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Authors: Onyango, Laura A., Quinn, Chloe, Tng, Keng H., Wood, James G., and Leslie, Greg

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A Study of Failure Events in Drinking Water Systems As a Basis for Comparison and Evaluation of the Efficacy of Potable Reuse Schemes

Laura A. Onyango[1], Chloe Quinn[2], Keng H. Tng[2], James G. Wood[1] and Greg Leslie[2]

[1]School of Public Health and Community Medicine, University of New South Wales, Sydney, NSW, Australia. [2]School of Chemical Engineering, University of New South Wales, Sydney, NSW, Australia.

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ABSTRACT: Potable reuse is implemented in several countries around the world to augment strained water supplies. This article presents a public health perspective on potable reuse by comparing the critical infrastructure and institutional capacity characteristics of two well-established potable reuse schemes with conventional drinking water schemes in developed nations that have experienced waterborne outbreaks. Analysis of failure events in conventional water systems between 2003 and 2013 showed that despite advances in water treatment technologies, drinking water outbreaks caused by microbial contamination were still frequent in developed countries and can be attributed to failures in infrastructure or institutional practices. Numerous institutional failures linked to ineffective treatment protocols, poor operational practices, and negligence were detected. In contrast, potable reuse schemes that use multiple barriers, online instrumentation, and operational measures were found to address the events that have resulted in waterborne outbreaks in conventional systems in the past decade. Syndromic surveillance has emerged as a tool in outbreak detection and was useful in detecting some outbreaks; increases in emergency department visits and GP consultations being the most common data source, suggesting potential for an increasing role in public health surveillance of waterborne outbreaks. These results highlight desirable characteristics of potable reuse schemes from a public health perspective with potential for guiding policy on surveillance activities.

KEYWORDS: drinking water outbreaks, potable reuse, public health, failure events, syndromic surveillance

SUPPLEMENT: Current Research in Water Treatment

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CORRESPONDENCE: g.leslie@unsw.edu.au

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Introduction

Access to safe drinking water is a major global health concern. The World Health Organization (WHO) estimates that one-fifth of the world's population inhabits regions where water is physically scarce, and across every continent, one in three people lacks access to a potable water supply to meet their daily needs. Consequently, diseases associated with water are a major cause of morbidity and mortality worldwide, and those related to drinking supplies account for ~5% of the global disease burden.[1–3] Failures in drinking water systems, treatment processes, and distribution networks can often lead to water contamination incidents, some of which result in disease outbreaks. Such outbreaks occur as a result of consuming drinks and products made from contaminated water. Most cases of contamination occur when sewage containing enteric pathogens infiltrates drinking water supplies leading to infections causing acute gastrointestinal symptoms.[4,5] Nonetheless, not all disturbances in water quality will lead to human illness or detectable outbreak scenarios.

Increased demand for potable water in areas with limited supplies of groundwater or surface water has prompted communities to evaluate the use of alternative, nontraditional water sources. In response, some jurisdictions have implemented potable reuse projects to replenish traditional supplies of groundwater or surface waters with treated water sourced from municipal wastewater.[6] These potable reuse schemes utilize a combination of advanced treatment technologies that are configured to form multiple barriers to the microbial risk factors present in wastewater to produce water of high quality without compromising public health when the water is extracted, treated, and reticulated through the potable water distribution system.[7]

The supply of potable water, however, is not only contingent on the deployment of robust treatment barriers. There are numerous examples of outbreaks of waterborne disease occurring in conventional water supply systems in communities in developed nations equipped with robust treatment technologies.[8] Systematic analysis of these outbreaks has identified causal factors including, but not limited to, poor operational and maintenance practices, aged infrastructure, inadequate monitoring, and failures in the distribution network.[8] Providing water quality with minimal risk to public health encompasses entire institutional processes beginning from the water source all through to delivery to the consumer. These processes include sourcewater protection strategies, trade waste handling, optimal operational management, public education, and keeping up with the best practices through ongoing research initiatives, all of which contribute significantly to safe water supply. Evaluation of outbreak events in conventional water systems and identifying any deficiencies in the critical infrastructure and institutional capacity provides an opportunity to develop a checklist of factors that must be included in potable reuse schemes in addition to the deployment of robust treatment. This approach assesses the efficacy of potable reuse schemes that extends beyond the performance treatment processes upstream of the groundwater or surface water reservoirs.

