Key Messages from a Decade of Water Quality Research into Roof Collected Rainwater Supplies

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Abstract

A research program into the quality of water supply from rainwater tanks over the last decade at the University of Newcastle in Australia has provided insights into water quality processes operating in rainwater tanks. A rainwater treatment train has been identified that includes processes in first flush devices, rainwater tanks and hot water services including the action of biofilms and heat death of bacteria in hot water services. The need for continuing scientific endeavour to improve understanding of this important water source is highlighted.

INTRODUCTION

Over 3 million Australians in mostly rural areas rely on rainwater tanks for drinking water supplies. It was a paradox that, prior to the 1990s, the use of rainwater tanks was virtually illegal in urban areas that had reticulated (mains) water supplies (Lloyd et al., 1992). It is commonly claimed by authorities that rainwater tanks were removed from urban areas due to health concerns. In contrast, Lloyd et al. (1992) explain that rainwater tanks were removed to increase the economic viability of water utilities. More recently, in response to water shortages, authorities throughout Australia encourage the use of rainwater tanks in urban areas to supplement mains water supplies and to manage urban stormwater runoff. Although rainwater tanks are widely used in Australia there is limited understanding about the quality of rainwater supplies. This paper provides an overview of a decade of research into the quality of rainwater conducted at the University of Newcastle in Australia.

MONITORING SITES

Monitoring of demonstration projects has provided valuable insight into the performance of rainwater harvesting systems. These projects include the Figtree Place, Maryville and Carrington sites that are presented below.

Figtree Place

Figtree Place is located in Hamilton an inner city suburb of Newcastle in New South Wales Australia. The site was developed as a prototype site for water sensitive urban design that includes 27 residential units, rainwater tanks, infiltration trenches and a central basin where cleansed stormwater enters an unconfined aquifer for water retention and retrieval (Figure 1). Rainwater runoff from roofs at Figtree Place passes through first flush pits and is captured in four underground tanks with capacities ranging from 9 kL to 15 kL for toilet flushing and hot water use in the residential units. Rainwater supplies are drawn from a depth of 0.4m from the base of the tanks. A low level monitor is used to transfer to mains water supply when water levels are low in the rainwater tanks (see Coombes et al., 1999; 2000).

The Figtree place project was proposed in 1995. However construction was not completed until 1998 due to strong resistance from water authorities and government departments to the use of rainwater for toilet flushing and in hot water services. Over 3.2 million Australians rely on rainwater for drinking water without widespread health impacts. Nevertheless authorities claimed that consumption of rainwater posed a high hazard that was likely to cause death. A combination of institutional resistance and construction errors led to the installation of underground tanks with holes in walls allowing entry of debris to the tanks. The Figtree Place site was also subject to high levels of air pollution due to location adjacent to roads with high traffic loads, a bus station and heavy industry. Poor quality rainwater was expected.

