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Microbial risk assessment of drinking water to set health-based performance targets to improve water quality and treatment plant operations

A. Shea[a,*], J. Poon[b] and S. Williamson[c]

[a] Western Water Authority, 36 Macedon Street, Sunbury, Victoria 3429, Australia

[b] CH2M HILL Australia, Level 40, 385 Bourke Street, Melbourne, Victoria 3429, Australia

[c] CH2M HILL Australia, Level 7, 9 Help Street, Chatswood 2067, Australia

*Corresponding author. E-mail: alan.shea@westernwater.com.au

Abstract

Western Water (WW) provides water, recycled water and wastewater services to almost 150,000 people whilst continuously striving to improve processes to provide its customers with safe, cost effective and reliable drinking water, recycled water and treatment services. Under this framework of continuous improvement, WW has reviewed the effectiveness of its drinking water treatment systems using quantitative microbial risk assessment (QMRA) techniques described by the World Health Organization (WHO). The microbial-related water quality targets in the Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy (2011) National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra are simply '*to ensure that drinking water is free of microorganisms that can cause disease*'. Whereas, the Australian Guidelines for Water Recycling adopted the WHO QMRA approach for setting health-based microbial targets to manage health risk to customers. WW has investigated adopting the AGWR methodology for drinking water risk management, and invested in the development of a convenient and practical QMRA tool for rapid assessment and reporting of the microbial safety of its drinking water systems. This action resulted in the identification of several drinking water system performance deficiencies, and recommendations for system improvements and optimization to improve health risk management to customers.

Key words: Australian Drinking Water Guidelines, Australian Guidelines for Water Recycling, drinking water, Quantitative Microbial Risk Assessment (QMRA), World Health Organization

INTRODUCTION

Under the Victorian Safe Drinking Water Act (2003), Western Water (WW) has implemented a Drinking Water Quality Management System and produced Water Quality Risk Management Plans. As part of the framework of continuous improvement outlined in the Risk Management Plans, WW undertook a review of the effectiveness of its seven drinking water filtration plants using the quantitative microbial risk assessment (QMRA) methods of the World Health Organization (WHO) and Australian Guidelines for Water Recycling (NRMMC *et al.* 2006).

There are a range of water quality guidelines that can be applied when setting health-based targets. Microbial-related targets described in the Australian Drinking Water Guidelines (NHMRC 2011) are simply: '*to ensure that drinking water is free of microorganisms that can cause disease*'. For the purpose of setting health-based targets and characterizing risk, the WHO Guidelines for Drinking Water Quality (WHO 2011) use a combination of QMRA and Disability-Adjusted Life Years (DALYs).

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Although not specific to drinking water, the Australian Guidelines for Water Recycling (NRMMC *et al.* 2006) also adopted this same methodology for setting health- based targets and characterizing risk.

QMRA methodology is applied to determine the likelihood of infection and illness occurring from exposure to specific pathogens contained in drinking water. DALYs are then used to convert the likelihood of illness into impacts or burdens of disease. The adopted tolerable risk of 10^{-6} DALY per person per year is about equivalent to a 10^{-5} excess lifetime risk of cancer or an annual diarrheal risk of illness of 10^{-3} (i.e. one illness per 1,000 people). The advantage of this methodology is that it is based on the recognition that not all microbial pathogens cause the same level or severity of disease burden.

The primary objective of the QMRA work performed as part of this investigation was to identify drinking water treatment deficiencies and opportunities, to improve and optimize the performance of WW's seven drinking water treatment systems by using historic microbial testing and plant performance data.

METHODS

Intensive data collection carried out during times of peak microbial challenge in August, September, and November 2010 for each water treatment system was performed to provide a rich data set for least time and cost. Analysis was performed for a wide range of microbes (including *Cryptosporidium* spp., *Giardia* spp., *E. coli*, Hepatitis A, Rotaviruses, Norovirus G, Adenovirus F, Reoviruses and Enteroviruses), which enabled estimates of maximum, average and minimum numbers of protozoa, viruses and bacteria per liter of source water to be derived. Inputs are shown in Table 1.

