Reference pathogen numbers in urban stormwater for drinking water risk assessment

D. W. Page, K. Barry, D. Gonzalez, A. Keegan and P. Dillon

ABSTRACT

Targeted stormwater event-based monitoring of adenovirus, *Cryptosporidium* and *Campylobacter*, the human health reference pathogens of viruses, protozoa and bacteria, respectively, was undertaken to determine numbers prior to water recycling via an aquifer. This allowed the determination of a 95th percentile of reference pathogen numbers in stormwater (2 n/L for adenoviruses, 1.4 n/L for *Cryptosporidium* and 11 n/L for *Campylobacter*) and was used in a quantitative microbial risk assessment to determine the required microbial inactivation targets. Log_{10} removals through treatments and/or control measures to manage pathogen risks were determined for different end uses based on the 95th percentile numbers. Public open space irrigation was found to require 1.6 log_{10} reduction for viruses, 0.6 log_{10} for protozoa and 1.2 log_{10} for bacteria; third pipe systems which include potential exposure through toilet flushing and washing machine use require 2.7 log_{10} reduction for viruses, 1.8 log_{10} for protozoa and 2.3 log_{10} for bacteria; and drinking water requires 5.8 log_{10} reduction for viruses, 4.8 log_{10} for protozoa and 5.3 log_{10} for bacteria. These results are the first reported for an Australian urban stormwater site with sufficient data for a drinking water risk assessment.

Key words | enteric pathogens, managed aquifer recharge, urban stormwater, water recycling

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INTRODUCTION

The harvesting of urban stormwater is expected to become increasingly important as the availability of water resources declines under climatic change and demand increases due to urbanisation. Urban stormwater in this context is rainwater plus anything the rain carries along with it. In Australian urban areas, rain that falls on paved areas such as driveways, roads and footpaths is carried away through a system of pipes that is separate from the sewerage system. Unlike sewage, stormwater is generally not treated prior to marine discharge. In some cases it is filtered through trash traps, usually located at the end of the pipe system, but it still flows directly from streets and gutters into local rivers, the harbour and the ocean.

Harvesting and reuse of urban stormwater has led to increased characterisation of its water quality parameters as well as treatment methods for non-potable uses such as wetlands, water sensitive urban design and biofilters (e.g. Zhang *et al.* 2014). However to date, most work on urban stormwater quality has focussed on traditional faecal indicators such as *Escherichia coli* (e.g. McCarthy *et al.* 2013; Sidhu *et al.* 2013). This has precluded the use of urban stormwater for potable use as in Australia. Currently the 95th percentile numbers of pathogens in source waters and the mean validated removal rates must be used for each preventative measure when used in risk assessments (NRMMC-EPHC-AHMC 2006). This is a risk-based approach consistent with that adopted internationally for drinking water quality management by the World Health Organisation (WHO 2011). This approach uses health-based targets (quantified as Disability Adjusted Life Years, or DALYs) that are measurable health performance objectives. In the absence of data on pathogen numbers, application of this approach to stormwater has been limited to date.

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In the absence of actual pathogen data, some default pathogen numbers have been adopted to support non-potable risk assessments. The default numbers utilised are 1 virus/L, 1.8 *Cryptosporidium* /L and 15 *Campylobacter* /L (NRMMC-EPHC-NHMRC 2009a). This has worked well to support stormwater harvesting and reuse generally, but specifically excludes the use of these default values for drinking water. This present study aims to fill a gap in urban stormwater pathogen data with the specific objectives to calculate the 95th percentile of reference virus, protozoa and bacteria in urban stormwater to allow for drinking water risk assessment. This allows a comparison with the default pathogen numbers, and also the calculation of the required level of treatment to meet the international health-based targets for potable use.

MATERIALS AND METHODS

Site and operational details

Urban stormwater is currently harvested from a mixed residential and industrial catchment area in the City of Salisbury, South Australia, and treated via passage through constructed wetlands and Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer Recovery (ASTR) systems before being utilised for municipal irrigation (Figure 1).

The Parafield catchment and ASR, ASTR and stormwater harvesting systems have been previously described by Page *et al.* (2010a, b, 2014, 2015a).

Stormwater sampling

Urban stormwater was sampled at the Parafield Data Station (PDS, see Figure 1) site using two techniques: grab sampling once during a storm event, and composite sampling across a storm event. An ISCO automated water sampler (6700 series) was used to collect a 240 L composite sample in 10 L subsamples at the PDS site. The sampler was set up to begin pumping after 5 minutes of stormwater flow in the drain. Each subsequent 10 L subsample was collected at a volumetric interval of 10 kL until 24 samples were collected. All subsamples were pumped into one large 250 L refrigerated container (4 °C) to form a single bulk composite sample. Single grab samples were also taken manually during flow at the PDS site. Samples were kept at 4 °C