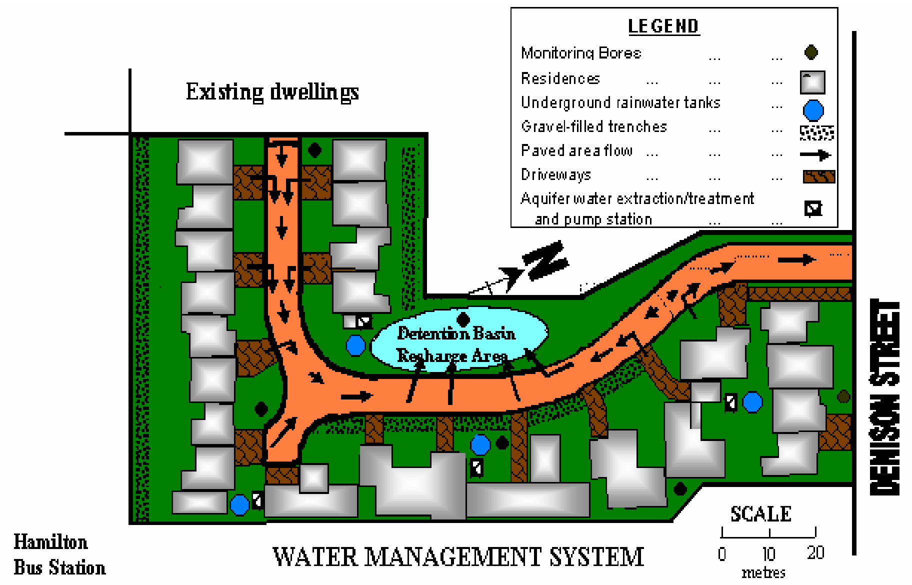

Figure 1: General plan and water sensitive elements of Figtree Place

A comprehensive monitoring program was implemented to understand water quality at the Figtree Place project (Coombes et al., 1999; 2000). Samples collected from rainfall, roofs, at the water surface in tanks, at the point of supply in tanks and from hot water were tested for the range of parameters shown in Table 1. The water quality analyses were conducted in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 1995). Annual average mains water savings of 45% were measured at Figtree Place. The bacterial indicator organisms (Fecal and Total Coliforms) were measured for compliance with the Australian Drinking Water Guidelines. Heterotrophic plate counts can reveal the presence of organic material in water and are a general indicator of water quality. *Pseudomonas Spp*. can be used to indicate the presence of nutrients in water and of biofilms on surfaces. Average values for water quality at different locations in the rainwater supply system are compared to Australian Drinking Water Guidelines (Guideline) in Table 1.

Table 1: Average water quality parameters from the Figtree Place rainwater system

Parameter	**Unit**	**Rain**	**Roof**	**Tank surface**	**Point of supply**	**Hot water**	**Guideline**
Fecal Coliforms	CFU/ 100 ml	0	135	119	20	0	0
Total Coliforms	CFU/ 100 ml	0	359	834	166	0	0
Heterotrophic plate counts	CFU/ml	3	1,360	3,256	331	3	NA
Pseudomonas Spp.	CFU/ 100 ml	5,200	59,600	6,768	7,544	0	NA
Sodium	mg/L	9.9	11.4	4.9	5.4	4.4	180
Calcium	mg/L	2	2.7	6.9	8.4	10	200
pH	-	5.9	5.8	6.2	6.1	6.24	6.5 – 8.5
Dissolved solids	mg/L	21	57	98.2	114	94	500
Suspended solids	mg/L	8.4	35	1.4	1.6	0.78	500
Chloride	mg/L	7.5	14.9	7.1	10.5	10	250
Nitrate	mg/L	0.2	0.3	0.06	<0.05	<0.05	3
Nitrite	mg/L	0.4	2.2	0.6	1.0	0.8	50
Sulphate	mg/L	3.5	6.7	4.9	7.3	9.6	250
Ammonia	mg/L	0.3	0.4	0.1	0.3	0.18	0.5
Lead	mg/L	<0.01	0.014	<0.01	<0.01	<0.01	0.01
Iron	mg/L	<0.01	0.05	0.01	0.01	0.02	0.3

Table 1 demonstrates the general water quality processes in the rainwater supply system. The quality of rainwater was compliant with drinking water guidelines. However the quality of roof runoff exceeds the guidelines for Coliform bacteria and lead. Microbial and elemental contamination was observed to accumulate on roofs.

Concentrations of Total Coliforms, heterotrophic plate counts and dissolved solids increased at the water surface in the tanks in comparison to roof runoff. Concentrations of the remainder of the parameters decreased. The increases were attributed to entry of soil into the damaged underground tanks during rainfall events whilst the action of the first flush pits and settlement processes in the tanks were responsible for the decreased concentrations. The elemental quality of rainwater at the water surface was compliant with the drinking water guidelines.

