Balancing Microbial Quality and Corrosion Potential of Instantaneous, Solar, and Storage Hotwater Systems Supplied by Harvested Rainwater in the Urban Environment

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ABSTRACT

The acceptability of the quality of hotwater supplied by harvested rainwater in the urban environment has been the subject of much debate in many developed countries as a result of attempts to maximise usage of harvested rainwater in order to improve city water-cycle management. Debate has centred around the issues of the microbiological quality of the heated rainwater, since many tank water samples fail drinking water guidelines due to the presence of Index Organisms, and the potential acceleration of hotwater system corrosion. The problem is complicated by the availability of a number of different types of hotwater systems including instantaneous, solar-powered, and conventional storage hotwater tanks. 27 rainwater tanks and associated hotwater systems from two major Australian cities were repeatedly tested over a period of 24 months for the index and indicator bacteria *E. coli*, total coliform, Heterotrophic Plate Counts and Pseudomonas, along with physicochemical parameters and a variety of heavy metals. The results showed that while temperature was a significant factor for determining the microbiological quality of heated rainwater, all hotwater systems achieved large reductions of *E. coli* (>98%) and HPC (62-99.99%). Lead and copper were found in increased concentrations in the hotwater of the solar powered systems. However, elements thought to be possibly associated with hotwater system corrosion, such as zinc and iron, were not found to be increasing.

INTRODUCTION

For millions of people around the world rainwater harvesting is the only feasible source of good quality water and provides the sole water supply. However, the benefits of rainwater harvesting are being increasingly acknowledged in urban centres, where water supply and stormwater management practices face increasing pressures from unsustainability. Attempts to mainstream rainwater harvesting in cities where an alternative municipal supply is available have been somewhat impeded by the lack of consensus on appropriate uses of harvested rainwater. The extent of benefits provided by rainwater tanks is determined by the extent to which the harvested rainwater is used. The use of rainwater for hotwater applications has been shown to be a significant factor in maximising the potential impact of rainwater tanks on urban water cycle sustainability (Coombes *et al*., 2002a).

However, heated rainwater must be of sufficiently high quality before the widespread recommendation to incorporate rainwater into hotwater systems (HWS) can be made. The issue has only been briefly examined by a limited number of past studies (Spinks *et al*., 2004; Spinks *et al*., 2003; Coombes *et al*., 2002b; Lye, 1991). The problem is complicated by the availability of a number of different types of hotwater systems including instantaneous, solar-powered, and conventional storage hotwater tanks. Domestic HWS operate in a range of sub-boiling temperatures, which is a critical factor when trying to distinguish between systems that will destroy bacteria and those that will promote bacterial growth. The issue is further complicated by concerns over corrosion of HWS. The potential exists for accelerated corrosion of HWS caused by the alternating use of acidic rainwaters with low dissolved solids content and municipal supplies with high dissolved solids.

The aims of this study were; Firstly, to evaluate the performance of electric-storage, solar-powered, and instantaneous HWS in improving the microbial quality of harvested rainwater; Secondly, to determine the importance of operating temperature on pasteurisation efficacy, and; Finally, to examine whether the use of harvested rainwater increased the rates of HWS corrosion.

METHODS

Water quality was monitored in 21 solar-powered HWS and associated rainwater tanks in the Brisbane City region and in five electric storage HWS in Newcastle, Australia. These results were compared to those of an instantaneous HWS previously published by Coombes *et al*. (2002b). Of the rainwater tanks supplying the solar-powered HWS, 15 were Aquaplate (3.24KL – 4.85KL), four were polyethylene (4.54KL – 5KL), and two were stainless steel (3KL – 4.5KL). Those supplying the electric storage HWS were Aquaplate (three, 2KL – 9KL), polyethylene (one, 7KL), and concrete (one, 16KL), while the instantaneous HWS was supplied by a 9KL Aquaplate tank. The plumbing configurations of the HWS were such that the heated rainwater was mixed with cold mains water to achieve the desired temperature at the point of use.

