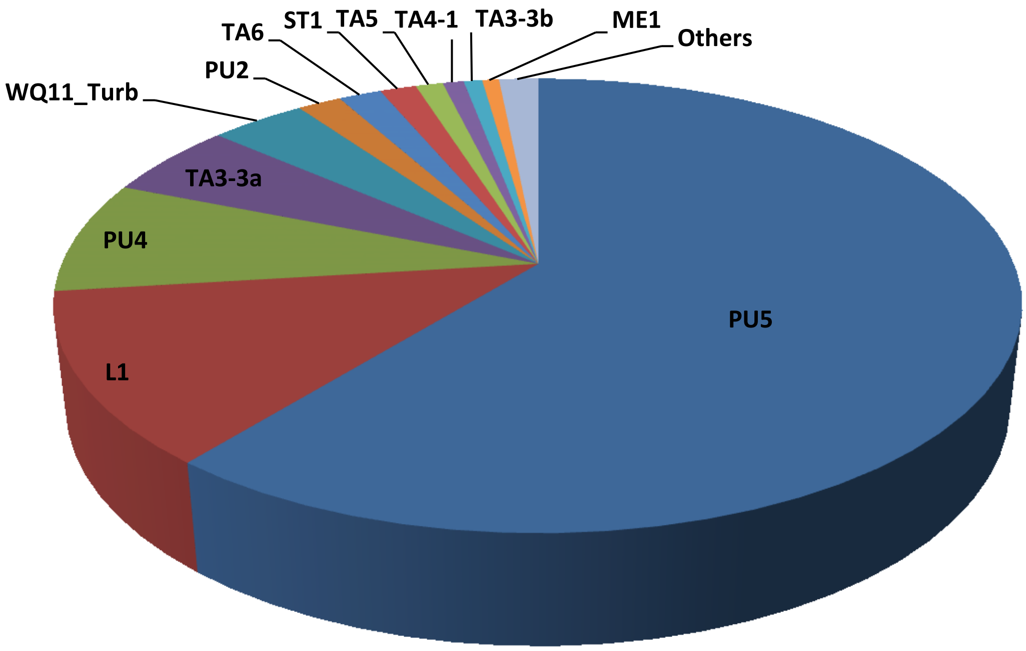

Figure 4.1: Capacity Model Shortfall Contributors

The Treated Water Delivery Pumps (PU5) are the main contributors to shortfall, comprising 60.85% of the total shortfall. This is due to the pumps' relatively low MTBF of 1,837 hours and extensive MTTR of 973 hours. Because the MTTR is such a long duration in comparison to the MTBF it is very likely that a pump will fail whilst one is still being repaired, causing system downtime. Each of these pumps spends on average a third of their life in an unavailable state. Reducing the MTTR of these components would have a positive effect on the system availability.

The next significant contributor to shortfall is the Anti-scalent Injection Point (L1), which although has a relatively short (compared to other components) MTTR of 28 hours, it is still a significant proportion of its MTBF of 782 hours, and as this component is not in redundancy, it spends a high proportion of its life in an unavailable state.

5 QUALITY MODEL

The resilience of a system or process is ultimately a function of the availability of its critical components, determined through quantifying their likelihood of failure, combined with the effect, or consequence, of their failure on the performance of the system or process under all possible conditions. As such, resilience assessment quantifies the risk of a 'Non-Compliance event' to which a treatment facility, process or system is exposed.

A Non-Compliance event occurs when equipment items relating to the water quality fail. The consequences of a Non-Compliance event depend on which equipment item has failed. Potential consequences of Non-Compliance events include aesthetic, health and environmental issues. However, the impact of Non-Compliance events for particular equipment items is outside the scope of this study.

This section of the report quantifies the expected number of Non-Compliance events and the total duration of Non-Compliance events over a 10 year period, based on the equipment configuration outlined in section 5.1.

5.1 Input Data

Table 5.1 lists all of the input data, which is used to build the Base Case quality model. Failure(s) of any of the equipment items, listed in Table 5.1, has the potential to cause a Non-Compliance event, providing that the critical number of failures has been met / exceeded. Where the outcome of a Non-Compliance event 'event' is defined outside of the model and is applied across all equipment items considered in this study.

Table 5.1: Quality Model Input Data—Base Case

Tag ID	Name	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	UV-H2O2 Advanced Oxidation System	4 x 33%	2	1,890	291	0
WQ1_Turb	Water Quality 1_Turb	1 x 100%	1	195	34	24
ME3	RO Membranes	12 x 11%	4	4,231	136	0
WQ10_pH	Water Quality 10_pH	1 x 100%	1	2,998	103	24
WQ1_pH	Water Quality 1_pH	1 x 100%	1	195	17	24
WQ8_pH	Water Quality 8_pH	1 x 100%	1	104	10	24
WQ7_ORP	Water Quality 7_User defined ORP	1 x 100%	1	6,780	72	24
ME1	MF/UF Membrane	12 x 10%	3	3,839	133	0
WQ12_ORP	Water Quality 12_ORP	1 x 100%	1	6,780	72	24
WQ15_Turb	Water Quality 15_Turbidity	1 x 100%	1	2,943	33	24
WQ11_Turb	Water Quality 11_Turbidity	1 x 100%	1	2,943	33	24
WQ11_Cond	Water Quality 11_Cond	1 x 100%	1	9,873	55	24
L1	Anti-scalent Injection Point	1 x 100%	1	3,126	28	24
WQ7_turb	Water Quality 7_Turb	1 x 100%	1	5,887	33	24
WQ15_FCL	Water Quality 15_Free Chlorine	1 x 100%	1	8,266	44	24

Tag ID	Name	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
FN1	Decarbonation fans	3 x 50%	2	1,864	35	0
WQ5_Turb	Water Quality 5_Turb	1 x 100%	1	11,676	34	24
ME5	Decarbonation Tower	1 x 100%	1	1,557	1	0
WQ15_pH	Water Quality 15_pH	1 x 100%	1	11,676	17	24
WQ2_Cl2	Water Quality 2_Cl2	1 x 100%	1	8,492	25	24
WQ11_pH	Water Quality 11_pH	1 x 100%	1	11,676	17	24
WQ1_Cond	Water Quality 1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	Water Quality 7_Total Cl	1 x 100%	1	14,401	3	24
WQ7_Cond	Water Quality 7_Cond	1 x 100%	1	46,706	5	24

5.2 Methodology

A Reliability Block Diagram (RBD), of the 'Quality' model, has been built using the input data listed in Table 5.1. Monte Carlo modelling has been used to simulate 10,000 combinations of failures and repairs in order to determine a mean total duration of Non-Compliance events and the mean number of Non-Compliance events, where the exponential distribution is used to generate random MTBF's and MTTR's for each of the 10,000 simulations.

For equipment items with a deferred effect greater than 0 hours, if the number of equipment failures meets or exceeds the critical number, the duration of the deferred effect needs to be exceeded before a Non-Compliance event can occur. For example, WQ1_Turb has a critical number of 1 and a deferred effect of 24 hours. Hence, once WQ1_Turb fails if it is not repaired within 24 hours a Non-Compliance event will occur. The duration of the Non-Compliance event is the total repair time minus 24 hours. For equipment items with a deferred effect of 0 hours, a Non-Compliance event will occur upon failure and the duration of this Non-Compliance event is equal to the repair time.

As distributions are used, all equipment items listed in Table 5.1 could potentially cause a Non-Compliance event in their own. However, if the MTTR for an equipment item is significantly less than the deferred effect, then, the likelihood of causing a Non-Compliance event is reduced. If a failed equipment item does not cause a Non-Compliance event on its own, its failure will need to coincide with the failing of at least one additional component for it to cause a Non-Compliance event.

There are many complexities within this model. Hence, it lends itself to Monte Carlo modelling.

6 QUALITY MODEL RESULTS

6.1 Base Case Results

The Base Case model was developed based on the input data and assumptions detailed in the preceding sections. The resilience of the proposed water treatment facility can be measured by the following key parameters:

- The mean number of Non-Compliance events.
- Mean total duration of Non-Compliance events.