At the point of supply in the tanks concentrations of heterotrophic plate counts, nitrite, Fecal and Total Coliforms were observed to decrease in comparison to concentrations at the water surface. The increased presence of *Pseudomonas Spp.* may indicate that biofilms have formed on the walls of tanks. Metabolic processes within biofilms can utilised nitrates and entrap bacteria (such as coliforms and heterotrophs) creating increases in ammonia. It was proposed that the formation of biofilms on tank surfaces contribute to improving water quality at the point of supply. The average concentrations of lead and iron remained low and compliant with the drinking water guidelines. Concentrations of most of the remaining parameters increased slightly. This result suggests that metal and chemical parameters settle to the bottom of tanks where they sorb to sludge thereby improving water quality at the point of supply. Samples taken from sludge at the bottom of tanks show accumulation of lead (0.033 mg/L) and iron (0.093 mg/L) support the assumption that contaminants settle to the bottom of tanks. All parameters, except fecal and total coliforms, were compliant with drinking water guidelines.

Roof runoff captured in tanks is used to supply electric hot water storage services (capacity: 250 L) that are subject to “off peak” heating during the periods 6 am to 8 am and 8 pm to 10 pm. Although the microbial quality of tank water exceeded guidelines, the microbial quality of hot water was compliant with the drinking water guidelines. The processes of pasteurisation and tyndallisation (small perturbations in temperature) were believed to eliminate the majority of bacteria from the hot water. Monitoring and analysis at the Figtree Place site has revealed the presence of a rainwater treatment train that includes first flush device, the rainwater tank and the hot water service.

Maryville house

Using the lessons learnt from the Figtree Place project, an old house in Maryville, a neighbouring inner city suburb of Newcastle was fitted with a large above ground 9.1 kL Aquaplate™ rainwater tank to supply hot water, toilet and outdoor uses to the three person household (Figure 2) (Coombes et al., 2003). An efficient dual water supply system was created that allowed the tank to be topped up with mains water to a minimum water level whenever rainwater supplies were low (Figure 3). This system eliminates the risk of backflow of rainwater into mains water supplies and ensures that water is always available. The average annual mains water savings provided by the tank was 52kL/annum.

Similar to the Figtree Place project, the Maryville House is located adjacent to Newcastle’s heavy industrial area and the industrial highway. The site is subject to high levels of industrial and urban pollution. Unlike the Figtree Place project, the house has a rusty galvanised iron roof, an instantaneous gas hot water system that was set at 55°C and no first flush device. Average values for water quality at different locations in the rainwater treatment train are shown in Table 2.