Bacteriological samples were collected in sterile 500mL polyethylene jars and analysed within 6 hours of collection. Hotwater samples were quenched in cold water immediately upon collection and kept in the dark during transport. Samples were analysed using Millipore Membrane Filtration with enumeration of *E. coli* and total coliform bacteria on m-ColiBlue24®, *Pseudomonas spp*. with Pseudomonas Selective broth, and Heterotrophic Plate Counts (HPC) on mEndo Media. Samples designated for metal analyses were sent to Brisbane Scientific Analytical Services or Hunter Water Laboratories and were analysed using Inductively Coupled Plasma Optical Emission Spectroscopy and Atomic Absorption Spectroscopy, respectively.

RESULTS

Microbial Quality

The harvested rainwater in tanks supplying solar-powered HWS contained an average of approximately 17000 CFU/mL for HPC and regularly contained coliform bacteria and *E. coli*, as shown in Table 1. Significant reductions occurred in all bacterial parameters when rainwater was passed through the solar-powered HWS. HPC were reduced by more than a log reduction while coliform and *E. coli* were reduced by greater than two logs. The average temperature of the solar-powered HWS was around 52°C with the temperature range varying 20°C either side of the average depending on the time of year. The correlations between hotwater temperature and all bacterial parameters were statistically significant though not particularly strong.

Table 1: Solar Hotwater Systems – Microbial Water Quality

	N	RWT Average	HWS Average	HWS Minimum	HWS Maximum	Correlation to Temp (r)
Temperature (°C)	441	24.1	51.8	31	71	-
HPC (CFU/mL)	455	16960	957	6	26000	-0.34*
Total coliform (CFU/100mL)	456	74	0.8	0	80	-0.20*
E. coli (CFU/100mL)	458	11.8	0.05	0	5	-0.15*
Faecal coliform (CFU/100mL)	458	13.5	0.08	0	11	-0.19*

*Significant to 95% ($P<0.05$)

Solar-powered HWS operated at a wide range of temperatures and bacterial quality varied accordingly, as shown in Table 2. One third of all hotwater samples were below 50°C, with the lowest levels of reductions achieved in these samples. The majority of systems operated in the range 50°C–59°C (63%) and achieved a ten-fold greater reduction in HPC and 2 log greater reduction in coliform and *E. coli* than hotwater systems operating below 50°C. Only a minor proportion of solar-powered HWS operated at, or above, 60°C (8%) and produced the highest quality water. Enteric bacteria were essentially eliminated at this temperature and HPC were reduced by a further 2 logs than hotwater systems operating at 50°C–60°C.

Table 2: Water Quality of Solar-Powered HWS Operating in Three Temperature Ranges

HWS Temp.	Parameter	Number of Samples	Average (CFU/100mL)	Minimum (CFU/100mL)	Maximum (CFU/100mL)
<50°C					
	Total Coliform	127	2.217	0.00	80
	Thermotolerant Coliform	129	0.271	0.00	11
	E. coli	129	0.171	0.00	5
	HPC (CFU/mL)	128	2220	0.00	26000
50°C-59°C					
	Total Coliform	276	0.0217	0.00	5
	Thermotolerant Coliform	276	0.00	0.00	0.00
	E. coli	276	0.00	0.00	0.00
	HPC (CFU/mL)	274	372	0.00	6000
>60°C					
	Total Coliform	36	0.00	0.00	0.00
	Thermotolerant Coliform	36	0.00	0.00	0.00
	E. coli	36	0.00	0.00	0.00
	HPC (CFU/mL)	36	7.47	0.00	52

Table 3 shows the microbial water quality from five electric-storage HWS and rainwater tanks. The temperature of electric-storage HWS averaged 9°C higher than that of solar-powered HWS. Similar proportions of log reductions were achieved for HPC, coliform and *E. coli* to solar-powered HWS, and greater than 3 log reductions were achieved for Pseudomonas. The correlations between hotwater temperature and bacterial parameters are not as statistically significant as those within solar hotwater systems but were much stronger, due in part to smaller sample size.