The number and duration of Non-Compliance events are not directly proportional to each other.

For the purpose of this study, all models are based on a system life of 10 years. Table 6.1 shows the summary of the Base Case results.

Table 6.1: Summary of Base Case Results

Mean number of Non-Compliance events per 10 years:	427 events
Mean total duration of Non-Compliance events over 10 years:	24,555 hours

The results show that the number of Non-Compliance events the proposed facility will experience is approximately 42.7 per year, over a 10 year period. The total duration of Non-Compliance events will be approximately 2,455.5 hours per year, over a 10 year period.

Table 6.2 shows the individual equipment results breakdown for the Base Case model sorted by descending Non-Compliance event duration. Table 6.2 lists each of the equipment items in the Base Case model complete with the number of Non-Compliance events and total duration of Non-Compliance events which can be attributed to the individual items. The duration and number of Non-Compliance events are not proportional. The repair count is also included in the results and is the number of times that equipment item has been repaired over the 10 year period.

Section 6.2 describes how the results listed in Table 6.2 can be interpreted.

Table 6.2: Individual Equipment Results Breakdown

Tag ID	Name	No of Non-Compliance events	Duration of Non-Compliance	% of Non-Compliance duration	Repair count
ME4	UV-H2O2 Advanced Oxidation System	-2	6,671	27%	161
WQ1_Turb	Water Quality 1_Turb	161	6,043	25%	384
ME3	RO Membranes	20	2,625	11%	201
WQ10_pH	Water Quality 10_pH	2	1,960	8%	28
WQ1_pH	Water Quality 1_pH	87	1,814	7%	414
WQ8_pH	Water Quality 8_pH	72	1,118	5%	767
WQ7_ORP	Water Quality 7_User defined ORP	2	513	2%	13
ME1	MF/UF Membrane	8	487	2%	265

Tag ID	Name	No of Non-Compliance events	Duration of Non-Compliance	% of Non-Compliance duration	Repair count
WQ12_ORP	Water Quality 12_ORP	2	463	2%	13
WQ15_Turb	Water Quality 15_Turbidity	8	459	2%	29
WQ11_Turb	Water Quality 11_Turbidity	8	437	2%	29
WQ11_Cond	Water Quality 11_Cond	3	362	1%	9
L1	Anti-scalent Injection Point	9	301	1%	28
WQ7_turb	Water Quality 7_Turb	5	269	1%	15
WQ15_FCL	Water Quality 15_Free Chlorine	3	264	1%	11
FN1	Decarbonation fans	5	166	1%	138
WQ5_Turb	Water Quality 5_Turb	1	139	1%	8
ME5	Decarbonation Tower	27	117	0%	56
WQ15_pH	Water Quality 15_pH	1	117	0%	7
WQ2_Cl2	Water Quality 2_Cl2	3	78	0%	10
WQ11_pH	Water Quality 11_pH	2	55	0%	7
WQ1_Cond	Water Quality 1_Cond	2	49	0%	112
WQ7_TCL	Water Quality 7_Total Cl	0	28	0%	6
WQ7_Cond	Water Quality 7_Cond	0	19	0%	2

ME4 is responsible for 27% of the total duration of Non-Compliance events, which is due to it having a significantly long MTTR of 291 hours and no deferred effect. If ME4 was 100% available then the mean duration of Non-Compliance events would reduce by approximately 6,671 hours, over a 10 year period. However, the mean number of Non-Compliance events would increase by 2, over a 10 year period. ME4 has failed and been repaired, on average, 16.1 times per year. However, as the configuration of ME4 is 4 x 33%, which means there is one redundant equipment item, not all of these failures would result in a Non-Compliance event.

WQ1_Turb is responsible for 25% of the total duration of Non-Compliance events, which is due to a combination of a relatively short MTBF and an MTTR greater than the deferred effect of 24 hours. Having a repair time greater than the deferred effect and no sparing will result in a Non-Compliance events upon most failures.

Components ME4 and WQ1_Turb account for the majority of the total duration of Non-Compliance events. Hence, these components should be focussed on in order to significantly reduce the total duration of Non-Compliance events.

Figure 6.1 and Figure 6.2 provide an indication of the vulnerability of the facilities performance in terms of likelihood of non-compliance. It should be noted that the total duration of Non-Compliance events per 10 years, shown in Figure 6.2, is only applicable to the “Non-Compliance events” bar shown in Figure 6.1.

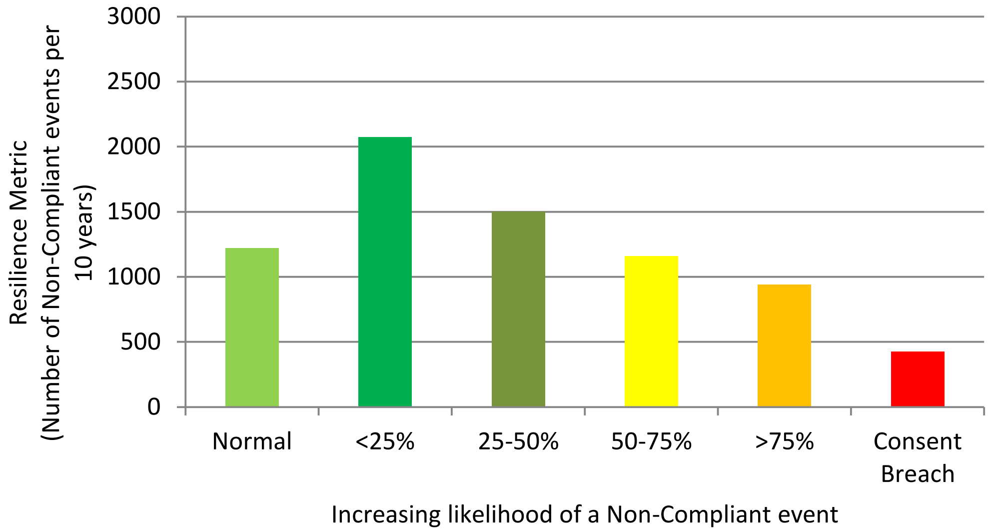

Figure 6.1: Non-Compliance event Risk Profile—Base Case

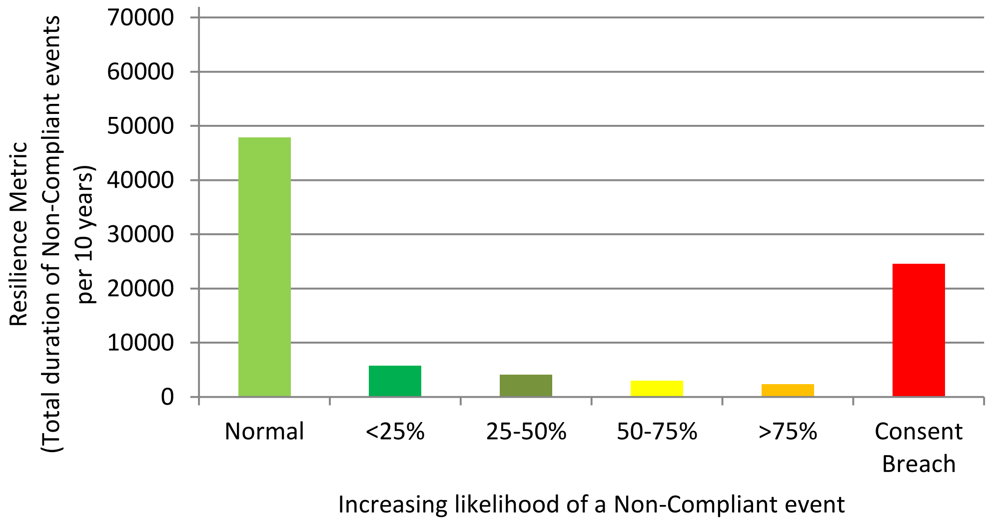

Figure 6.2: Non-Compliance event Duration Risk Profile—Base Case

6.2 Interpretation of Results

When X amount of Non-Compliance events and Y duration of Non-Compliance events are attributed to a piece of equipment, this means that if that equipment item was 100% available then the number of Non-Compliance events would reduce by approximately X amount and the duration of Non-Compliance events would reduce by approximately Y amount, this is called the 'delta'. Furthermore, the attribution of Non-Compliance time and the number of Non-Compliance events are not necessarily directly linked – i.e. the time in Non-Compliance, attributed to a particular component, is not necessarily caused by the respective number of Non-Compliance events attributed to that component. If it were, this would wrongly assume that everything else stayed unchanged – ignoring the fact that much of the time the component under investigation merely takes the plant to a state of increased likelihood of Non-Compliance without actually causing a Non-Compliance event.