Figure 2: The Maryville House

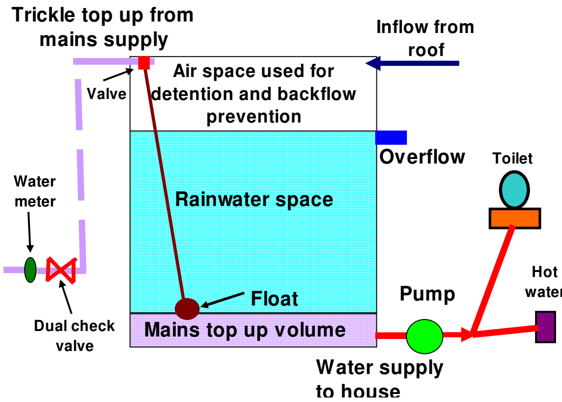

Figure 3: Design of the dual water supply system

Table 2: Average water quality parameters from the Maryville rainwater system

Parameter	Unit	Roof	Point of supply	Hot water	Guideline
Fecal Coliforms	CFU/100 ml	135	1	0	0
Total Coliforms	CFU/100 ml	359	18	0	0
Heterotrophic plate count	CFU/ml	1,360	784	4	NA
Pseudomonas Sp.	CFU/100 ml	59,600	1,673	0	NA
Sodium	Mg/L	11.4	7.5	8.4	180
Calcium	Mg/L	2.7	2.5	2	200
pH	-	5.8	5.7	5.5	6.5 – 8.5
Dissolved solids	Mg/L	57	67	16	500
Suspended solids	Mg/L	35	19	0.5	500
Chloride	Mg/L	14.9	9.9	9.9	250
Nitrate	Mg/L	0.3	<0.05	<0.05	3
Nitrite	Mg/L	2.2	1.4	1	50
Sulphate	Mg/L	6.7	5.9	5.2	250
Ammonia	Mg/L	0.4	0.3	0.2	0.5
Lead	Mg/L	0.01	<0.01	<0.05	0.01
Iron	Mg/L	0.05	<0.05	<0.05	0.3
Zinc	Mg/L	-	3.9	3.9	3

Table 2 reveals that the quality of rainwater at the point of supply in the above ground rainwater tank at Maryville was better than the quality at the point of supply in the damaged underground rainwater tanks at Figtree Place for most parameters. The microbial quality of rainwater exceeded the guidelines for presence of Fecal Coliforms on a single occasion immediately following a rainfall event that preceded construction activity on the house roof. Notably, no fecal contamination was evident on the roof. Fairly high levels of zinc were found in the rainwater that originated from the rusty roof. This level of zinc contamination was not considered a health hazard (NHMRC, 1996). Nevertheless, in spite of the absence of a first flush device, the quality of rainwater was seen to improve in the rainwater tank and the hot water service. A majority of parameters were compliant with drinking water guidelines. The rainwater treatment train was confirmed.

Elimination of bacteria in the instantaneous hot water service at Maryville indicated that pasteurisation may not be the dominant process for reduction of bacteria in domestic hot water services. It was postulated that the instantaneous heat differential between the rainwater tank and the hot water service also eliminated bacteria. Prescott et al., (1999) report that moderate heat eliminates bacteria more readily at low population numbers, in acid conditions that are consistent with rainwater and with rapid changes in temperature.

Carrington house

A third rainwater harvesting system was installed at Carrington, an inner city suburb located in the docklands within the industrial area of Newcastle. Two small rainwater tanks (2.1 kL each) with a mains water top up scheme are used to supply all water uses to the two person household (Figure 4). The mechanical top up system relies on vertical movement of the float valve to top up the tank to a minimum level at a variable rate dependent on the water depth in the tank (Figure 5).

Figure 4: Picture of rainwater tanks

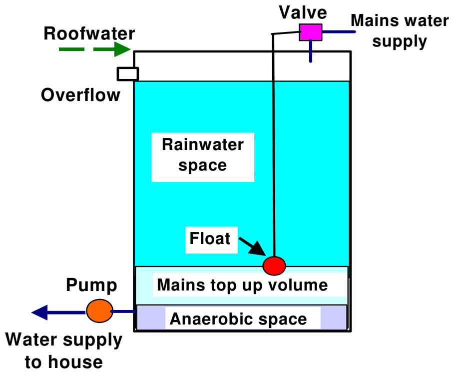

Figure 5: Rainwater tank details

The house is situated close to roads with high traffic loads and, unlike the Figtree Place and Maryville sites, trees containing birds overhang the house roof. A first flush device has not been installed and a small 125 L hot water service set at a maximum temperature of 60°C operates within the house. Water quality within the tank and at cold and hot water taps was found to the compliant with drinking water guidelines for metal, physical and elemental parameters. The average microbial results at different locations within the tank and at hot and cold taps are shown in Table 3.