Table 1 | Achievable Log_{10} reductions from source to first customer for typical and partial treatment system performance

Drinking Water System	Group	Maximum	Average	Minimum	Sample Count
A	Viruses	>0.025000	<0.025000	<0.025000	8
	Protozoa	0.000132	<0.000107	<0.000089	3
B	Viruses	>4.000000	≈0.587000	<0.010000	33
	Protozoa	0.000111	<0.000097	<0.000089	3
C	Viruses	>1.000000	≈0.496000	<0.010000	33
	Protozoa	=0.000580	≈0.000275	<0.000088	3
D	Viruses	=0.055000	≈0.033000	<0.025000	8
	Protozoa	0.000500	<0.000372	<0.000116	3
E	Viruses	>4.000000	≈1.075000	<0.010000	33
	Protozoa	=0.000508	≈0.000347	<0.000263	3
F	Viruses	>4.000000	≈0.705000	<0.010000	33
	Protozoa	0.000116	<0.000092	<0.000078	3
G	Viruses	>1.000000	≈0.500000	<0.010000	33
	Protozoa	0.000263	<0.000207	<0.000172	3

A spreadsheet based on a QMRA modelling tool was developed by CH2M HILL to indirectly estimate the risk to human health by using documented infection rates for given densities of pathogens. This involved quantitative assessment of microbe-based health risks (a QMRA) using reference bacterial (*Campylobacter jejuni*), viral (rotavirus and adenovirus) and protozoan (*Cryptosporidium parvum*) pathogens, and a combination of actual and theoretical $\log_{10}$ removal performance values for the treatment processes employed at each drinking water treatment plant.

Valuation of the effectiveness of the preventative treatment measures was performed by calculating risk using the QMRA modelling tool and comparing the results against the adopted tolerable risk of

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10^{-6} DALYs per person per year. Although only slightly different, with respect to the application of the dose-response equation, the QMRA methodologies as described in WHO (2011) and NHMRC (2006) were calculated and compared simultaneously using the QMRA tool.

The QMRA tool also calculated risk for the two exposure scenarios using the maximum, average and minimum source water reference organism concentrations. The exposure scenarios assessed

