Risk Management and Cross-Connection Detection of a Dual Reticulation System

M. V. Storey[1*], D. Deere[2], A. Davison[2], T. Tam[3] and A. J. Lovell[1]

[1]Sydney Water Corporation, 115-123 Bathurst Street Sydney, NSW 2000, Australia. Tel: (02) 93505432, Fax (02) 93505929, E-mail: michael.storey@sydneywater.com.au. Corresponding author*.
[2]Water Futures, PO Box 212, Killara NSW 2071, Australia
[3]Sydney Water Corporation, 51 Hermitage Rd, West Ryde, NSW 2114, Australia

Abstract

Taking into consideration the event of accidental ingestion, water utilities provide multiple barriers that ensure the safety of recycled water designated for non-potable domestic use (*e.g.* toilet flushing and domestic irrigation). With the advent of extensive urban water recycling through dual reticulation, there is potential for accidental (and deliberate) cross-connection to a potable water distribution system. Whilst these barriers mean that such events are unlikely to lead to measurable health effects, water utilities must nonetheless have a means to detect such instances to maintain public confidence and acceptance of recycled water initiatives.

Sydney Water has a targeted research programme aimed at the rapid detection of cross-connection and malevolent events within a dual reticulation system. Currently being evaluated are three approaches (anti-ingestants, colourants and early warning systems). Underpinning this however is a comprehensive risk management approach that ensures the safety of customers in the event of occasional cross-connection.

Keywords: anti-ingestants; colourants; recycled water; sensor technology

1. Background

From 1981 to 1998, the Centres for Disease Control and Prevention in the United States documented 57 waterborne disease outbreaks related to cross-connection events, resulting in more than 9,000 illnesses (AWWA, 2001). In each case cross-connection occurred through backpressure or back-siphonage to a non-potable source, and in most cases, a sewerage system (Craun and Calderon, 2001). There have been outbreaks within Australia associated with cross-connections from 'Class C' recycled water to drinking water (Borensztajn, 2007) and a number of incidents of non-potable to potable cross-connections leading to disease outbreaks including a large incident in the Netherlands and several reports from the United States (Liang *et al.*, 2006). To date however, we have not identified a documented case of illness directly attributed to cross-connection from a tertiary-treated recycled water distribution system to drinking water. Nonetheless water utilities maintain ongoing vigilance in case of such an event.

Commencing with the Rouse Hill Development Area (RHDA), the first and largest full-scale dual reticulation system of its type, Sydney Water has pioneered dual reticulation systems within Australia and currently supplies potable and recycled water to more than 16,000 residential properties via such "third-pipe" systems. Increasing urbanisation throughout Sydney's north and south-west growth corridors will see this number increase to more than 160,000 over the next 25 years, equating to a residential population in excess of 450,000.

Since the introduction of domestic recycled water in 2001 there have been four cross-connection events detected within the RHDA; three isolated events and one multiple exposure affecting 82 residential homes; the latter being detected through a customer complaint that the water had a salty taste. More recently during November 2005, a cross connection occurred in the Newington suburb within the Sydney Olympic Park precinct for a period up to 3 weeks. This event was detected only after a customer reported that the water imparted a musty odour and taste.

Cross-connection events are spatially and temporally rare within a distribution system, with the incidence so far being on average within the order of 1 event in 10,000 dwellings per year. Australian Recycled Water Guidelines recommend supplying dual reticulation water with a quality whereby the pathogen concentration is tolerable with an annual cross-connection frequency of around 1 event in 1,000 dwellings per year. This estimate is supported by a conservative quantitative risk assessment which found that an annual cross-connection frequency of around 1 event in 1,250 dwellings per year would be routinely tolerable where water just meets state water quality requirements for dual reticulation (D. Deere, unpublished data). Therefore, with the existing exposure control measures in place at Rouse Hill, there currently exists a safety margin of around one order of magnitude.

Notwithstanding this, in 2003 Sydney Water commenced a targeted research programme aimed at the rapid detection of cross-connection events within a dual reticulation system. This paper describes research undertaken into the evaluation of two aesthetic agents; anti-ingestants and colourants, which make recycled water readily discernible to customers. It should be noted that these options are not the only means of rapidly identifying cross-connections; on-line early warning systems (EWS), including sensor-based technology could provide the next generation of tools for this purpose.