Table 3: Average microbial water quality results at various locations

Location/ Criteria	Fecal Coliform (CFU/100 ml)	Total Coliform (CFU/100 ml)	Pseudomonas Spp. (CFU/100 ml)	Heterotrophic plate count (CFU/ml)
Water surface	108	1,050	3,100	1,050
Mid depth	34	900	780	427
Bottom	55	862	4,060	1,252
Cold tap	<1	200	412	76
Hot tap	0	2	<1	<1
Guideline	0	0	NA	200*

* Japanese and American drinking water guidelines (Fujiwara et al., 1992)

Table 3 shows substantial reductions in concentrations of bacteria in rainwater from the tank water surface to the hot and cold water taps. A natural rainwater treatment train is clearly evident. The quality of the hot water supply was compliant with drinking water guidelines with the exception of Total Coliforms. Interestingly, further analysis using Polymerase Chain Reaction (PCR) processes of rainwater samples that tested positive for Total Coliforms revealed that the water samples actually contained *Bacillus Spp.* (Spinks et al., 2004). This result has significant implications for the assessment of the quality of rainwater using presence/absence of Coliforms in accordance with drinking water guidelines.

Significant reductions in concentrations of Pseudomonas Spp., heterotrophic plate counts, Fecal and Total Coliforms were observed between the bottom of the rainwater tank and the cold tap. It was assumed that high pressures in the pump also eliminated bacteria from rainwater supplies.

Water quality at the cold tap exceeded the guidelines for Fecal and Total Coliforms. The significance of exceeding drinking water guidelines for Coliform bacteria is unknown. Total

Coliforms are no longer recognised as a suitable indicator of fecal contamination of water or having any relevance to health (Cunliffe, 2004). Although most studies find Coliform bacteria in rainwater storages and over 3 million Australians rely on rainwater for drinking water supplies only a small number of health concerns have been attributed to rainwater supplies. It is noted that the epidemiological study by Heyworth (2001) found that drinking rainwater posed a lesser health risk than drinking mains water in Adelaide Australia. A relationship between the presence of Coliform bacteria in rainwater tanks and frequency of illness could not be established.

BIOFILMS IN RAINWATER TANKS

One of the dominant processes in the rainwater treatment train appears to be flocculation of organic, metallic and chemical parameters at the tank water surface with subsequent settlement of flocs to the sludge at the bottom of the tank or attachment to the walls of the tank. These flocs form biofilms at the interface between tank surfaces and stored rainwater potentially improving the quality of stored rainwater by removing contaminants. A monitoring programme has been established to confirm the existence of biofilms in rainwater tanks and determine the impacts of biofilms on water quality in tanks. Preliminary monitoring by Piggott (2003) has targeted three different rainwater tanks as shown in Table 4.

Table 4: Details of preliminary study into biofilms

Location	Material	Land use	Age (yrs)	Maintenance	Observed slime layer	Confirmed biofilm
Largs	Concrete	Rural	20	Frequent	None	Yes
Merewether	Plastic	Urban	3	Irregular	Slight	Yes
West Wallsend	Corrugated iron	Urban	14	None	Large	Yes

Table 4 shows that the location, construction material and level of maintenance relating to each tank is different. Nevertheless microbial testing of samples scraped from the walls of each tank has confirmed the existence of biofilms. Samples were taken from the walls of the tanks and PCR analysis used to identify the microbial organisms that make up biofilms in each tank as shown in Figure 6.