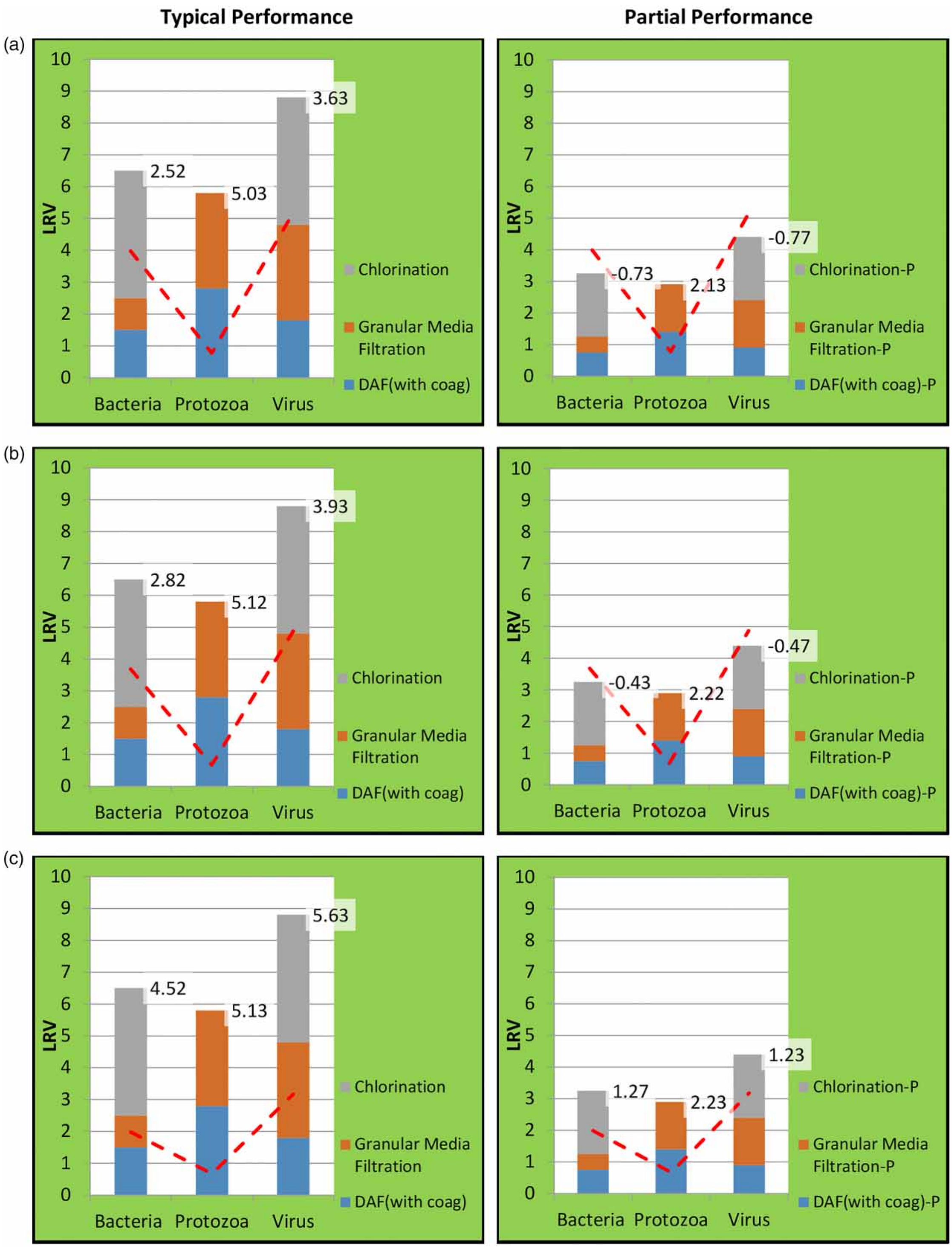

Figure 1 | Risk statement for Drinking Water System G under (a) maximum, (b) average, and (c) minimum source pathogen scenarios, for typical and partial treatment efficacy. The dashed line represents the tolerable risk LRV.

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Table 2 | Achievable Log_{10} reductions from source to first customer for typical and partial treatment system performance

Treatment System Performance	**Reference Pathogen**	**Drinking Water System**						
		A	**B**	**C**	**D**	**E**	**F**	**G**
Treatment Process Summary		DAFF Chlorination	Clarification, Sand filtration Chlorination	DAFF Chlorination	MF Chloramination	DAFF Chlorination	DAFF Chloramination	DAFF Chlorination
Typical Treatment	*Campylobacter*	6.5	10.1	6.5	5	6.5	3.5	6.5
	Cryptosporidium	5.8	6.5	5.8	4	5.8	5.8	5.8
	Viruses	8.8	9.7	5.8	5	8.8	5.8	5.8
Partial Treatment	*Campylobacter*	3.25	2.49	3.25	4	3.25	1.75	3.25
	Cryptosporidium	2.9	1.4	2.9	2.3	2.9	2.9	2.9
	Viruses	4.4	2.45	4.4	3	4.4	2.9	4.4

Note: DAFF, dissolved air flotation filtration.

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included the exposure of a healthy young adult individual drinking water treated from one of the systems at the point of the closest connection in the reticulation system during:

- Typical or normal operating conditions – maximum documented achievable log removal capped at 4 $\log_{10}$.
- Abnormal (partial) treatment performance or operating conditions – minimum documented achievable $\log_{10}$ removal (worst case treatment scenario).

RESULTS AND DISCUSSION

For each plant graphical output was generated to highlight buffers or shortfalls in the ability of the plant to achieve the $\log_{10}$ reduction value (LRV) required so as not to exceed the level of tolerable risk. Figure 1 provides an example of this output for System G, with the number of each pathogen group representing the buffer or shortfall between the tolerable LRVs and those calculated as achievable.

Table 2 summarizes the log reductions for each pathogen group calculated as achievable for each system under typical and partial treatment performance.