WHO characterizes disease outbreaks as the occurrence of an increased number of disease cases that is more than what would normally be expected in a community, geographical region, or season.[2] In the absence of sensitive surveillance techniques and together with symptoms being mild and self-limiting, outbreak detection can be difficult. Traditionally, identification and confirmation of increased enteric infections and their consequent outbreak scenarios are primarily done through laboratory-based testing. As such, the lag time between the onset of an infection and its notification may delay effective outbreak detection and implementation of strategies to prevent additional cases. Unlike traditional surveillance, syndromic surveillance relies on alternative multiple data sources, such as visits to general practitioners (GPs) and emergency departments (EDs), over-the-counter drug sales, school and work absenteeism, calls to national health lines, and many other sources, for the early detection and intervention of infectious disease outbreaks where clinical or laboratory data are yet not available.[9,10]

One feature common to both conventional drinking water plants in developed countries and advanced water treatment plants producing water for potable reuse is the deployment of multiple barriers. Given that there are a limited number of water-recycling plants producing water to augment potable supplies, a systematic study of reported failures in traditional drinking water systems was studied to identify any trends or cluster of events that may result in failures in the multiple barrier approach. The approach does not imply that the types of failures that occur in drinking water systems are necessarily identical to the types of failures that could occur in potable recycling plants. The article is based on a summary of causal factors in drinking water outbreaks in communities in developed nations from 2003 to 2013. This is followed by a comparative assessment of the critical infrastructure and capacity of two potable reuse schemes in Windhoek, Namibia, and Orange County, California. Elements of the approach evaluate usefulness of information collected by syndromic surveillance used to detect waterborne outbreaks in drinking water systems.

Methods

Despite advances in water treatment technology, drinking water outbreaks still occur in the developed world. A drinking water outbreak is described as an event where two or more people become ill with the same disease after consumption of the same water source, and there is epidemiological evidence that implicates the water source as the vehicle of infection.[11,12]

Global Infectious Diseases and Epidemiology Online Network (GIDEON) database search. Outbreak data were sourced from the GIDEON, which is an online repository of over 340 infectious diseases, their causative agents, as well as their prevalence in 231 nations and territories.[13] Expanding on the work performed by Hrudey and Hrudey on microbial infection of drinking water between 1970 and 2002,[11] information was gathered for industrialized nations covering the period between 2003 and 2013. Searches in GIDEON were limited to outbreaks arising from microbial contaminants, with water as the vehicle of transmission. Of the notable outbreaks listed, the search was further refined to those involving drinking water only. Incidences where the water source was not specified were excluded. From the GIDEON database, references for corresponding outbreaks were utilized to derive outbreak location, causal information, and pathogen type. Alternative references sourced from online published and grey literature (PubMed, Google Scholar and online newspaper articles) were used for outbreak events that were not referenced in GIDEON using a similar search criteria and epidemiological, microbiological and institutional information was extracted. In addition, syndromic surveillance indicators and the implemented water safety plan were also collected (Fig. 1).

Alphanumeric categorization. Using the Australian Drinking Water Guidelines' drinking water management framework (Chapter 3),[14] an alphanumeric coding system was developed to categorize drinking water failure incidents recorded in the GIDEON database (Table 1).

This system allowed for classification of failures into five possible failure locations and types with the failure location assigned a number (1–5), which represents the location of the failure along the drinking water system and a letter (A–E), which represents the type of failure that occurred. For example, a 2BCD failure would mean that a failure, which led to a pathogenic outbreak, occurred at the raw water extraction point due to a combination of equipment failure, poor engineering design, and inadequate maintenance.

Potable reuse scheme evaluation. A critical assessment of scheme infrastructure and institutional capacity was also conducted in parallel for the New Goreangab water reclamation plant (NGWRP) in Namibia, practicing direct potable delivery, and the groundwater replenishment system

Table 1. Alphanumeric coding system for failure events.

NUMBER	REPRESENTATION
1	Catchment management and protection failure.
2	Water source extraction failure.
3	Treatment failure (Coagulation, flocculation, sedimentation, and filtration).
4	Disinfection system failure.
5	Distribution system failure.
LETTER	**REPRESENTATION**
A	Failure in upper management framework resulting in issues with operation and maintenance as well as assessment and mitigation of risks.
B	Failure due to breakage of equipment (cracked pipes, malfunctioning pumps, etc.)
C	Failure occurring due to poor engineering design resulting in a system that was not suitable to treat the capacity or composition of the raw water.
D	A failure in the system due to inadequate maintenance and monitoring of the plant.
E	A failure resulting from human error that involved a team without appropriate knowledge or expertise.