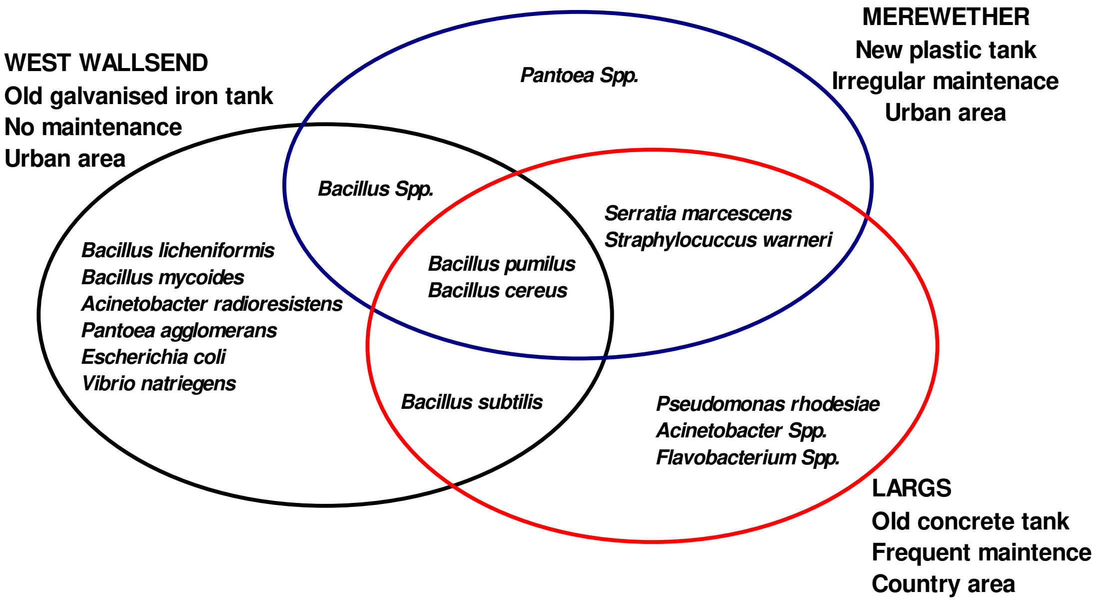

Figure 6: Distribution of microflora in biofilms in rainwater tanks at different locations

Figure 6 reveals that *Bacillus pumilus* and *Bacillus cereus* are common to the biofilms in all tanks whilst *Bacillus subtilis*, *Bacillus Spp.* (other than *Bacillus pumilus*, *Bacillus cereus* and

Bacillus subtilis), Serratia marcescens and *Staphylococcus warneri* are common to the biofilms in two of the tanks. Biofilms in the rainwater tanks consisted of a core group of bacteria that are predominately *Bacillus Spp.* that originate from soils and the environment. These core bacteria isolated from the biofilms were not isolated in the stored rainwater in the tanks indicating that the process of forming biofilms may be removing bacteria from the tank water.

Elemental analysis using high resolution ICP-MS revealed accumulation of metals including lead, zinc, copper, manganese, chromium, mercury and arsenic in the biofilms in all tanks. Significant concentrations of metals were not found in the tank water indicating that the action of biofilms may be removing metals from the tank water.

EFFICACY OF BACTERIAL INDICATOR TESTS IN RAINWATER

The use of PCR methods to examine the DNA of bacteria sampled from rainwater harvesting systems revealed bacterial species that were not consistent with results implied by Coliform tests. Indeed the measurement of Fecal and Total Coliforms in rainwater samples indicated the potential presence of pathogens but subsequent analysis using PCR methods reveals that the bacteria was actually relatively harmless environment species such as *Bacillus Spp.* Given that the Coliform group of bacteria are used to indicate the safety of water supplies these potentially misleading results has profound implications for the utilisation of rainwater for domestic supplies.

Preliminary experiments were conducted to determine if bacteria other than *E.Coli* and Fecal Coliforms are isolated by commercial media providing misleading interpretation of rainwater quality. Two bacterial media that are approved by the USEPA were analysed namely: m-ColiBlue24® that is approved for isolating Total Coliforms and *E.Coli* from drinking water and m-FC broth with Rosolic Acid that is approved for isolating Fecal Coliforms from wastewater. Both media were inoculated with *E.Coli* from a human source, and *E.Coli*, *Bacillus cereus*, *Bacillus licheniformis*, *Aeromonas hydrophila* and *Enterococcus faecalis* from environmental sources. The resulting growth after incubation at 35°C for 24 hours is shown in Table 5.