Table 3: Storage Hotwater Tanks – Microbial Water Quality

	N	RWT Average	HWS Average	HWS Minimum	HWS Maximum	Correlation to Temp (r)
Temperature (°C)	48	18.2	60.9	47	70.5	-
HPC (CFU/mL)	53	2030	63	0	3000	-0.69
Total coliform (CFU/100mL)	55	1617	6.2	0	90	-0.40*
E. coli (CFU/100mL)	55	204	0.4	0	7	-0.17
Pseudomonas (CFU/100mL)	55	5860	4	0	150	-0.22

*Significant to 95% (P<0.05)

Table 4: Microbial Water Quality of Storage HWS Operating in Three Temperature Ranges

HWS Temp.	Parameter	N	Average (CFU/100mL)	Minimum (CFU/100mL)	Maximum (CFU/100mL)
<55°C					
	Coliform	11	22.3	0	90
	Pseudomonas	11	15.4	0	150
	E. coli	11	0.7	0	7
	HPC (CFU/mL)	10	317	1	3000
55°C-59°C					
	Coliform	5	2.4	0	10
	Pseudomonas	5	3	0	15
	E. coli	5	0	0	0
	HPC (CFU/mL)	5	12	0	42
>60°C					
	Coliform	34	1.7	0	10
	Pseudomonas	34	1.0	0	19
	E. coli	34	0.09	0	1
	HPC (CFU/mL)	33	1.9	0	16

Table 4 presents bacterial counts for electric-storage HWS operating in three temperature ranges. As in Table 2, the levels of bacteria in the higher temperature samples are significantly lower than those in lower temperature samples. The apparent residual coliform bacteria surviving the 50-59°C and >60°C hotwater samples were regularly identified as *Bacillus sp.*, resulting from false positives given by the m-ColiBlue24® chromogenic media.

The water quality from a domestic instantaneous HWS operating at 55°C, as previously described by Coombes et al. (2002b), also achieved significant reductions in bacterial concentrations. Table 5 shows the 2log reductions in HPC and the elimination of coliform, thermotolerant coliform, and Pseudomonas bacteria from the rapidly pasteurised water.

Table 5: Instantaneous Hotwater Systems – Microbial Water Quality

	N	RWT Average	HWS Average	HWS Min.	HWS Max.
Temperature (°C)	-	-	55	-	-
HPC (CFU/mL)	5	784	4	1	10
Total coliform (CFU/100mL)	5	18	0	0	0
Thermo coliform (CFU/100mL)	5	0.8	0	0	0
Pseudomonas (CFU/100mL)	5	1673	0	0	0

Corrosion and Heavy Metal Leaching

Concerns over potential rapid corrosion of hotwater systems had been expressed by a number of local water suppliers and local government authorities. Heavy metals were therefore monitored in samples from the solar and instantaneous hotwater systems to determine levels of metal leaching within the pipework and storage tanks.

Figures 1 to 6 show the levels of zinc, iron, magnesium, aluminium, copper and lead in the rainwater tanks, solar hotwater systems, and mains water of the Brisbane City region. Zinc and iron are often bi-products from the corrosion of galvanised iron tanks. Zinc and iron levels in the samples from the solar hotwater systems were lower than in the associated rainwater tanks, shown in Figures 1 and 2, respectively.