Component ME4 is a perfect example of this. For the Base Case configuration, if the availability of this component was 100%, the 'delta' in number of Non-Compliance events is -2. However, the 'delta' Non-Compliance time is 6,671 hours. This does not mean that the additional 6,671 hours is caused by the -2 events – what is actually happening is that the inclusion of ME4 extends the Non-Compliance time of many other Non-Compliance events (to the sum of 6,671 hours) that are already occurring and caused by other components failing.

If a model was run, which only contained ME4, there would be approximately 41 Non-Compliance events and a total Non-Compliance event duration of approximately 6,774 hours over 10 years. However, when the complete model is run these Non-Compliance events are absorbed into the total number of Non-Compliance events (427) and for this specific configuration, the inclusion of ME4 actually reduces the number of Non-Compliance events.

Figure 6.3 aims to explain this. The following plots illustrate, what is understood to be, the three most likely types of Non-Compliance events when ME4 is included in the model. The Blue line represents ME4 and the Red line represents the rest of the components within the model. For the purpose of this illustration, the duration of the Red events are 1 unit and the duration of the Blue events are 3 units. The results for each case are outlined in Table 6.3.

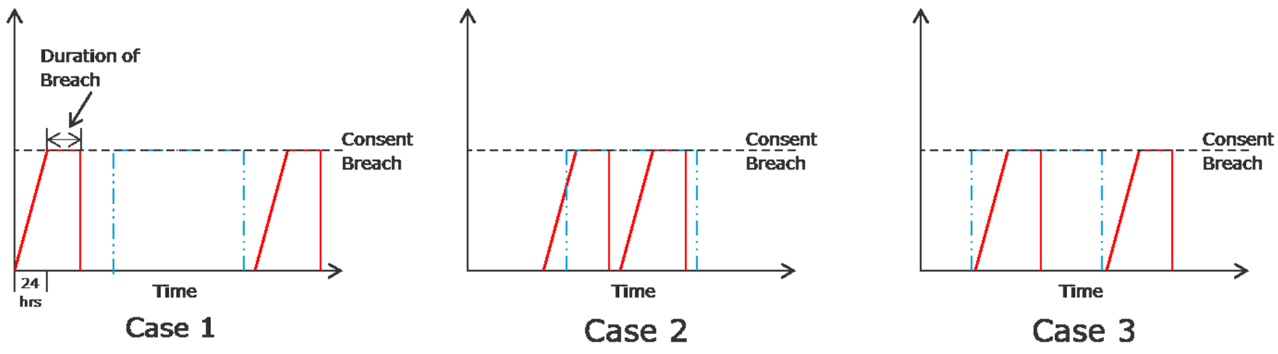

Figure 6.3: Non-Compliance events with and without ME4

Table 6.3: Non-Compliance events Cases Results (ME4)

	Case 1		Case 2		Case 3	
	No. Non-Compliance events	Duration	No. Non-Compliance events	Duration	No. Non-Compliance events	Duration
Inc ME4	3	5 Units	1	3 Units	2	4 Units
Exc ME4	2	2 Units	2	2 Units	2	2 Units

A higher proportion of Case 1's than Case 2's would result in a positive number of Non-Compliance events being attributed to ME4. Conversely, a higher proportion of Case 2's than Case 1's would result in a negative number of Non-Compliance events being attributed to ME4. In addition, it is possible for an approximately equal number of Case 1's and Case 2's occurring. Finally, Case 3 does not affect the total number of Non-Compliance events being assigned to ME4.

For the Base Case, the assumption is that there is a higher chance of Case 2 occurring than Case 1. Hence, the overall number of Non-Compliance events attributed to ME4 is negative. Please note that for Case 2, where ME4 overlaps 2 Non-Compliance events caused by other equipment failures, there are multiple versions of this as a Non-Compliance event caused by ME4 could overlap more than 2 Non-Compliance events caused by other equipment items.

These results are based on 10,000 simulations, and the mean number of Non-Compliance events after 10,000 simulations is the value that is assigned to each component. For example, the plot shown in Figure 6.4 shows how the mean number is obtained. Each Red dot represents the number of Non-Compliance events attributed to ME4 after each simulation, for the first 250 simulations. The blue line shows how the mean number of Non-Compliance events attributed to ME4 converges to -2 as the number of simulations increases.

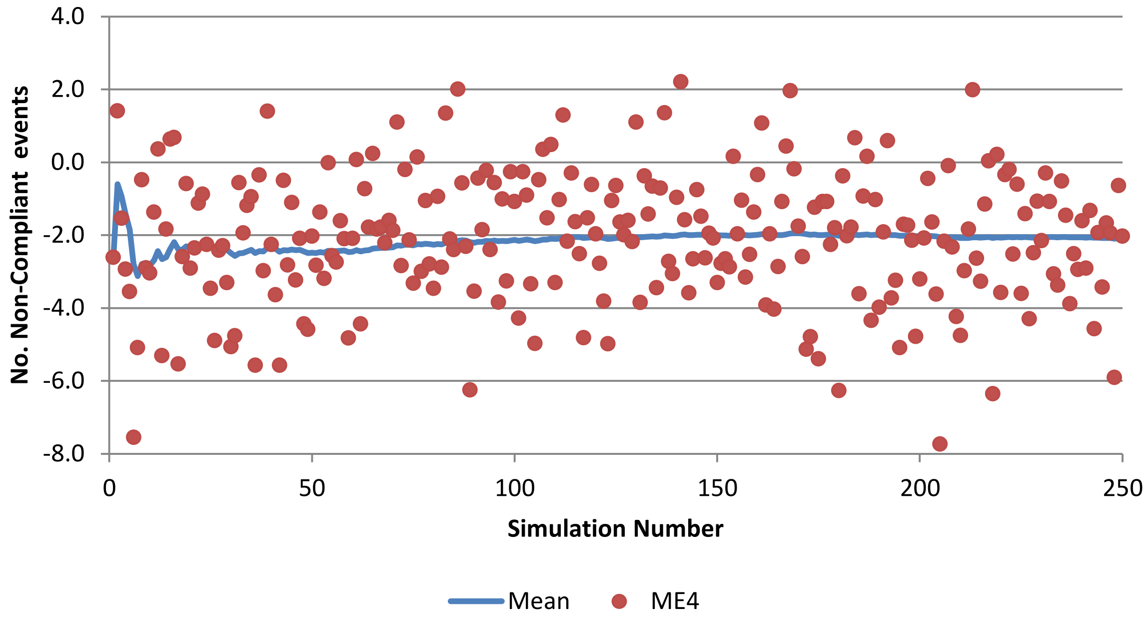

Figure 6.4: Number of Non-Compliance events attributed to component ME4

Risk profiles

Two risk profiles are provided with the results, a Non-Compliance risk profile and a Non-compliance duration risk profile.

The first risk profile, the Non-Compliance profile, can be used to derive the probability of being in each state. Here, the simulation software counts the number of times the system is in each state.

The second risk profile, the Non-Compliance Duration profile, shows the mean amount of time spent in each state. Here, the simulation software counts duration the system is in each state.