2. Risk Management

Sydney Water was the first utility in Australia to undertake a comprehensive risk-based ‘catchment to tap’ water quality planning and management strategy for drinking water (Deere *et al*., 2001, Deere and Davison, 2005). This approach was ultimately encapsulated in the *Framework for Management of Drinking Water Quality* of the *Australian Drinking Water Guidelines* (2004) and the analogous framework in the *Australian Guidelines for Water Recycling* (2006). In addition to providing confidence to regulators, consumers and utilities, such frameworks ensure that risks are being managed proactively and systematically and corrective actions, in the case of non-compliance, are undertaken efficiently.

Recycled water at Rouse Hill Recycled Water Plant is treated through multiple barriers to ensure compliance beyond the requirements of the existing *1993 NSW Guidelines for Urban and Residential Use of Reclaimed Water* (Sydney Water, 2004). Such multiple barrier risk management provides a safety margin under normal operating conditions, with water quality being higher than the minimum required for its intended use. The multiple barriers also provide redundancy, helping to ensure no adverse impacts on health in the event of failure by one barrier.

Recycled water is also monitored extensively for microbiological, chemical and physical quality at both the outlet at the point of use, and results are reported directly to NSW Health and independently audited as part of the annual Sydney Water Operating Licence. NSW Health advises that the high quality of recycled water consistently demonstrated at Rouse Hill is unlikely to cause public health issues if accidentally ingested. Furthermore, an independent study undertaken by the Australian Centre for Value Management (ACVM) found no epidemiological evidence to suggest that customers have suffered adverse health effects arising from the use of recycled water within the RHDA. This latter statistic is important given the high level of customers that are unaware of the use of recycled water within the RHDA, and anecdotal evidence that ingestion of recycled water occasionally takes place, accidentally or otherwise. Nonetheless, and as part of its multiple barrier philosophy and due diligence, Sydney Water has a responsibility to ensure that cross-connections do not occur and that if they do, are rapidly and comprehensively dealt with. In this respect, control of exposure is one of the multiple risk management barriers employed by Sydney Water.

In practice, Sydney Water already applies a comprehensive set of risk management practices that limit exposures to recycled water including: (i) installation regulations and codes of practice that include systematic processes to reduce the probability of cross-connections at the customer; (ii) materials codes and regulations that easily discriminate potable and recycled water plumbing; (iii) regulations that limit the legal installation and modification of plumbing systems to licensed individuals; (iv) education to explain the need to avoid creating cross-connections; (v) opportunities to apply pressure differentials in certain situations to ensure that if cross-connections occur, they are from higher to lower quality water; (vi) installation of backflow prevention systems to reduce the extent of hydraulic influence from any cross-connections that do occur; and (vii) operational checking and connection auditing (Sydney Water, 2001; De Rooy and Engelbrecht, 2003).

3. Anti-ingestants

A desktop study was undertaken to source anti-ingestant agents that could be used to discriminate potable and recycled water (Davison *et al.*, 2006). In total, 142 candidate compounds were identified of which eight were short-listed for further investigation by Sydney Water. Based on the offensive odour of two of these, (E)-2-nonenal (trans-2-nonenal) and 3-methyl butanoic acid (isovaleric acid), this list was further reduced to six compounds (Table 1).

In addition to their perceptible taste, the candidate compounds satisfied no less than 15 essential criteria including: (i) can be dosed into recycled water to reach concentrations above the objectionable taste threshold; (ii) has a taste threshold significantly below the threshold for acute toxigenic, mutagenic, teratogenic, carcinogenic or allergenic effects; (iii) does not cause environmental, including ecotoxicological, or property damage (*e.g.* to plants, animals, clothes or surfaces); and (iv) the taste threshold is discernible across the general (sensitive and non-sensitive) population.

A sensitivity panel was convened to determine the taste threshold concentration (detection limit) of each of the six short-listed compounds and likely variation in the general population to their detection. The detection panel comprised 25% of individuals being sensitive members of the Sydney Water taste and odour panel, 25% being "non-tasters", and the remainder randomly selected. This ratio of participants is recommended on the basis of the ratio in the general population (Centre for Chemosensory Research, UNSW, *pers. comm.*).