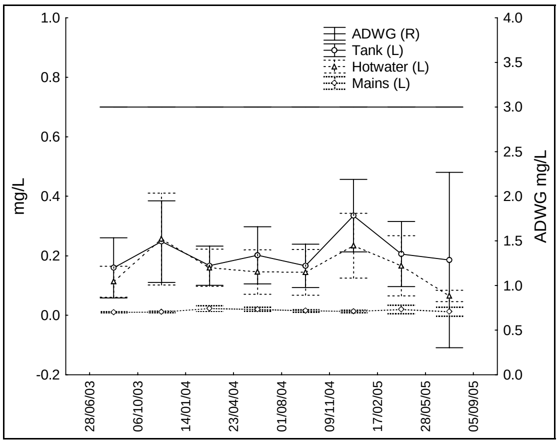

Figure 1: Average Zinc concentrations in Rainwater Tank, Mains and Solar HWS (left axis) compared against ADWG (right axis)

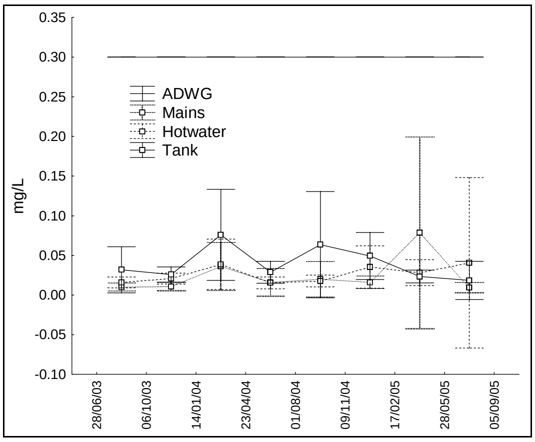

Figure 2: Average Iron concentrations in Rainwater tanks, Mains and Solar HWS Systems compared against ADWG

Most HWS anodes are made of magnesium, aluminium or zinc. The levels of magnesium and aluminium in tankwater and hotwater were both consistently below levels in the municipal water supply, shown in figures 2 & 3. The slightly higher average concentrations of these metals in hotwater samples than in rainwater tank samples seem marginal given the standard deviations.

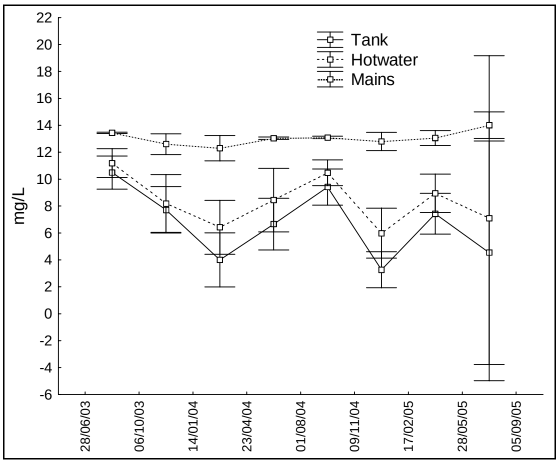

Figure 3: Average Magnesium concentrations in Rainwater Tanks, Mains and Solar-Powered Hotwater Systems

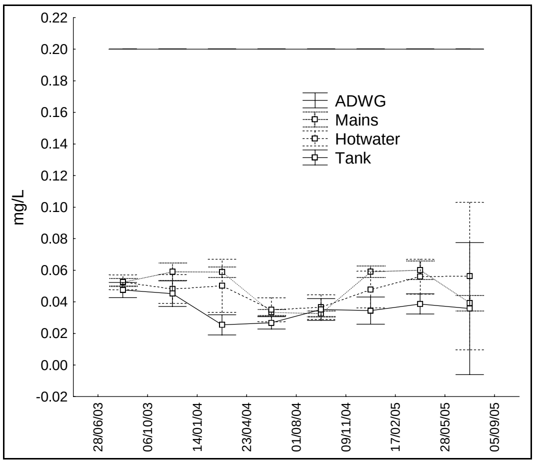

Figure 4: Average Aluminium concentrations in Rainwater tanks, Mains and Solar HWS compared against ADWG

Copper concentrations were consistently higher in hotwater samples than rainwater tank samples, shown in Figure 5. This is to be expected as heating elements of hotwater systems are typically composed of copper. The levels of copper leaching from the hotwater system were well within expected background levels (<1mg/L) and as such do not indicate accelerated corrosion (Personal Communication, Dr David Nicholas, Manager – Corrosion Consulting, Hunter Water Australia - *nicholasd@labs.hwa.com.au*). Lead levels were often higher in hotwater samples than rainwater samples and at times exceeded the ADWG limits of 10 µg/L, as shown in Figure 6.