Each risk profile shows five possible system states. The default system state is 0%, which means the deferred effect clock is not 'ticking'. The next few interim states (<25%, 25 – 50%, 50 – 75%, >75%) show that the deferred effect clock is currently ticking. For example, consider a plant consisting of only one equipment item, which has a deferred effect of 24 hours. Prior to failure, the plant is in the 0% state. Upon failure, the plant is in the <25% state. After 12 hours the plant will be in the 50 – 75% state etc. Finally, after 24 hours the plant will be in the final state (100%), the Non-Compliance event state (assuming the equipment item has not been repaired). Equipment items with a deferred effect time will cause the plant to pass through each of the states. Conversely, equipment items with a deferred effect of 0 hours will cause the plant to go straight from the 0% state to the Non-Compliance event state upon failure.

6.3 Sensitivity Cases

Sensitivity cases are adjustments with respect to the Base Case. Based on discussions with Black & Veatch, the following five Sensitivity Cases have been modelled:

Sensitivity Case 1

For Sensitivity Case 1 an additional, redundant, instrument has been added to each of the following critical instruments:

- WQ11_Cond
- WQ15_FCL
- WQ7_Turb
- WQ15_pH
- WQ12_ORP

Sensitivity Case 2

For Sensitivity Case 2 an additional, redundant, equipment item has been added to each of the following critical equipment (non-instrumental):

- ME1
- ME3
- ME4

Sensitivity Case 3

For Sensitivity Case 3, the MTTR for the following equipment items has been changed to 8 hours:

- WQ1_Turb
- WQ1_pH
- WQ2_Cl2
- WQ5_Turb
- WQ7_turb
- WQ7_ORP
- WQ8_pH
- L1
- WQ11_Cond
- WQ11_pH

- WQ11_Turb
- WQ12_ORP
- WQ15_Turb
- WQ15_FCL
- WQ15_pH
- WQ10_pH

In addition, the MTTR for the following equipment items has been changed to 72 hours:

- ME1
- ME3
- ME4

Sensitivity Case 4

For Sensitivity Case 4 the deferred impact time for the following equipment items has been increased to 12 hours:

- ME1
- ME3
- ME4
- ME5
- FN1

Sensitivity Case 5

For Sensitivity Case 5, the MTTR for the following equipment items has been changed to 8 hours:

- WQ1_Turb
- WQ1_pH
- WQ2_Cl2
- WQ5_Turb
- WQ7_turb
- WQ7_ORP
- WQ8_pH
- L1
- WQ11_Cond

- WQ11_pH
- WQ11_Turb
- WQ12_ORP
- WQ15_Turb
- WQ15_FCL
- WQ15_pH
- WQ10_pH

In addition, the MTTR for the following equipment items has been changed to 72 hours:

- ME1
- ME3
- ME4

Finally, a range of deferred effect times (12, 24, 48, 72 and 144 hours) for the equipment items listed below has been analysed:

- ME1
- ME3
- ME4
- ME5
- FN1

This range of deferred effect times has been denoted in the results section as follows:

Case	Deferred Effect (hours)
Sensitivity Case 5a	12
Sensitivity Case 5b	24
Sensitivity Case 5c	48
Sensitivity Case 5d	72
Sensitivity Case 5e	144

6.3.1 Sensitivity Case 1

Modelling input changes are highlighted in blue in Table 6.4.

Table 6.4: Quality Model Input Data—Sensitivity Case 1

Tag ID	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	4 x 33%	2	1,890	291	0
WQ1_Turb	1 x 100%	1	195	34	24
ME3	12 x 11%	4	4,231	136	0
WQ10_pH	1 x 100%	1	2,998	103	24
WQ1_pH	1 x 100%	1	195	17	24
WQ8_pH	1 x 100%	1	104	10	24
WQ7_ORP	1 x 100%	1	6,780	72	24
ME1	12 x 10%	3	3,839	133	0
WQ12_ORP	2 x 100%	2	6,780	72	24
WQ15_Turb	1 x 100%	1	2,943	33	24
WQ11_Turb	1 x 100%	1	2,943	33	24
WQ11_Cond	2 x 100%	2	9,873	55	24
L1	1 x 100%	1	3,126	28	24
WQ7_turb	2 x 100%	2	5,887	33	24
WQ15_FCL	2 x 100%	2	8,266	44	24
FN1	3 x 50%	2	1,864	35	0
WQ5_Turb	1 x 100%	1	11,676	34	24
ME5	1 x 100%	1	1,557	1	0
WQ15_pH	2 x 100%	2	11,676	17	24
WQ2_Cl2	1 x 100%	1	8,492	25	24
WQ11_pH	1 x 100%	1	11,676	17	24
WQ1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	1 x 100%	1	14,401	3	24
WQ7_Cond	1 x 100%	1	46,706	5	24

Table 6.5: Summary of Sensitivity Case 1 Results

	Sensitivity Case 1	Base Case
Mean number of Non-Compliance events per 10 years:	418 events	427 events
Mean total duration of Non-Compliance events over 10 years:	23,286 hours	24,555 hours

Table 6.5 shows the results for Sensitivity Case 1. Compared to the Base Case, the mean number of Non-Compliance events have been reduced by 9 and the mean total duration has been reduced by 1,269 hours. The risk profiles for the mean number of Non-Compliance events and the mean total duration of Non-Compliance events, compared to the Base Case, are shown in Figure 6.5 and Figure 6.6 respectively.