Nine percent of respondents (1/11) could not detect caffeine at any concentration (up to 0.4 parts per million, ppm), with the remainder detecting this compound at threshold values spanning nine orders of magnitude. The published upper limit of caffeine detection is 296 ppm, with its lower limit being 4 x 10^{-7} ppm. Quinine was also detected at a threshold concentration spanning seven orders of magnitude, with its upper detection concentration being 20 ppm (published value 144 ppm). Neither compound was labelled as "highly offensive" in taste though based on the wide variability in detection, their high actual and published detection limits, and the prohibitive cost of adding these compounds at such concentrations, both were excluded from further investigation.

Citric acid had a wide range of threshold detection limits, spanning more than nine orders, with 20% of respondents (2/10) detecting this compound only at a concentration of 0.25 ppm. Taking into consideration the inherent variation in the community and published data suggesting an upper detection limit of 590 ppm, this compound was excluded from further investigation on the basis of cost. Although not systematically assessed, other concerns about citric acid were that it would be an effective substrate for microbial growth as well as being a reducing agent that might readily oxidise any chlorine present in the recycled water distribution network.

TABLE 1. Candidate anti-ingestant agents and their published working concentration (ppm). The detection range presents the highest and lowest concentrations at which the compound was detected by the Sydney Water taste panel. The upper detection limit (ppm) was sourced from published data. The cost of adding compounds was calculated at the highest concentration detected by the Sydney Water panel (*e.g.* 0.1 ppm for denatonium saccharide) and recommended retail price (Sigma Chemical Company) of each compound per kg added per 1000 Litres (kL) of recycled water. Costs were estimated at the time of publication and consideration was not given to the bulk purchase of these compounds. [A]Price calculated from RRP of Bitrex™

Compound	Use	Working Concentration (ppm)	Detection Range (ppm)	Upper Detection Limit (ppm)	Estimated. Cost ($AUD/kL)
denatonium saccharide	anti-ingestant (Vilex™)	0.01	0.0001 – 0.1	0.01	0.07[A]
sucrose octaacetate	anti-ingestant (Chew-Stop™)	0.01	0.0001 - 10	-	1.25
caffeine	beverages	4.0 x 10^{-7}	4.0x10^{-9} – 0.4	296	0.09
denatonium benzoate	anti-ingestant (Bitrex™)	0.05	0.0005 – 0.05	0.05	0.03
quinine-HCl	pharmaceutical	0.002	0.00002 – 20	144	11.7
citric acid	food additive	2.5 x 10^{-7}	2.5x10^{-9} – 0.25	590	0.02
Aquatint™	colourant	0.5 – 1.5 ppm	0.1 - 1	1	0.10

Eighteen percent (2/11) of respondents could only detect sucrose octaacetate (Chew-Stop™) at a concentration of 10 ppm, making its addition to recycled water at $1.25 per kL prohibitive (Table 1). Denatonium benzoate (Bitrex™) and denatonium saccharide (Vilex™) had narrow (upper and lower) detection thresholds, spanning two and three orders of magnitude, respectively. One hundred percent of respondents (11/11) could detect Bitrex™ at a concentration of 0.05 ppm and Vilex™ at a concentration of 0.1 ppm, at a cost of $0.03 and $0.07 per kL, respectively. At its threshold concentration each compound was labelled as "highly offensive".

While Bitrex™ and Vilex™ performed well in terms of low detection limits and narrow thresholds, both performed poorly in terms of chlorine stability. At working concentrations of 0.05 ppm for Bitrex™ and 0.01 ppm for Vilex™, each compound effected a >99% reduction of 2 $mg.L^{-1}$ free chlorine after 3 days. Free chlorine concentrations in the RHDA were 1.4 ± 0.7 $mg.L^{-1}$ at the outlet of the recycled water reservoir during 2006/2007 (n = 13), while combined chlorine (monochloramine) was generally measured at a concentration of 0.4 ± 0.7 $mg.L^{-1}$. The potential for the simultaneous loss of both the taste properties of the anti-ingestant and the loss of the chlorine residual therefore precluded the use of such compounds in practice. It is possible that oxidants other than chlorine could be used to help preserve recycled water quality during distribution, though given the massive scale of dual reticulation planned within Sydney Water's area of operations, the need for control measures to have a reasonable cost was thought to preclude such strategies.