(GWRS) in the USA, practicing groundwater recharge. This comparative study between NGWRP's advanced water treatment process and GWRS's advanced membrane water treatment process was used to assess the established institutional processes from water source to tap and to evaluate each process against the range of public health risks that have been associated with the identified drinking water outbreaks in the past 10 years.

Results and Discussion

In the past decade, there have been over 280 reported drinking water outbreaks in the industrialized world associated with microbial contaminants. Detailed information for 83 outbreaks was collated from both the GIDEON database as well as published and gray literature records (Table 2).

Outbreak investigation. Several microbial agents were identified in these outbreaks with the most common cases involving *Campylobacter* spp, *Norovirus* and *Cryptosporidium* spp. with 14%, 16% and 29% respectively. Pathogen identification and confirmation involved traditional laboratory analyses, and in 75% of these cases, a single microbial species was implicated in the outbreak. However, caution should be exercised when analyzing published outbreak data due to the lack of proper microbial agent reporting regulations, with 9% of the cases failing to report the type of microbial agent and 16% of the cases identifying multiple aetiologies of infection (Fig. 2).

The largest number of estimated individuals exposed to contaminated drinking water was 250,000 people in the UK in 2008 (media reports). Despite this large number, only 33 cases were confirmed to be infected with the *Cryptosporidium* spp. implicated in this outbreak.[15] The largest number of confirmed

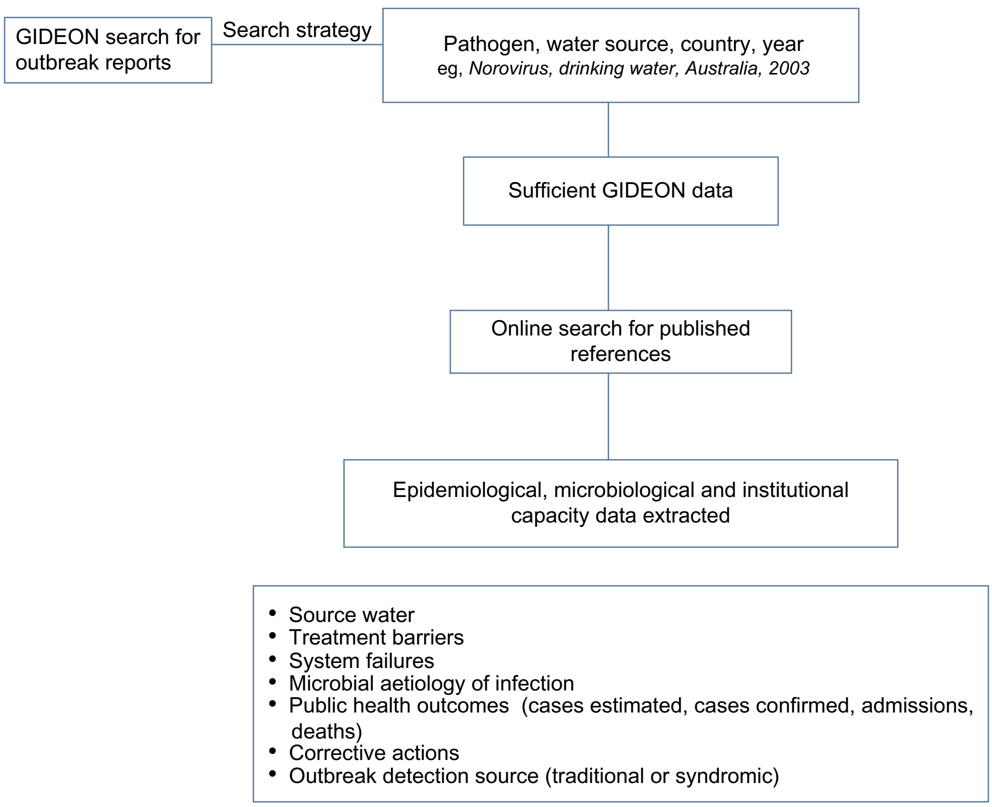

Figure 1. Schematic of search strategy used for drinking water outbreaks.