Table 3 | Minimum Log_{10} reduction required to achieve tolerable risk for minimum and maximum reference pathogen values

		Drinking Water System						
Source Number	**Reference Pathogen**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Maximum	*Campylobacter*	2.38	4.59	3.98	2.72	4.59	4.59	3.98
	Cryptosporidium	0.47	0.40	1.12	0.43	1.06	0.43	0.77
	Viruses	3.57	5.77	5.17	3.91	5.77	5.77	5.17
Minimum	*Campylobacter*	2.38	1.98	1.98	2.38	1.98	1.98	1.98
	Cryptosporidium	0.30	0.30	0.30	1.05	0.77	0.25	0.67
	Viruses	3.57	3.17	3.17	3.57	3.17	3.17	3.17

The results of the QMRA are presented in Table 3, which shows the minimum system treatment performance (in terms of $\log_{10}$ reductions) required for each drinking water system to produce drinking water that would not exceed the adopted tolerable risk level (10^{-6} DALYs or 1 μDALY).

Table 4 | Ability to meet tolerable risk level for partial treatment system performance

		Drinking Water System						
Source Number	**Reference Pathogen**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Maximum	*Campylobacter*	✓	×	×	✓	×	×	×
	Cryptosporidium	✓	✓	✓	✓	✓	✓	✓
	Viruses	✓	×	×	×	×	×	×
Minimum	*Campylobacter*	✓	✓	✓	✓	✓	×	✓
	Cryptosporidium	✓	✓	✓	✓	✓	✓	✓
	Viruses	✓	×	✓	×	✓	×	✓

Comparison of Tables 2 and 3 shows that, under typical performance, all systems, except System F, could achieve the log reductions required to reduce risk to below the tolerable limit. However, under partial system performance, only System A could achieve the log reductions required. Table 4 summarizes the ability of each system to achieve the required log reductions for the three reference pathogen groups and Figure 2 shows, graphically, the LRV required to achieve tolerable risk levels compared to the achievable LRVs for System F.

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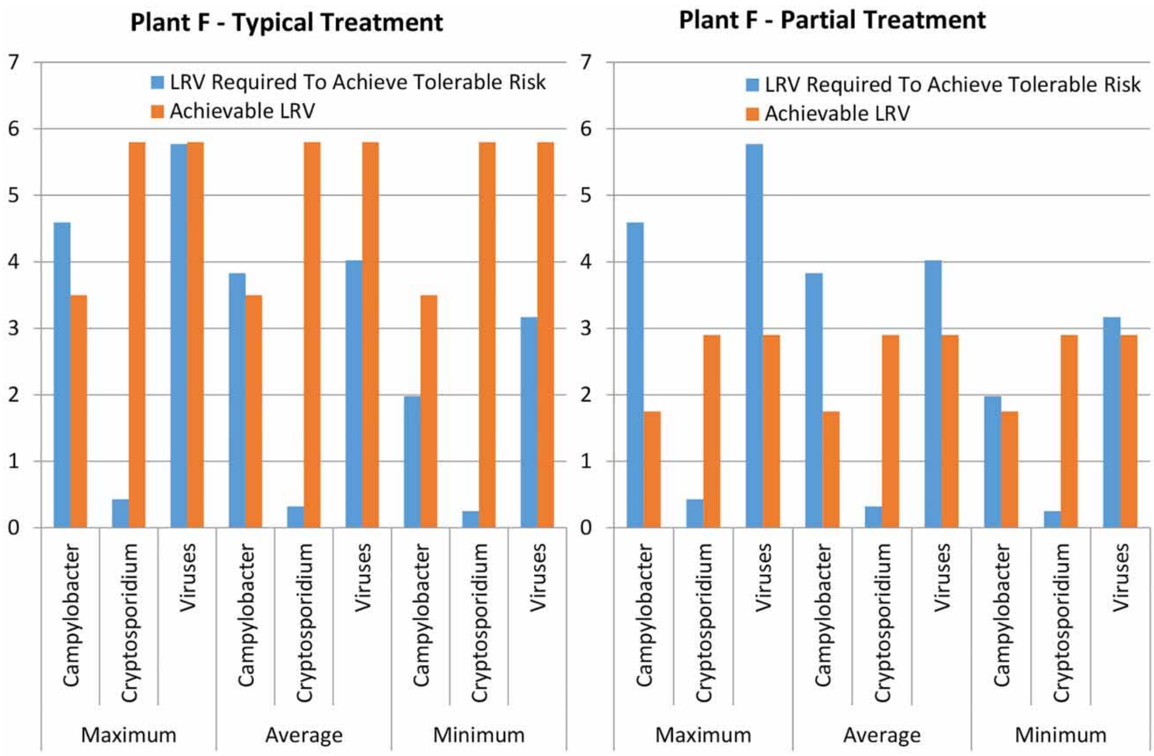

Figure 2 | LRV required to meet adopted tolerable risk versus LRV achievable at Drinking Water System F.