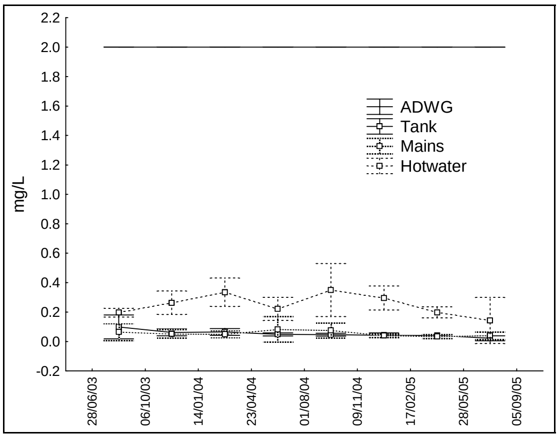

Figure 5: Average Copper concentrations in Rainwater tanks, Mains and Solar HWS compared against ADWG

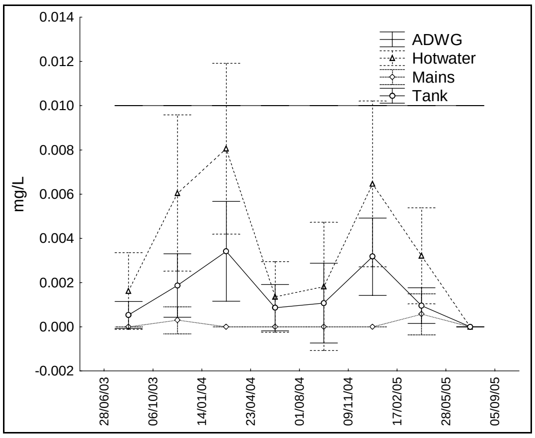

Figure 6: Average Lead concentrations in Tank, Mains and Solar HWS compared against ADWG

Table 6: Metal Concentrations in Rainwater supplying Instantaneous HWS

	Average	Maximum	Minimum	Guideline
pH	5.7	6.1	4.9	6.5-8.5
Dissolved Solids (mg/L)	67.3	168	4	500
Lead (mg/L)	<0.01	<0.01	<0.01	0.01
Iron (mg/L)	<0.06	<0.06	<0.06	0.3
Zinc (mg/L)	3.90	5.30	0.40	3
Cadmium (mg/L)	<0.002	<0.002	<0.002	0.002

Instantaneous hotwater systems do not include a storage tank and hence contact time between the water and the hotwater system pipes is minimised. The pipework of the particular instantaneous HWS under investigation did not appear to be leaching into the hotwater. The levels of dissolved solids, lead, iron, zinc and cadmium were higher in rainwater tank samples (Table 6) than the associated hotwater samples (Table 7).

Table 7: Metal Concentrations in Hotwater from Instantaneous HWS

	Average	Maximum	Minimum	Guideline
pH	5.5	6.1	5.1	6.5-8.5
Dissolved Solids (mg/L)	15.8	26	4	500
Lead (mg/L)	<0.01	<0.01	<0.01	0.01
Iron (mg/L)	<0.06	<0.06	<0.06	0.3
Zinc (mg/L)	3.90	5.00	0.40	3
Cadmium (mg/L)	<0.002	<0.002	<0.002	0.002

DISCUSSION

Microbial Water Quality

In this study, the microbial quality of harvested rainwater was shown to be significantly improved as it passed through the various hotwater systems, irrespective of design. Some of the major operational factors influencing the extent of microbial destruction between various designs of HWS include operating temperature (most importantly temperature range), contact time (residence time of water in the HWS), and the surface area (of heating element or pipe) to volume (of water) ratio. It was clear from this study that, while HWS design differences may have a small influence on microbial water quality, the single most important factor in determining water quality from HWS was the operating temperature.