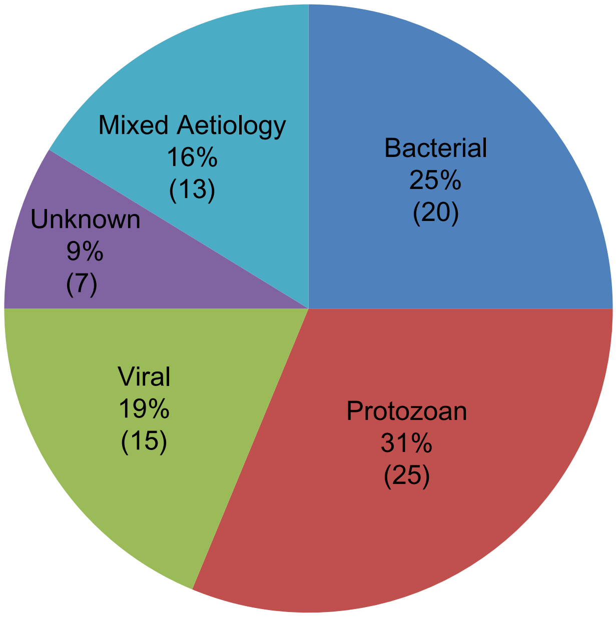

Figure 2. Microbial agents in pathogenic outbreaks.

clinical cases involved 1268 individuals in an outbreak in Norway in 2004 where drinking water supplies were infected with *Giardia lamblia*, following sewage runoff contaminated the lake water in which the city sourced its drinking supply from and was coupled with insufficient treatment.[16] The largest number of hospitalized cases was in Nokia, Finland in 2007 where 200 individuals were admitted following infections with multiple aetiologies.[17,18] At least 5 fatalities were recorded.[19–21] Source waters identified in the 83 outbreaks included surface water, ground water, rain/tank water, and bottled water. Water treatments commonly employed in these scenarios included sedimentation, rapid sand filtration,

Table 2. Types of failures and outbreaks in developed countries from 2003 to 2013.

COUNTRY	NO OF OUTBREAKS	FAILURE TYPES											
Australia	7	1C	5ACE	5ACE	5ACE	1A	3C	1A					
Austria	2	2C	2C										
Belgium	2	UNK	5E										
Canada	4	3A	2A	UNK	5B								
China	4	2BD	4ABD	1A	UNK								
Denmark	3	5C	UNK	5B									
England	12	3A	3A	1AC	3AE	1BCD	2CD	1BD	2CD	2ACE	2CD	UNK	3A
Finland	6	2ACE	5BD	5ACE	UNK	1A	UNK						
France	2	UNK	5C										
Greece	3	1C	1C	UNK									
Ireland	9	1C	1A	UNK	1BD	2AC	UNK	1A	UNK				
Italy	2	3AC	4D										
New Zealand	3	2ACD	3A	1A									
Norway	3	1ABD	2CD	5ACE									
Sweden	4	1ABD	2C	5ACE	UNK								
Switzerland	2	5ACE	1A										
Turkey	2	2AC	5ACE										
USA	11	1A	1AC	2BCDE	3AC	3AD	UNK	UNK	UNK	UNK	UNK	UNK	
Wales	2	1C	UNK										

Note: *UNK indicates an outbreak with causative failure not identified.

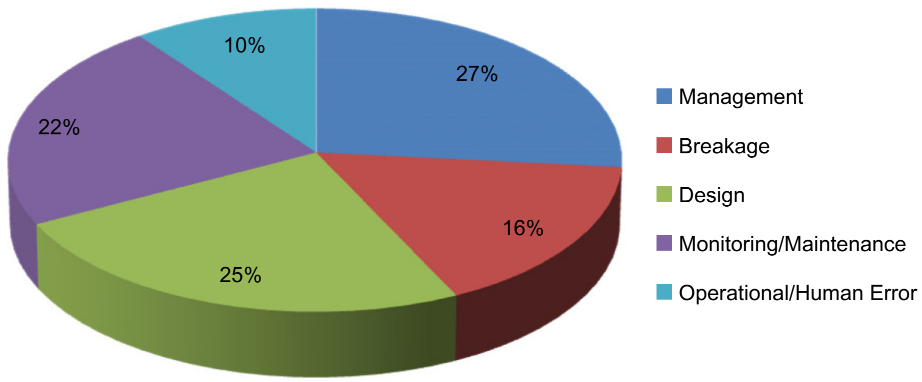

Figure 3. Causes of pathogenic outbreaks.

coagulation, pH adjusting, chlorination, and UV disinfection. Diverse institutional failures were identified in these outbreaks, and the most common included poor source water protection, ineffective or insufficient treatment processes prior to water distribution, aged infrastructure, poor operational and maintenance protocols, and staffing issues (Table 3). In 44% of the outbreak cases reviewed, syndromic surveillance sources were noted as being essential in outbreak detection before confirmation using traditional laboratory techniques. Such sources included clinician reports to public health departments, increased visits to GPs and EDs, increased calls to healthcare centers, and school absenteeism. In 39% of the outbreak cases, a boil water advisory, which lasted from 3 to 90 days, was issued to ensure public health and safety.