The following observations were made as part of the QMRA investigation regarding the results:

- Due to very low concentrations of protozoa observed in the catchments, tolerable risk is not exceeded by protozoa at any plants under any operational performance scenarios (typical or partial).
- Although sand filtration can be highly effective at pathogen removal, having units that are not operated optimally increases the risk from viral and bacterial pathogens to exceed the tolerable limit under most source water quality scenarios.
- Systems with higher source pathogen numbers using dissolved air flotation filtration (DAFF) (i.e. Systems E, F and G) do not reliably remove/inactivate bacteria at source water pathogen concentrations below average.
- Primary disinfection by chloramination is insufficient when upstream processes to remove viruses and bacteria are not optimized, and alternative approaches such as addition of UV disinfection or conversion to free chlorine residual are needed.

It is noted that the dose-response coefficients used in this assessment were taken from the Australian Guidelines for Water Recycling (NRMMC, EPHC & AHMC, 2006). They were selected for use with recycled water and differ slightly from those used in WHO (2011). When the WHO coefficients are applied instead, the overall LRV required to reduce risk to below the tolerable limit increases for protozoa and viruses.

CONCLUSIONS

The QMRA modelling tool was developed using the methodology and dose-response coefficients given in the Australian Guidelines for Water Recycling and the WHO guidelines. Using the tool to assess the effectiveness of the preventive measures in the seven drinking water treatment systems, a

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range of recommendations was made by CH2M HILL to help WW to improve the management of drinking water risk to customers.

The recommendations made included consideration of:

- Replacing the chloramination systems at Systems D and F with chlorination, to reduce the chlorine contact time required to maximize the $\log_{10}$ reduction of bacteria and virus pathogens.
- Improving the chlorine dosing controls, and the monitoring of chlorine or chloramine residuals, plus pH correction chemical dosing, to maximize the $\log_{10}$ reduction of bacteria and virus pathogens.
- The Australian Drinking Water Guidelines (NHMRC 2011) and WHO guidelines clearly state that disinfection should not be compromised in order to manage risks from disinfection by-products (DPBs). Therefore it is also recommended that the focus of treatment should also be on the removal of organics to minimize the formation of DBPs when using chlorination, where DBPs are of concern.
- Achievement of a 10^{-6} DALY pathogen performance target at System B under all operating conditions, would require improvements to both the chlorination and the clarification/sand filtration systems. Therefore, it was recommended that further investigation be undertaken to determine whether System B could be optimized to achieve a 1 μDALY performance benchmark, or otherwise identify and cost the range of options available to achieve a minimum performance target.

Further reduction in source-water data uncertainties would improve understanding of the risk characterization of the operational capabilities of the existing plants and the scenarios that lead to exceeding the tolerable risk. Therefore, it is recommended further actions are undertaken to improve the risk characterization for the water treatment systems:

- Contribute to the broader body of national and international work intended to improve the accuracy of determination of the achievable log reductions of process units within water treatment plants, the scenarios during which the achievable log reductions are compromised (e.g. during filter backwash and/or high turbidity source water events, after extreme weather events, during high demand scenarios), and the correlation to measurable process performance parameters (which assists with the next recommendation).
- Continuous analysis of available treatment unit performance/operational data to determine how each unit performs under different scenarios and to fully understand the performance of each system as a whole with regard to parameters that are monitored within the overall treatment process (e.g. turbidity, suspended solids, etc.).

In addition to the improvement/optimization recommendations made, a major outcome of the study was production of a QMRA tool that WW could use to assess:

- Drinking water treatment plant performance
- Shortfalls in the treatment system performance
- Risk mitigation measures
- Water Quality Risk Management Plans for each drinking water system

It also provided the opportunity and flexibility to use the QMRA tool on other water supply systems chosen for assessment by WW.

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