4. Colourants

Sydney Water is currently investigating the feasibility of colour compounds (colourants) to provide a visual medium that allows users to discriminate potable and recycled water. The colourant Aquatint™ (David Stewart Holdings Pty Ltd) is a locally distributed and commercially available polymeric compound that has provided the focus of ongoing investigation for the real-time detection of cross-connection to recycled water systems. Colourants of this nature (non-dye) are intended for use in the soap and detergent industry and have been used safely in the United States and Europe for many years. They furthermore have low oral (LD_{50} = >5000 $mg.kg^{-1}$ in rats) and aquatic (LC_{50} = >1000 $mg.L^{-1}$ in *Oncorhynchus mykiss*) toxicity, and given their polymeric nature and application in laundry products, are desirable for their low staining potential.

A sensitivity panel determined the threshold concentration (visual detection limit) of Aquatint™ to be within the order of 0.1 – 1.0 ppm. At a working concentration of 1 ppm however, Aquatint™ demonstrated poor stability to free chlorine (> 95% reduction in colour after 24 hours, measured as absorbance at 628 nm), though had low chlorine demand (10% reduction in 2 $mg.L^{-1}$ free chlorine after 24 hours and 25% after 5 days). At a concentration of 10 ppm, Aquatint™ effected a free chlorine demand of > 80% after 24 hours, increasing to > 90% after 5 days. The colour intensity (A_{628}) of Aquatint™ decreased by 77% and 85% respectively during this time.

Being a less reactive species than free chlorine, monochloramine did not combine as readily with Aquatint™. There was no significant difference in the rate of decay of 2.0 $mg.L^{-1}$ chloramine at Aquatint™ concentrations of 0, 2, 4 and 10 ppm. At a working concentration of 10 ppm, Aquatint™ effected a 17% reduction in monochloramine after 48 hours (11% in negative control), increasing to 18.5% after 4 days. After this time, and for the duration of the experimental period (20 days), there was no significant difference between the test compound and control at all concentrations examined.

A combined chlorine (monochloramine) concentration of 2.0 $mg.L^{-1}$ effected a 11% reduction in colour intensity of 2 ppm Aquatint™ after 48 hours, increasing to 41% after 20 days. During the corresponding period of time, the colour intensity (A_{628}) of

Aquatint™ at a working concentration of 10 ppm decreased by 1% and 16%, respectively; remaining within the detectable optical range after 48 hours. This period of time was considered to be representative of the residence time within the RHDA distribution system.

Used at a recommended concentration of 1.0 ppm, the addition of Aquatint™ to recycled water would add approximately $0.10 per kL to the cost of the finished product per application. It should be appreciated though that at this concentration the ingress of recycled water into potable water may not exceed the lower limit of optical detection for Aquatint™. Taking into consideration its stability to free and combined chlorine therefore, a more reliable working concentration of Aquatint™ could therefore be in the order of 5 to 10 ppm, which adds considerably to the cost of recycled water distribution.

Sydney Water recently engaged the services of a NATA accredited public textile testing facility, Australian Wool Testing Authority (AWTA) Ltd. in Melbourne to undertake analysis into the staining potential of Aquatint™ and its suitability for domestic laundering. The assessment of removability was evaluated using an integrating sphere spectrophotometer. At a working concentration of 1 ppm, Aquatint™ was found to be impart colour to textiles ($\Delta E = 2.92$ at 25 °C), and at a concentration of 10 ppm, a pale though visible hue was observed on white linen ($\Delta E = 7.21$ at 25 °C). The suggested (or allowable) level of staining is $\Delta E = 0.2$, and no tests on the fastness of the colourant were carried out.