From Figure 3, majority of the outbreaks stemmed from both failures in the management framework (27%) and inadequate infrastructural design (25%) while monitoring/maintenance failures accounted for 22%. Failures due to breakage of equipment from catchment to tap and operational/human errors led to 16% and 10% of the total number of failures, respectively. Water utilities implemented several corrective measures to remedy the outbreak, which included flushing of the entire water delivery system, repairing and replacing damaged and aged infrastructure, implementing the additional treatments, and increasing the frequency of water quality monitoring.

From the data obtained, it is evident that outbreaks usually occur due to a combination of events rather than just solely

Table 3. Causes of outbreaks in developed countries from 2003 to 2013.

Human error	• Cross connections between drinking water and wastewater during and after maintenance work • Incorrectly positioned gutters into water storage unit following maintenance work • Poorly installed sewage systems • Miscommunication between operational staff and maintenance staff regarding disabled controls • Mixing of treated water with untreated supplies prior to distribution • Unqualified personnel handling water pipeline reconnections • Alarm noted but no action was taken • Backup switch disabled due to maintenance
Infrastructural/institutional deficiencies	• Lack of physical source water protection from livestock contamination and effects of seasonal flow changes • Seepage of sewage into drinking water systems • Porous and fractured aquifer • Old, blocked and leaking sewage pipes in close vicinity to drinking water systems • Negative pressure allowed contaminated groundwater to penetrate broken pipes • Poor risk identification and management • Backflow of partially treated wastewater into drinking supplies • Failure to meet regulatory approval of distance between a well and surface water (15 m)
Treatment deficiencies	• No treatment in place • Lack of adequate treatment • Obsolete treatment measures and devices • Lack of adequate testing devices • Poor water quality testing measures • Sewage directly released into surface source without treatment • Treatment plant offline for maintenance • Malfunctioning flow control meter led to automated fluoride dosing

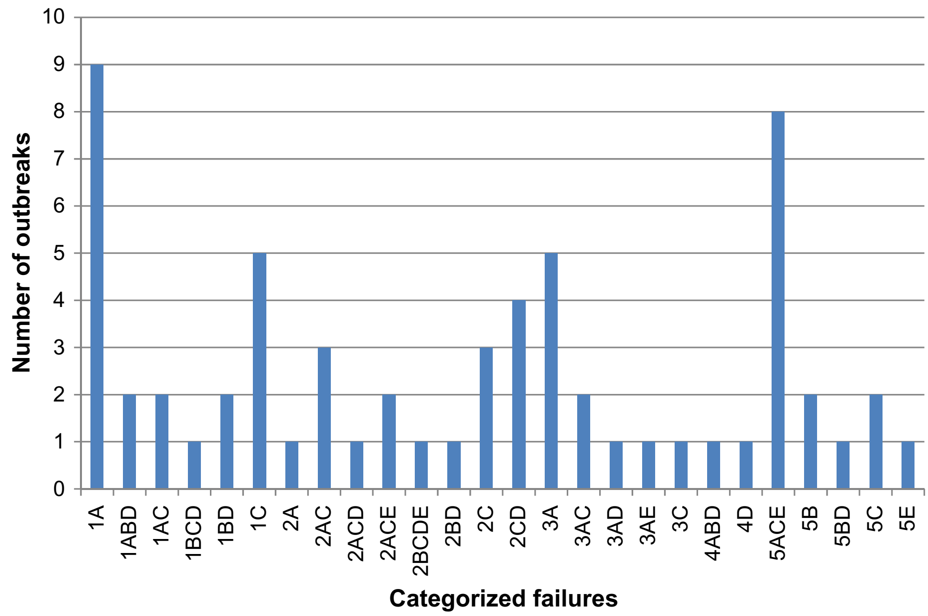

Figure 4. Alpha-numeric Categorization of Known Failures that Led to Outbreaks.