Table 5: Results of bacterial plate analysis

Bacteria	**Present on Media**	
	m-ColiBlue24	**m-FC**
E.Coli	Yes	Yes
Bacillus licheniformis	Yes	Yes
Bacillus cereus	No	No
Aeromonas hydrophila	Yes	No
Pseudomonas aeruginosa	No	No
Enterococcus faecalis	Yes	No

The results from the preliminary experiment, shown in Table 5, confirmed that bacteria other than Fecal Coliforms, Total Coliforms and *E.Coli* can grow on commercially approved media. This indicates that the use of approved Coliform indicator tests can potentially result in the misleading view that rainwater supplies are unsafe. It should be noted that the results presented here are preliminary. More comprehensive analysis is needed and indeed necessary. Nevertheless this analysis does indicate the need for a comprehensive and critical review of the range of industry methods used to indicate the safety of rainwater supplies.

ELIMINATION OF BACTERIA IN DOMESTIC HOT WATER SERVICES

The use of rainwater in hot water systems can have a significant impact on the viability of a dual water supply strategy that utilises rainwater (Coombes 2005; Coombes et al., 2002). Continuing research by Spinks et al. (2004; 2003) has extended the finding that hot water services can eliminate bacteria by Coombes et al., (2000; 2003) to analysis of the heat death behaviour of selected pathogens. The time to eliminate 90% of a bacterial population at a given water temperature (D-value) is shown for selected bacteria are shown in Table 6.

Table 6: Preliminary heat death results for selected bacteria (after Spinks et al. 2003)

Bacteria	**D-value (seconds)**		
	55°C	**60°C**	**65°C**
E. coli	1,493	66	3
Shigella sonnei	586	54	3
Pseuodomonas aeruginosa	304	49	5
Salmonella typhimurium	77	4	<2
Klebsiella pneumoniae	35	<2	<2

Table 6 shows that potentially pathogenic bacteria (note that *E. coli* is not usually pathogenic) are eliminated rapidly from rainwater at temperatures of 60°C or greater. These results suggest that rainwater supplied to hot water services maintained at 60°C will provide water of adequate hygienic quality. These results extend the knowledge gained from analysis of the quality of rainwater in hot water services at the Figtree Place, Maryville and Carrington sites.

CONCLUSIONS

This paper has provided an overview of some key observations from the research program into the quality of water supply from rainwater tanks conducted over the last decade at the University of Newcastle in Australia. The research journey provides some key insights into water quality processes in rainwater tanks and highlights the need for continuing scientific endeavour to replace myths and agendas with facts about this important water source.

The importance of applied research into the performance of carefully monitored demonstration sites is established by the key observations from the Figtree Place, Maryville and Carrington housing projects. Monitoring of these projects revealed the existence of a rainwater treatment train that includes first flush devices, the rainwater tank and domestic hot water services. In addition establishment of these projects exposed many myths and assumptions about the quality of rainwater. Significantly, a sparsity of knowledge about the microbial processes in rainwater tanks was revealed.

One of the dominant processes in the rainwater treatment train appears to be flocculation of organic, metallic and chemical parameters at the tank water surface with subsequent settlement of flocs to the bottom of the tank or attachment to walls in the tank. Ongoing analysis, resulting from this initial observation, has revealed that biofilms do exist in rainwater tanks and that a core group of environmental bacteria such as *Bacillus Spp.* are likely to form biofilms in rainwater tanks.

Monitoring of the demonstration projects also led to a discovery that domestic hot water services set at temperatures greater than 52°C consistently eliminated bacteria from rainwater. This discovery led to laboratory experiments into the impact of hot water on the viability of selected pathogens. Potentially pathogenic bacteria were observed to be rapidly eliminated from rainwater at temperatures of 60°C or greater.

The use of Polymerase Chain Reaction (PCR) processes to determine the DNA of bacteria found in rainwater has increased concerns about the efficacy of the use of traditional coliform indicator organisms to determine the safety of rainwater supplies. Preliminary experiments confirmed that bacteria other than Fecal Coliforms, Total Coliforms and *E.Coli* can grow on commercially approved media. This indicates that the use of approved Coliform indicator tests can potentially result in a misleading view that rainwater supplies are unsafe.

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