As with the anti-ingestants, continual use of colourants is impractical under current disinfection regimes, given their poor stability in chlorine and disinfectant demand, and potential to stain laundry, given the intended application of recycled water in laundry use. It is possible however that alternative disinfectants be used, and applied intermittently in sections of a distribution system over 24–48 hours and with adequate notice to customers, Aquatint™ or other colourants may provide a positive step in regular auditing of distribution systems and for maintaining customers' trust. Furthermore, Aquatint™ may be used for the immediate restoration of confidence in the event of a cross-connection event.

5. Future Directions – Early Warning Systems

Analysis of available tools and technologies has identified the potential for greater utilisation of early warning systems (EWS) for the real-time analysis of water infrastructure security through accidental or deliberate (malevolent) contamination by chemical, biological and radioactive agents (AwwaRF, 2002). Using sophisticated data analysis and complex algorithms, EWS can draw upon a multitude of operational data and other information garnered through epidemiological studies and surveillance systems (*i.e.* SCADA) to provide water utilities an effective system for developing early responses to changes in distribution water quality (Bukhari & LeChevallier, 2006).

EWS, which can incorporate micro- and nano-structured devices including optical and chemical sensors, may provide a means to detect anomalies in the physicochemical properties or fingerprints of potable water systems, and may have potential application in the detection of cross-connection events within a dual reticulation system. Inherent properties of recycled water such as conductivity, pH, redox potential, temperature, dissolved gases, organic matter, and optical properties such as fluorescence or UV absorbance can be utilised for this purpose (van der Gaag, 2007). Alternatively, recycled water can be augmented with chemical tracers or other artificial signatures to discriminate in real time, potable and recycled water types.

The use of EWS and sensor-type technology has a number of limitations, least of which is scale, and at what magnitude of analysis offers the level of sensitivity required to detect what is otherwise a rare event of cross-connection within a distribution system. On-line microsensors should therefore be inexpensive, sensitive, robust and simple to use, and would need to be strategically deployed (Ostfeld & Salomons, 2004), ideally at a household level and no greater than a small community scale. The theoretical protection offered by sensors and other EWS is furthermore dependent upon a number of factors, largely the site and size of the cross-connection event, and the number and location of sensors. As an estimate though, and to provide an adequate level of protection (>99%), numerical modeling of a small city has demonstrated the need for one EWS per 250 connections, rendering expensive technologies prohibitive.

To be practical, EWS must furthermore offer an appropriate level of sensitivity (and specificity) and as such, have a low level of false positives and false negatives. If conductivity is used as an example, the total dissolved solids (TDS) fraction within the RHDA is no greater than four-fold that of the potable water system. In the event of minor ingress into a potable system, a single analyte such as this may not offer the level of sensitivity required to discriminate such an event. There may be a substantial need therefore for the development of a multi-parametric approach using two or more analytes or discriminants. Appropriate EWS should furthermore be able to distinguish between normal variations, contamination events, and/or quality deteriorations as a result of the complex physicochemical properties of the two water types (van der Gaag, 2007).

6. Conclusion

The most effective means of ensuring the safety of water distribution systems is through the use of a comprehensive risk framework that encompasses all steps in water supply and delivery. Rather than focusing on numerically driven compliance and maximum contaminant levels, risk-based management shifts the focus of performance assessment towards operational and process-driven evaluation of water supplies (operator training, operational practices and best management approaches). That approach has furthermore created a level of redundancy in routine monitoring, which does not provide adequate protection of public safety in real time.

Despite due diligence and best management practices though, cross-connection occurs within municipal dual reticulation systems. Although unlikely to present a measurable source of health concern, the detection of such events nonetheless requires vigilance by water utilities for reasons of public confidence and acceptance of recycled water initiatives, and well as due diligence and regulatory compliance. In summary:

- Despite thorough investigation, this study has failed to identify a suitable anti-ingestant agent for application in a non-potable recycled water system. Eight candidate compounds short-listed for further investigation were eliminated on the basis of their malodour, variable detection range, chlorine demand and/or cost;
- Colourants, including the polymeric agent Aquatint™ will remain the subject of ongoing evaluation by Sydney Water Corporation. Colourants may be used for the intermittent auditing of dual reticulation systems and management of potential and confirmed cross-connection events; and
- Sensor technology may provide promise for the rapid (real-time) detection of cross-connection within a dual reticulation system. Such technologies need to be

inexpensive, reliable and sensitive, and would ideally utilise the inherent physicochemical properties of recycled water.