Surprisingly, the correlation r-values between temperature and bacterial concentrations were not particularly strong. This can be largely explained by the significant variance of bacterial concentrations within the initial rainwater samples, and also partly by the presence of varying concentrations of spore forming bacteria which are not generally inactivated by HWS temperatures. Residence time of water in the HWS was not recorded and this may also have contributed to low r-values, as some hotwater systems may have heated water to a lower temperature but maintained that temperature for a longer period of time.

While plumbing standards in most countries state that hotwater systems for domestic supply should be maintained at a minimum of 60°C to inhibit the growth of the respiratory tract pathogen *Legionella pneumophila*, it was apparent that the majority of hotwater systems did not operate at this temperature for the majority of the time. A number of HWS showed large seasonal variations in operating temperature, particularly amongst the solar-powered HWS, with summer temperatures surprisingly lower than winter temperatures. This may have been due to the regular cloud cover in Brisbane which experiences a summer rainy season, or due to householders tampering with HWS, possibly to increase the proportion of rainwater used in the HWS during the wet season. It is not common for residents to be aware of such specific guidelines, which proves problematic when trying to promote an unenforceable hotwater system guideline.

The actual ability of HWS to achieve set temperatures did vary between different types of HWS. Electric-storage HWS achieved consistently higher temperatures (averaging 61.1°C) than solar-powered HWS (averaging 51.8°C) which often fell below 50°C. This may have been due to the regular supply of power from the grid to electric-storage tanks allowing them to maintain higher temperatures all year round. However, it is equally likely that the difference was simply a confounding factor of geographic location, as the solar HWS were all located in the warmer northern city of Brisbane, where presumably hotter water temperatures were not as desirable as in the cooler city of Newcastle where the electric storage systems were located. Conversely, Lee et al. (1988) reported that gas-heated HWS maintain significantly higher temperatures than electric storage HWS. The lower temperatures of the electric HWS resulted in higher frequencies of isolation of *L. pneumophila*, which were associated with systems operating below 48.8°C (Lee et al., 1988)

Instantaneous HWS are perhaps the most reliable in terms of consistently achieving their designated temperature. Martinelli et al. (2000) found that *L. pneumophila* were isolated much more frequently from hot water tanks (30%) as opposed to instantaneous hotwater systems (6.4%) in an area of Italy suffering an endemic outbreak of Legionellosis. The study concluded that temperature was critical, as the hotwater tanks in the study had been maintaining water at 50˚C +- 5˚C, while the tap water averaged 45˚C and dropped to 40˚C during flow. Instantaneous systems, however, always maintained temperatures above 60˚C [Martinelli, et al., 2000].

While the concentration of bacteria in water is an important aspect in determining health risk, the type of bacteria present is even more so. Previous laboratory work has shown that the most pronounced effect of increasing temperature on bacterial populations is reduction in species diversity rather than reduction in concentration, although concentration does clearly decline with increasing temperature (Spinks et al., unpublished).

Given that people do not regularly drink from the hotwater tap, health risks posed by enteric pathogens seem minimal. Respiratory tract pathogens, such as *L. pneumophila*, may be of greater significance to public health, but were not tested for in this study. However, findings by Spinks et al. (2003) have shown that while hotwater are maintained in accordance with guidelines to prevent the growth of *L. pneumophila*, then other less heat resistant enteric pathogens should also not pose significant health risks.