Table 4. Comparative assessment of two different potable reuse schemes.

SCHEME FEATURES	GROUNDWATER REPLENISHMENT SYSTEM (GWRS)	NEW GOREANGAB WATER RECLAMATION PLANT (NGWRP)
Water delivery	• Indirect potable reuse	• Direct potable reuse
Source water	• Domestic wastewater	• Domestic and business wastewater
Permit criteria	• Based on USEPA and State of California criteria	• Based on Namibian, USEPA, WHO, EU and Rand Water
Operational monitoring	• Online SCADA & composite water quality monitoring • Performance of each process unit monitored through critical control points (CCP's)	• Online SCADA & composite water quality monitoring • Samples taken after every process step • Final product water (FPW) continuously sampled and analyzed for range of pathogens
Industrial waste management	• Industrial pre-treatment and trade waste control programs implemented by Orange County Sanitation District (OCSD) • Industrial wastewater treated separately	• Industries localized separately from the city to prevent wastewater interaction with dam water. • Industrial wastewater recycled separately at the old plant and is used for irrigation purposes only
Treatment train	• Microfiltration • Reverse osmosis • Ultra-violet disinfection with hydrogen peroxide • De-carbonation and lime stabilization	• Pre-ozonation • Enhanced coagulation and flocculation • Dissolved air flotation • Dual media sand filtration • Main ozonation • Activated carbon filtration • Ultra-filtration • Chlorination
Water quality monitoring body	• California Department of Public Health & California Regional Water Quality Control Board (RWQCB)	• City of Windhoek Department of Infrastructure, Water and Technical Services
Water quality assessments	• Microbial, Chemical, Aesthetic	• Microbial, Chemical, Aesthetic
Regulatory surveillance	• Monitored by an independent advisory panel and the California Regional Water Quality Control Board	• Monitored by Bureau Veritas (BV)
Staff and training	• 4 operators/12 hr shift, 4 instrument and electrical technicians, 14 maintenance technicians, 2 process and control experts	• 2 management staff, 3 technicians, 13 operators, 5 maintenance artisans, administrators and general workers. • Staff are trained at internal, nationally and international levels
Quality control assurance	• Unsatisfactory water sent to ocean outfall	• Penalties levied if water parameters are unsatisfactory • Water pumped back for retreatment • Plant goes into recycle mode if breaches occur

due to one particular cause[20] and thus was further categorized using the alphanumeric coding system.

Through the alphanumeric categorization, the failure types were categorized and compared. From Figure 4, it can be concluded that the most common type of known failures was a Type 1A (14%), which involved improper management of the catchment area. Downstream treatment processes tend to be compromised by a loss of effectiveness due to an adverse event that originated at the water source. Such situations usually involve a sudden, large influx of raw water due to unforeseen weather conditions that exceeded the treatment system's designed capability.

The second most common failure type was a Type 5ACE (13%), which was a result of a failure in the distribution system coupled with failures due to poor management, inadequate engineering design, and human error. Water quality in the distribution system was affected by poor management of risk assessment and mitigation resulting in improperly designed open storage systems, crosscontamination in pipelines, and contamination during maintenance. Human error was also one of the contributing factors with operators not having the appropriate skills required to address and prevent contamination in the distribution system with 10% of the total outbreak causes.

The failures, identified by the alpha-numeric categorization, were then used to evaluate the infrastructure and institutional practices to understand each scheme's efficacy in augmenting drinking water supplies.

Potable reuse scheme evaluation. Ensuring sufficient supply of safe drinking water is an essential aspect of any water utility and more so where potable reuse is concerned. Introduction of potable reuse schemes has been hampered in some communities due to the public's lack of knowledge and information of alternative water sources, as well as the perception of their risks and associated health issues.[21] In evaluating the safety of potable reuse schemes, this study assessed the efficacy of the NGWRP and GWRS in mitigating the range of risks associated with outbreaks. The features of each scheme including the regulatory conditions covering water production, source water protection, trade waste management, advanced water treatment technologies, and water quality monitoring requirements are presented in Table 4.