Acknowledgments. The authors of this paper would like to gratefully acknowledge Dr Mark Angles, Dr Heri Bustamante and George Kastl (Sydney Water) for their valuable contributions to the study and input into this manuscript.

7. References

AWWA (2001). Potential Contamination Due to Cross-Connections and Backflow and the Associated Health Risks. Issues Paper prepared for US Environmental Protection Authority.

AwwaRF (2002). Online Monitoring for Drinking Water Utilities. Cooperative Research Report. Hargesheimer, E., Conio, O., and Popvicova, J. (Eds.).

Borensztajn, J. (2007). Staff ill from recycled water. Herald Sun, 20th March 2007.

Bukhari, Z., and LeChevallier, M. (2006). Enhanced Monitoring to Protect Distribution system Water Quality. Proceedings of the American Water Works Association WQTC Conference.

Craun, G. F., and Calderon, R. L. (2001). Waterborne Disease Outbreaks Caused by Distribution System Deficiencies. *JAWWA*. **93**:64-75.

Davison, A., Krogh, M., and Deere, D. (2005) Identification and Recommendation of Additives for the Prevention of Unsuspecting Ingestion of Recycled Water: Water Futures Pty Ltd confidential report to Sydney Water Corporation.

Deere, D., Stevens, M., Davison, A., Helm, G., and Dufour, A. (2001). Management Strategies. In: Water Quality: Guidelines, Standards and Health. Assessment of risk and risk management for water-related infectious disease. Fewtrell L, Bartram J. (eds). IWA Publishing, London. ISBN 1 900222 28 0. Ch 12. p 257-288.

Deere, D. A., and Davison, A. D. (2005). The Ps and Qs of Risk Assessment, *Water (Aust)*. **32**(3):38-43.

De Rooy, E. and Engelbrecht, E. (2003). Experience With Residential Water Recycling at Rouse Hill. *Proc*. Water Recycling Australia, Second National Conference, Brisbane, 1-2 September 2003, Australian Water Association, Australia.

LeChevallier, M. W., Gullick, R. W., and Karim, M. (2002). The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients.

Liang, J. L., Dzuiban, E. J., Craun, G. F., Hill, V., Moore, M. R., Gelting, R. J., Calderon, R. L., Beach, M. J. and Roy, S. L. (2006) Surveillance for Waterborne Disease and Outbreaks Associated with Drinking Water and Water not Intended for

Drinking - United States, 2003—2004. Morbidity and Mortality Weekly Reports, 55(SS12);31-58.

Muston, M., (2004). Integrated Concepts for Reuse of Upgraded Wastewater. Failure Mechanisms Literature Review. University of Wollongong. AQUAREC report EVK1-CT-2002-00130.

NSW Recycled Water Coordinating Committee (1993) NSW Guidelines for Urban and Residential Use of Reclaimed Water. 1st Edition, May 1993. Sydney: NSW Government.

Ostfeld, A., and Salomons, E. (2004). Optimal Layout of Early Warning Detection Stations for Water Distribution Systems Security. *J. Wat. Res. Plan & Manag*. 130(5):377-385.

Rodriguez-Mozaz, S. Lopez de Alda, M. J., and Barceló, D. (2006). Biosensors as useful tools for Environmental Analysis and Monitoring. *Anal. Bioanal. Chem.* **386**:1025-1041.

Sydney Water (2001). Rouse Hill Recycled Water Area Plumbing Guidelines. Fact Sheet. Publication Number CSD37. Sydney: Sydney Water Corporation.

Sydney Water (2004). Rouse Hill Recycled Water Plant. Fact Sheet. Publication Number SWC 315: 07/04. Sydney: Sydney Water Corporation.

van der Gaag, B., and Volz, J. (2007). State-of-the-Art "Real-Time On-Line Monitoring of Contaminants in Water." Preparatory report of the GWRC workshop, KIWA Water Research, Nieuwegein, Netherlands.