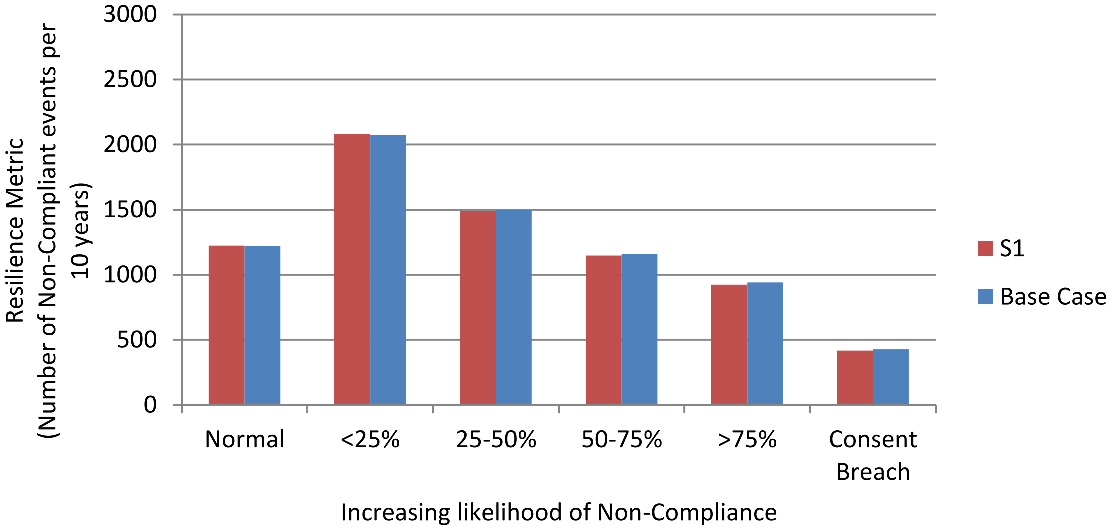

Figure 6.5: Non-Compliance Risk Profile—Sensitivity Case 1

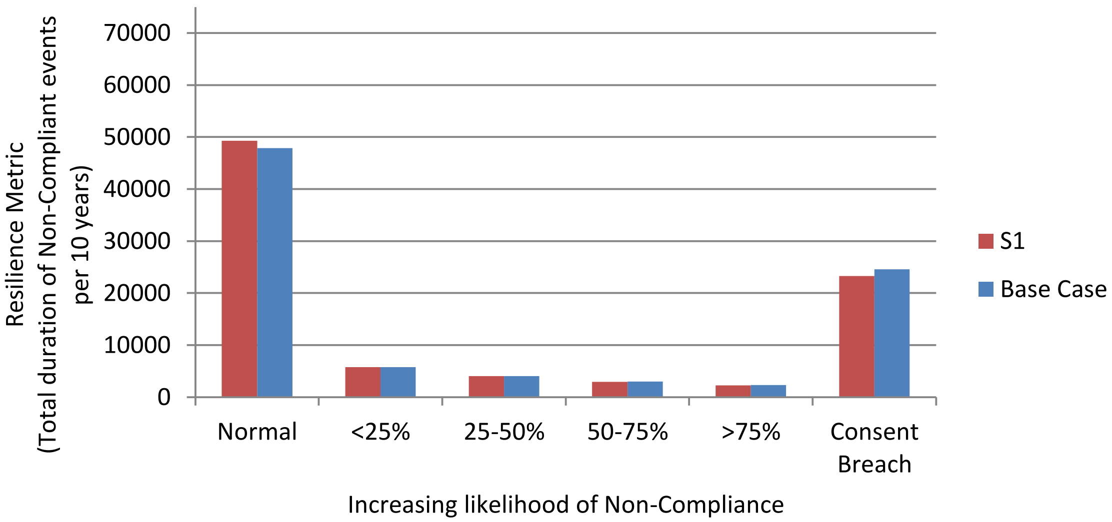

Figure 6.6: Non-Compliance Duration Risk Profile—Sensitivity Case 1

6.3.2 Sensitivity Case 2

Modelling input changes are highlighted in blue in Table 6.6.

Table 6.6: Quality Model Input Data—Sensitivity Case 2

Tag ID	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	5 x 33%	3	1,890	291	0
WQ1_Turb	1 x 100%	1	195	34	24
ME3	13 x 11%	5	4,231	136	0
WQ10_pH	1 x 100%	1	2,998	103	24
WQ1_pH	1 x 100%	1	195	17	24
WQ8_pH	1 x 100%	1	104	10	24
WQ7_ORP	1 x 100%	1	6,780	72	24
ME1	13 x 10%	4	3,839	133	0
WQ12_ORP	1 x 100%	1	6,780	72	24
WQ15_Turb	1 x 100%	1	2,943	33	24
WQ11_Turb	1 x 100%	1	2,943	33	24
WQ11_Cond	1 x 100%	1	9,873	55	24
L1	1 x 100%	1	3,126	28	24
WQ7_turb	1 x 100%	1	5,887	33	24
WQ15_FCL	1 x 100%	1	8,266	44	24
FN1	3 x 50%	2	1,864	35	0
WQ5_Turb	1 x 100%	1	11,676	34	24
ME5	1 x 100%	1	1,557	1	0
WQ15_pH	1 x 100%	1	11,676	17	24
WQ2_Cl2	1 x 100%	1	8,492	25	24
WQ11_pH	1 x 100%	1	11,676	17	24
WQ1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	1 x 100%	1	14,401	3	24
WQ7_Cond	1 x 100%	1	46,706	5	24

Table 6.7: Summary of Sensitivity Case 2 Results

	Sensitivity Case 2	Base Case
Mean number of Non-Compliance events per 10 years:	419 events	427 events
Mean total duration of Non-Compliance events over 10 years:	16,927 hours	24,555 hours

Table 6.7 shows the results for Sensitivity Case 2. Compared to the Base Case, the mean number of Non-Compliance events has been reduced by 8 and the mean total duration has been reduced by 7,628 hours. The risk profiles for the mean number of Non-Compliance events and the mean total duration of Non-Compliance events, compared to the Base Case, are shown in Figure 6.7 and Figure 6.8 respectively.

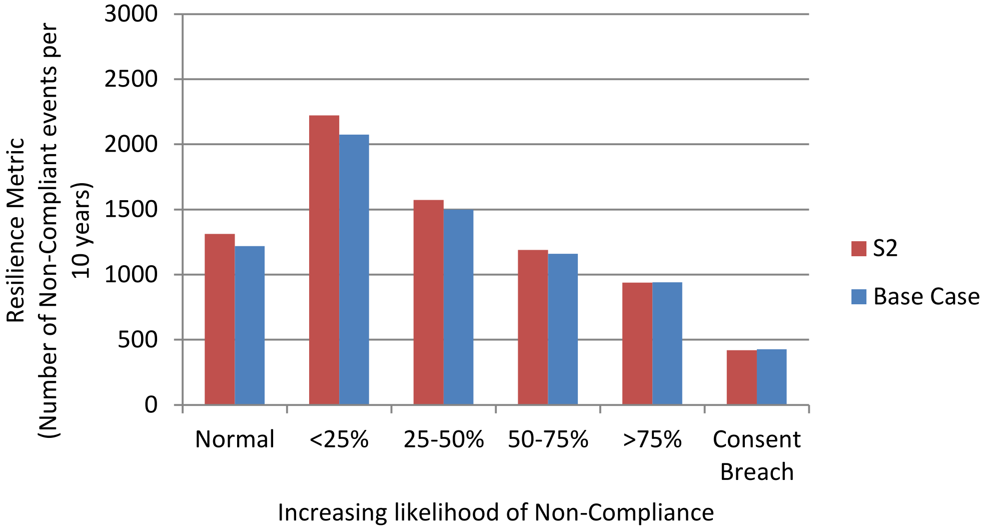

Figure 6.7: Non-Compliance Risk Profile—Sensitivity Case 2

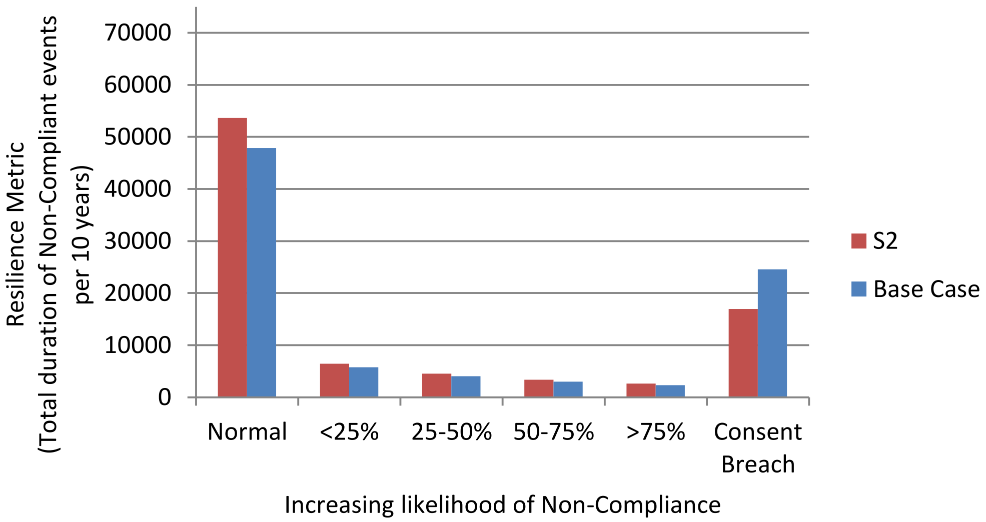

Figure 6.8: Non-Compliance Duration Risk Profile—Sensitivity Case 2

6.3.3 Sensitivity Case 3

Modelling input changes are highlighted in blue in Table 6.8.