Hotwater System Health: Corrosion

While the preservation of human health is a vital area in gaining approval of using rainwater to supply HWS, the maintenance of HWS health is as practically important. Accelerated corrosion of hotwater systems due to the use of rainwater has been a concern amongst Australian councils and water suppliers. Corrosion itself is a complex phenomenon which relates to a number of factors. One important factor is the electrical conductivity (relating to total dissolved solids) of the medium which surrounds the metal being corroded. Pure water is a very poor electrical conductor, but as substances dissolve in it, particularly those which ionise, conductivity rapidly increases. Perhaps the most common corrosion-causing ‘contaminant’ is dissolved oxygen. Oxygen reacts with and removes reaction products from the cathode during electrochemical corrosion, thereby permitting the attack to continue.

In order to restrict the rates of corrosion in HWS, anodes are used. These are usually a magnesium, aluminium or zinc based alloy rod submerged in the tank to absorb the chemical action that causes tank corrosion. The anodes are therefore referred to as sacrificial, as they attract the corrosion that would otherwise attack the walls of the HWS. While the sacrificial anodes within the HWS themselves were not inspected in this project, the levels of iron and copper, which may leach from the HWS tank walls and heating element, and the levels of magnesium, aluminium, and zinc, which may leach from the sacrificial anode, were not found in significantly higher concentrations in the hotwater samples.

One complicating factor is the concentration difference of dissolved solids between rainwater and mains water. Harvested rainwater generally contains low concentrations of dissolved solids, and therefore has a low electrical conductivity. In such environments, anodes with high electrical outputs are required to ‘drive’ the corrosion circuit toward the sacrificial anode, and hence confer protection. However, the electrical conductivity of mains water is much higher, and therefore requires anodes with a relatively low electrical output. It is suspected that during the switch from rainwater to mains water the high-output anode designed for rainwater will drive the sacrificial process at an accelerated rate, resulting in the rapid degeneration of the anode and subsequently the HWS. As no commercially available anode has, as yet, been designed to handle both water sources, the resolution to this problem has been left balancing on the results of experimental observation.

It is not definitively known whether the use of rainwater in hotwater systems increases the rates of corrosion, or whether the standard M2 hotwater system anodes are adequate to protect hotwater systems against both rainwater and mains water containing differing pH and TDS levels. However, the results of this project do not indicate that accelerated corrosion of hotwater systems is occurring beyond that which occurs through the use of only mains water.

Consistently high levels of lead, exceeding ADWG, were found in some solar hotwater systems. These exceedances only occurred within a limited number of systems, possibly due to soldering within the pipework. While this is probably not indicative of the degenerating health of the HWS, it does suggest that human health may be compromised if large amounts

(>1L/d) of this water were ingested daily over a long period of time, although this seems unlikely given typical water use trends.

CONCLUSIONS

Solar-powered, electric-storage and instantaneous HWS consistently delivered greatly improved water quality over the two year study period. The single most important factor for producing hotwater of high microbial quality was the operating temperature. Guidelines for domestic HWS operation in many countries state that storage temperatures should be above 60°C in order to inhibit the growth of *L. pneumophila*, although most other pathogenic bacteria can be controlled by temperatures above 55°C.

One concern was the large variations in operating temperatures of the solar-powered HWS, in which hotwater temperatures fluctuated significantly over seasons, with minimal temperatures reaching below even optimal growth temperatures for a range of pathogenic bacteria. These large temperature variations suggest that the promotion of a 'safe' hotwater system temperature may require the educating of householders themselves about HWS processes rather than only plumbers.

Corrosion of the sacrificial anodes and HWS did not appear to be occurring at accelerated rates within the solar-powered and instantaneous HWS. However, this is a complicated issue, and ongoing observation and experimentation would be beneficial in elucidating some of the corrosion processes occurring within HWS supplied by both harvested rainwater and municipal water. Development of a commercially available anode capable of protecting against multiple water sources would be an ideal solution.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Australia Research Council in conjunction with Hunter Water Corporation, Hunter Councils, Gosford Wyong Councils' Water Authority, Brisbane City Council, Department of Commerce and NSW Public Health Unit.

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