Online instrumentation and monitoring. Failures in conventional water systems in the past decade can be attributed to a suite of factors including unit performance, maintenance works (cross-connection errors), reenabling of disabled devices, not attending to alarms, and poor water quality monitoring, resulting in water contamination and disease outbreaks. Via this comparative study, it was determined that the two potable reuse schemes both utilized online operational and monitoring programs to evaluate system performance, schedule, and track maintenance tasks and thereby reduced the probability of human error. Online and automated systems with in-built alarms and protocols ensured that all appropriate actions were performed before and after maintenance and that operational systems were working optimally before the supply of water was resumed. Use of continuous online programs and instrumentation to monitor water quality parameters, in addition to composite sampling and testing, also ensured that water quality was continuously evaluated throughout each step of the treatment process prior to distribution or aquifer recharge. When unsatisfactory parameters are detected, treatment systems are designed to shut down until the problem is rectified, to pump the water back for retreatment (NGWRP), or to redirect the water to ocean outfall (GWRS). NGWRP is a direct potable reuse scheme and thus operates under a permit agreement that levies penalties if operational performance and water quality parameters are not met.[22] Such regulations ensure that water quality is consistently met and some cases even exceed the existing guidelines for conventional water sources.

Staff, training, and regulatory elements. A water treatment system is only as effective as the sum of its institutional parts. A weakness in one aspect can affect the quality of water produced and thereby compromises public health. Several outbreak incidents identified inadequate number of staff and unqualified or undertrained personnel as a factor that led to outbreak events. Evaluation of the personnel employed at both NGWRP and GWRS, including operators, technicians, and maintenance personnel, concluded that personnel were skilled and trained under national and international standards and capable of handling the day-to-day operations of their respective schemes. Reliability of these schemes is also ensured as they are subjected to regular regulatory surveillance and audits by experts in the field.

Multiple barrier approach. The drinking water outbreaks also identified another recurring major failure – the lack of proper treatment system design. The majority of such outbreaks occurred in communities with groundwater sources (springs and wells) that suffered from the lack of treatment coupled with seasonal flow changes and no source water protection. Mitigating the situation usually involved implementing water disinfection (usually chlorination) and source water protection. In contrast, the two potable reuse schemes adopted a multiple barrier approach in the form of source water protection and utilization of various types of advanced treatment strategies that were capable of reducing the risks of microbiological contaminants found in conventional water sources and wastewater. Source water protection strategies required industrial dischargers to adhere to trade waste agreements, and in both reuse scenarios, industrial wastewaters were directed and treated separately.

Syndromic surveillance data sourcing. Syndromic surveillance has emerged as a tool in outbreak detection for the evaluation of the nature and progression of gastrointestinal disease in an outbreak.[23] Despite some studies that highlight the flaws of syndromic surveillance,[24] an increasing number of studies have documented its usefulness in enabling a rapid response that would aid in reducing morbidity and mortality rates.[10] Furthermore, rapid detection of water contamination incidences coupled with effective interventions is necessary in order to limit the public health impacts and economic costs of such occurrences. In the examined outbreaks, syndromic surveillance was able to detect 44% of the incidents compared to only 10% through laboratory confirmations. Nonetheless, both results emphasize the need for better, more rapid techniques in outbreak detection and intervention. Following outbreak detections, boil water advisories were most commonly issued and found to be sufficiently effective in curbing further infection.[4,25] However, in a few of the incidences, bottled water was also supplied to affected consumers, especially where prolonged investigations were required.

Conclusion

Fluctuations in source water quality combined with failures in treatment processes and distribution networks can all result in contamination of drinking water and consequently lead to waterborne outbreaks. Despite advancements in technology and awareness of pathogenic influence in the water industry, drinking water outbreaks still occur in many developed nations, and these incidences still pose a significant risk to public health. Syndromic surveillance integrates multiple data sources in outbreak detection and is a more effective approach that provides early warning signs that alert relevant agencies to act promptly and curb the spread of infection. A comparative evaluation of the critical infrastructure of two potable reuse water schemes found that both their operational and monitoring frameworks were designed to prevent and reduce the range of risks and failures that have occurred in conventional drinking water systems. In potable reuse schemes, the use of multiple barriers, online instrumentation, and operational measures was found to be sufficient in mitigating the events that have resulted in waterborne outbreaks in conventional systems that have occurred in the past decade.

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Author Contributions

Conceived and designed the experiments: LAO. Analyzed the data: CQ. Wrote the first draft of the manuscript: LAO. Contributed to the writing of the manuscript: KHT. Agree with manuscript results and conclusions: JGW. Jointly developed the structure and arguments for the article: JGW. Made critical revisions and approved the final version: GL. All authors reviewed and approved the final manuscript.

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