Table 6.8: Quality Model Input Data—Sensitivity Case 3

Tag ID	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	4 x 33%	2	1,890	72	0
WQ1_Turb	1 x 100%	1	195	8	24
ME3	12 x 11%	4	4,231	72	0
WQ10_pH	1 x 100%	1	2,998	8	24
WQ1_pH	1 x 100%	1	195	8	24
WQ8_pH	1 x 100%	1	104	8	24
WQ7_ORP	1 x 100%	1	6,780	8	24
ME1	12 x 10%	3	3,839	72	0
WQ12_ORP	1 x 100%	1	6,780	8	24
WQ15_Turb	1 x 100%	1	2,943	8	24
WQ11_Turb	1 x 100%	1	2,943	8	24
WQ11_Cond	1 x 100%	1	9,873	8	24
L1	1 x 100%	1	3,126	8	24
WQ7_turb	1 x 100%	1	5,887	8	24
WQ15_FCL	1 x 100%	1	8,266	8	24
FN1	3 x 50%	2	1,864	35	0
WQ5_Turb	1 x 100%	1	11,676	8	24
ME5	1 x 100%	1	1,557	1	0
WQ15_pH	1 x 100%	1	11,676	8	24
WQ2_Cl2	1 x 100%	1	8,492	8	24
WQ11_pH	1 x 100%	1	11,676	8	24
WQ1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	1 x 100%	1	14,401	3	24
WQ7_Cond	1 x 100%	1	46,706	5	24

Table 6.9: Summary of Sensitivity Case 3 Results

	Sensitivity Case 3	Base Case
Mean number of Non-Compliance events per 10 years:	180 events	427 events
Mean total duration of Non-Compliance events over 10 years:	2,874 hours	24,555 hours

Table 6.9 shows the results for Sensitivity Case 3. Compared to the Base Case, the mean number of Non-Compliance events has been reduced by 247 and the mean total duration has been reduced by 21,681 hours. The risk profiles for the mean number of Non-Compliance events and the mean total duration of Non-Compliance events, compared to the Base Case, are shown in Figure 6.9 and Figure 6.10 respectively.

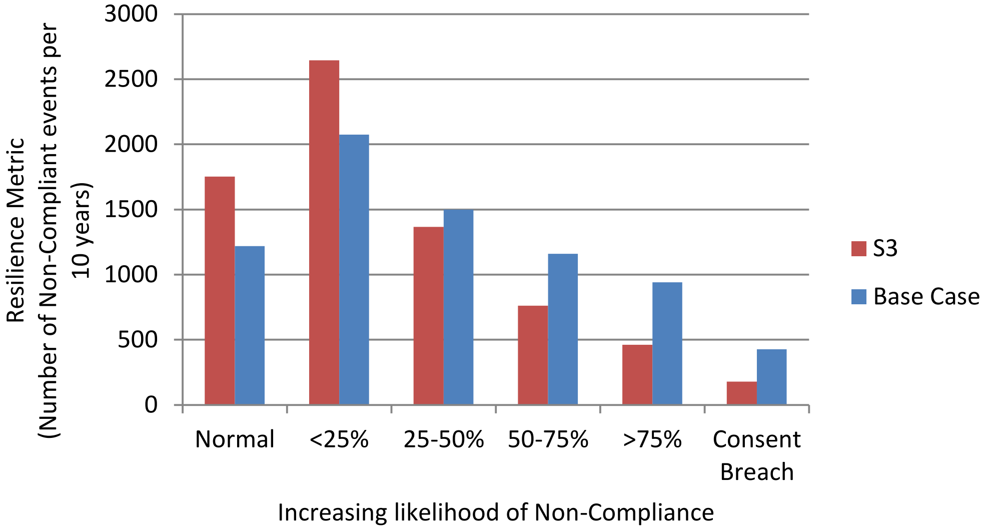

Figure 6.9: Non-Compliance Risk Profile—Sensitivity Case 3

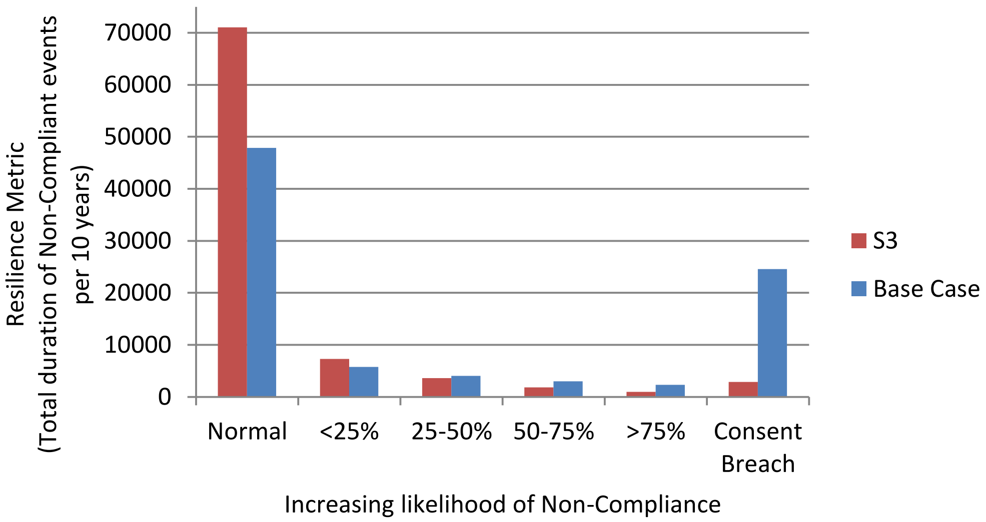

Figure 6.10: Non-Compliance Duration Risk Profile—Sensitivity Case 3

6.3.4 Sensitivity Case 4

Modelling input changes are highlighted in blue in Table 6.10.

Table 6.10: Quality Model Input Data—Sensitivity Case 4

Tag ID	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	4 x 33%	2	1,890	291	12
WQ1_Turb	1 x 100%	1	195	34	24
ME3	12 x 11%	4	4,231	136	12
WQ10_pH	1 x 100%	1	2,998	103	24
WQ1_pH	1 x 100%	1	195	17	24
WQ8_pH	1 x 100%	1	104	10	24
WQ7_ORP	1 x 100%	1	6,780	72	24
ME1	12 x 10%	3	3,839	133	12
WQ12_ORP	1 x 100%	1	6,780	72	24
WQ15_Turb	1 x 100%	1	2,943	33	24
WQ11_Turb	1 x 100%	1	2,943	33	24
WQ11_Cond	1 x 100%	1	9,873	55	24
L1	1 x 100%	1	3,126	28	24
WQ7_turb	1 x 100%	1	5,887	33	24
WQ15_FCL	1 x 100%	1	8,266	44	24
FN1	3 x 50%	2	1,864	35	12
WQ5_Turb	1 x 100%	1	11,676	34	24
ME5	1 x 100%	1	1,557	1	12
WQ15_pH	1 x 100%	1	11,676	17	24
WQ2_Cl2	1 x 100%	1	8,492	25	24
WQ11_pH	1 x 100%	1	11,676	17	24
WQ1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	1 x 100%	1	14,401	3	24
WQ7_Cond	1 x 100%	1	46,706	5	24

Table 6.11: Summary of Sensitivity Case 4 Results

	Sensitivity Case 4	Base Case
Mean number of Non-Compliance events per 10 years:	402 events	427 events
Mean total duration of Non-Compliance events over 10 years:	23,697 hours	24,555 hours

Table 6.11 shows the results for Sensitivity Case 4. Compared to the Base Case, the mean number of Non-Compliance events has been reduced by 25 and the mean total duration has been reduced by 858 hours. The risk profiles for the mean number of Non-Compliance events and the mean total duration of

Non-Compliance events, compared to the Base Case, are shown in Figure 6.11 and Figure 6.12 respectively.

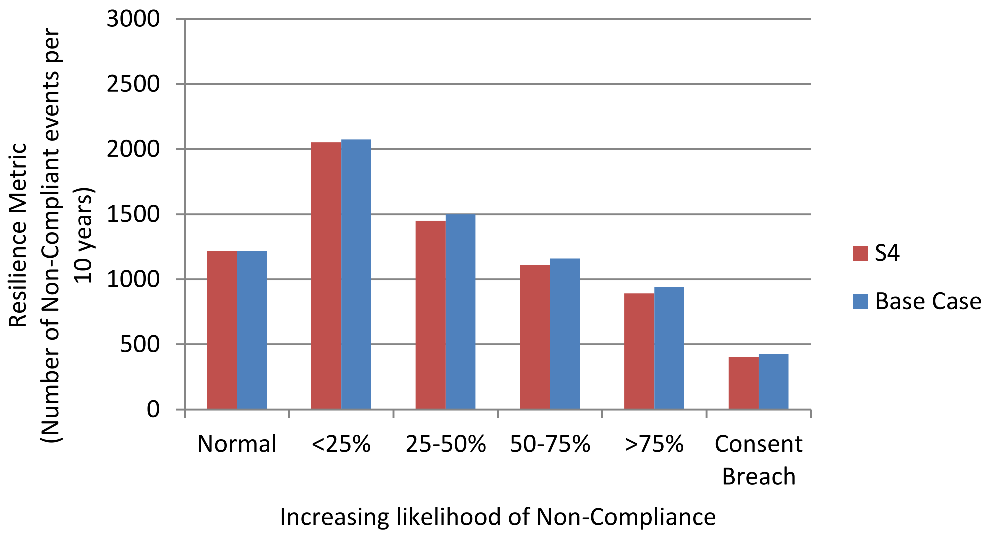

Figure 6.11: Non-Compliance Risk Profile—Sensitivity Case 4

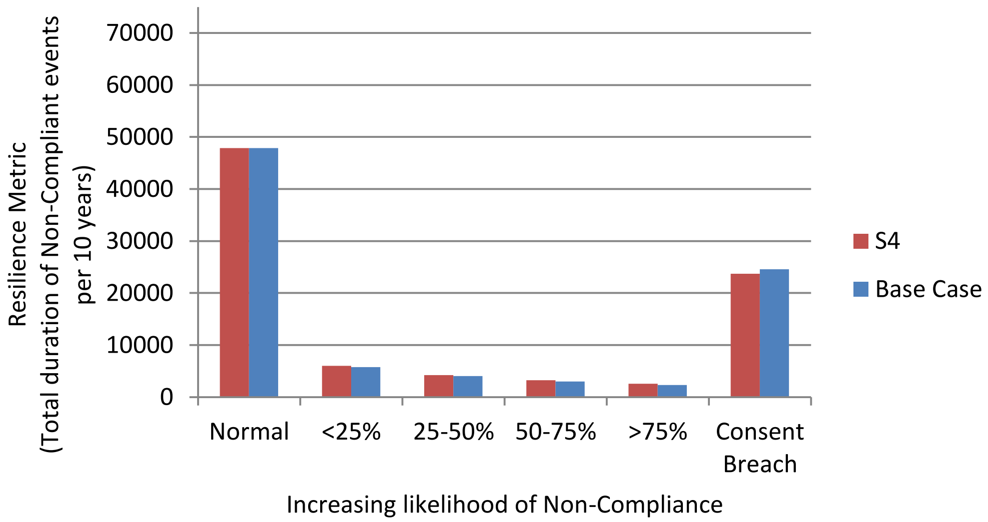

Figure 6.12: Non-Compliance Duration Risk Profile—Sensitivity Case 4

6.3.5 Sensitivity Case 5

Modelling input changes are highlighted in blue in Table 6.12.

Table 6.12: Quality Model Input Data—Sensitivity Case 5

Tag ID	Configuration	Critical Number	MTBF (Hours)	MTTR (Hours)	Deferred Effect (Hours)
ME4	4 x 33%	2	1,890	72	-
WQ1_Turb	1 x 100%	1	195	8	24
ME3	12 x 11%	4	4,231	72	-
WQ10_pH	1 x 100%	1	2,998	8	24
WQ1_pH	1 x 100%	1	195	8	24
WQ8_pH	1 x 100%	1	104	8	24
WQ7_ORP	1 x 100%	1	6,780	8	24
ME1	12 x 10%	3	3,839	72	-
WQ12_ORP	1 x 100%	1	6,780	8	24
WQ15_Turb	1 x 100%	1	2,943	8	24
WQ11_Turb	1 x 100%	1	2,943	8	24
WQ11_Cond	1 x 100%	1	9,873	8	24
L1	1 x 100%	1	3,126	8	24
WQ7_turb	1 x 100%	1	5,887	8	24
WQ15_FCL	1 x 100%	1	8,266	8	24
FN1	3 x 50%	2	1,864	35	-
WQ5_Turb	1 x 100%	1	11,676	8	24
ME5	1 x 100%	1	1,557	1	-
WQ15_pH	1 x 100%	1	11,676	8	24
WQ2_Cl2	1 x 100%	1	8,492	8	24
WQ11_pH	1 x 100%	1	11,676	8	24
WQ1_Cond	1 x 100%	1	778	5	24
WQ7_TCL	1 x 100%	1	14,401	3	24
WQ7_Cond	1 x 100%	1	46,706	5	24

Table 6.13: Summary of Sensitivity Case 5 Results

Case	Mean number of Non-Compliance events per 10 years (events)	Mean total duration of Non-Compliance events over 10 years (hours)
Base Case	427	24,555
3	180	2,874
5a	142	2,340
5b	131	1,966
5c	122	1,617
5d	117	1,451
5e	113	1,264

Table 6.13 shows the summary results for Sensitivity Cases 5a to 5e, compared to the Base Case. In addition, Sensitivity Case 3 has been included as the input parameters are the same as Sensitivity Case 5 and it represents a 0 hour deferred effect. The largest relative reduction in the number of Non-Compliance events and total duration, excluding the Base Case, occurs between Sensitivity Case 3 and Sensitivity Case 5a. Risk profiles, for Sensitivity Case 5a, for the mean number of Non-Compliance events and the mean total duration of Non-Compliance events, compared to the Base Case, are shown in Figure 6.13 and Figure 6.14 respectively. Again, Sensitivity Case 3 has been included for comparison. For clarity, the full risk profile data is listed in Table 6.14.

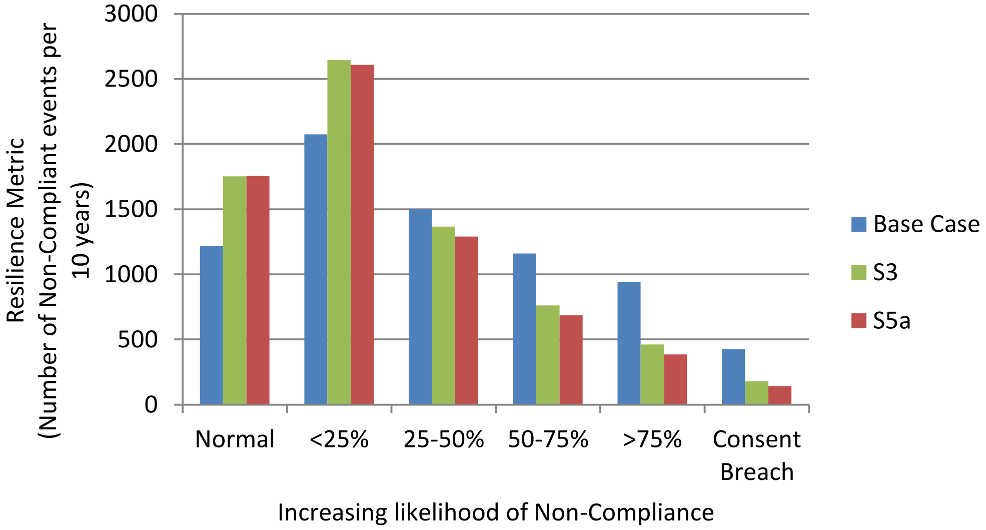

Figure 6.13: Non-Compliance Risk Profile—Sensitivity Case 5a

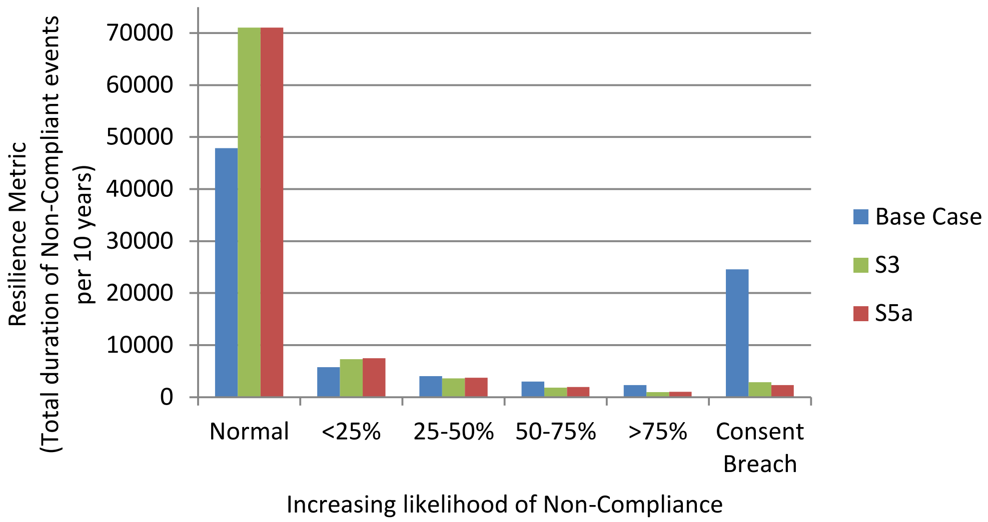

Figure 6.14: Non-Compliance Duration Risk Profile—Sensitivity Case 5a

Table 6.14: Risk Profile Data for Base Case, S3 and S5a

	Base Case		Sensitivity Case 3		Sensitivity Case 5a	
	Count	Time (hours)	Count	Time (hours)	Count	Time (hours)
Normal	1,218	47,864	1,754	71,015	1,754	71,049
<25%	2,075	5,776	2,645	7,327	2,609	7,495
25-50%	1,499	4,056	1,365	3,605	1,290	3,731
50-75%	1,161	3,017	762	1,830	684	1,940
>75%	942	2,332	462	950	384	1,045
Non-Compliance events	427	24,555	180	2,874	142	2,340

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Capacity model

The Production Availability assessment of the components influencing capacity demonstrates a Production Availability of 75.93% and corresponding shortfall of 24.07%, indicating that the system spends around a quarter of time not producing any output.

The Operational Availability assessment of the components influencing capacity demonstrates an Operational Availability/Uptime of 40.54%, indicating that the system spends a high proportion of time not at maximum capacity.

The main contributors to shortfall for the capacity model are the Treated Water Delivery Pumps, equipment ID PU5. These pumps have a relatively high MTTR compared to their MTBF and spend a high proportion of their life in a failed state. Improving the MTTR of these components, or increasing redundancy, would have the greatest impact on reducing the system shortfall.

7.2 Quality model

The Quality Model is separate from the Capacity model. Hence, events that occur in the capacity model do not impact the quality model.

The following predictions were made for the Base Case Quality model:

- The mean number of Non-Compliance events expected over a 10 year period is 427.
- Approximately 38% of the Non-Compliance events are caused by the inclusion of the component WQ1_Turb (Water Quality 1 Turbidity) in the model.
- The mean total duration of Non-Compliance events, over the 10 year period, is 24,555 hours.
- Approximately 27% of the total duration of Non-Compliance events is caused by the inclusion of ME4 (UV-H2O2 Advanced Oxidation System) in the model.

The top 5 contributors to Non-Compliance events are shown, in their respective proportions of the total 427 Non-Compliance events, as a pie chart in Figure 7.1.

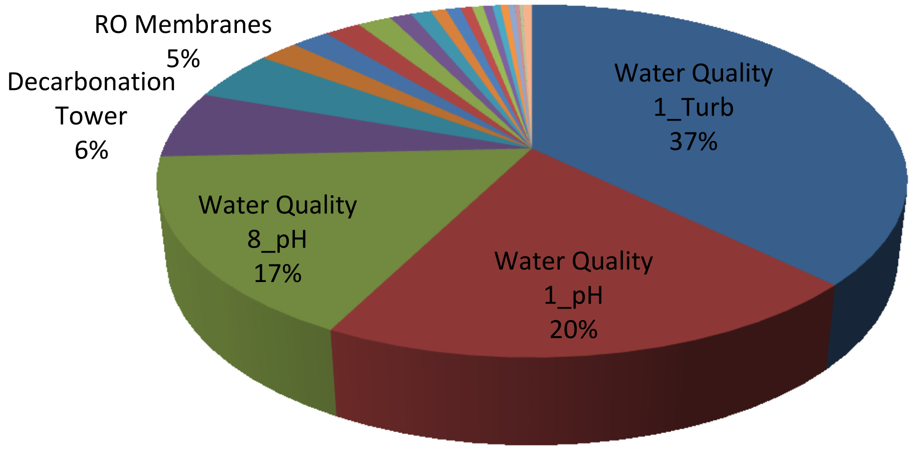

Figure 7.1: Base Case Non-Compliance events

In addition, the top 6 contributors to the total duration of Non-Compliance events are shown, in their respective proportions of the total 24,555 hours, as a pie chart in Figure 7.2.

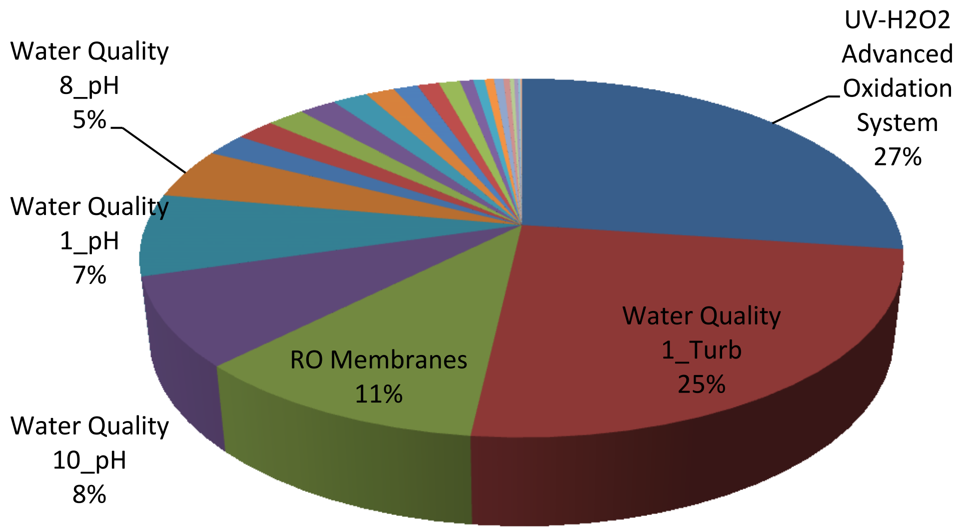

Figure 7.2: Base Case Breakdown of Non-Compliance event Durations

Following the presentation of the Base Case results, five Sensitivity Cases were modelled. Table 7.1 shows a summary of the Base Case and Sensitivity Case results for the quality model. The most significant drop in Non-Compliance events and the duration of Non-Compliance events can be seen in Sensitivity Cases 3 and 5. This demonstrates that the most significant input parameters, which impact the number of Non-Compliance events and the duration of Non-Compliance events, are the MTTR and the deferred effect. Hence, adequate storage should be included in the proposed facility to maintain a suitable deferred effect time. In addition, for equipment with long repair times, either storing spare components on site to reduce any logistic delays within the repair times or further sparing of these equipment items could be considered.

Table 7.1: Summary of Base Case and Sensitivity Case Results

Case	No. Non-Compliance events	Duration of Non-Compliance events (Hours)
Base Case	427	24,555
Sensitivity Case 1	418	23,286
Sensitivity Case 2	419	16,927
Sensitivity Case 3	180	2,874
Sensitivity Case 4	402	23,697
Sensitivity Case 5a	142	2,340
Sensitivity Case 5b	131	1,966
Sensitivity Case 5c	122	1,617
Sensitivity Case 5d	117	1,451
Sensitivity Case 5e	113	1,264

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Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.