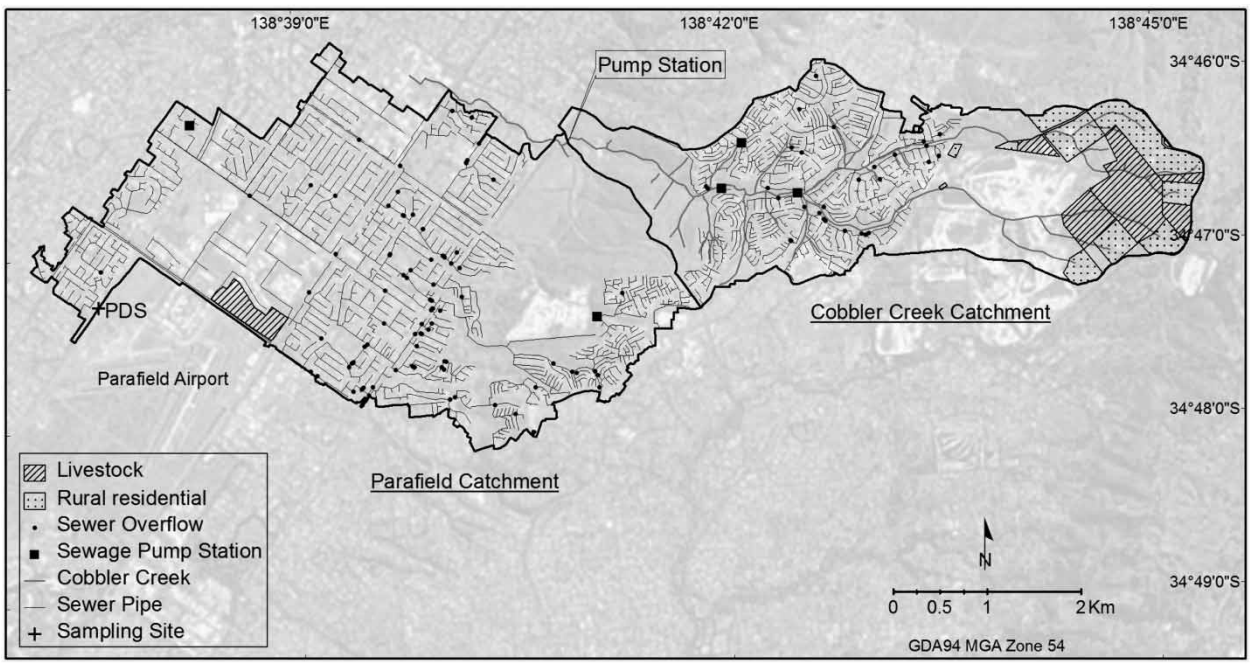

Figure 1 | Stormwater sampling sites and sewer overflows in the Parafield and Cobbler Creek catchments. PDS is the Parafield Data Station sampling point.

before being transported to the laboratory for analyses within 24 hours from collection of the final subsample according to procedures and storage times recommended in the APHA AWWA & WEF (2005). Manual grab sampling was problematic, as runoff events were of very short duration and unless they occurred during daylight hours of Monday to Wednesday, samples could not be dispatched to the commercial laboratory in time for analysis to comply with APHA, AWWA & WEF (2005).

Pathogen analysis

Protozoan analysis

Stormwater samples (10–20 L volume) were processed by initially adding *Giardia* and *Cryptosporidium* ColorSeed (BTF Pty Ltd) as a recovery control according to USEPA Method 1623 (1999) *Cryptosporidum* and *Giardia* in Water by filtration/IMS/FA. The mixture was concentrated by calcium carbonate flocculation (Vesey *et al.* 1993); IMS concentration was performed adhering to the manufacturer's protocol (Dynal, Oslo, Norway). Enumeration was performed using EasyStain (BTF, NSW, Australia), which contains antibodies specific for *Giardia* and *Cryptosporidium*. The staining procedure was performed according to the manufacturer's protocol.

Virus concentration, detection and enumeration

Water samples (20–55 L volumes) were concentrated by ultrafiltration using hollowfibre ultrafiltration dialysis filters. Concentrates were further processed using polyethylene glycol precipitation based on the method of Lewis & Metcalf (1988).

Nucleic acid extraction and quantitative real-time polymerase chain reaction (qPCR)

DNA extraction of 200 μL of sample was performed using the DNAEasy kit (Qiagen, Doncaster, NSW, Australia) in accordance with the manufacturer's protocol. DNA extracts were eluted in 200 μL of nuclease-free water (Sigma) and stored at −20 °C until analysed. Detection and enumeration of adenovirus was performed using an Adenovirus Taqman PCR. The reaction mixture was composed of 0.2 mM dNTP (dATP, dGTP, dCTP, and dTTP), 3 mM $MgCl_2$, 1 × PCR buffer, 2.5 units/reaction of AmpliTaq DNA polymerase, 0.5 μM of each forward (AQ1: 5′-GCCACGGTGGGGTTTC-TAAACTT-3′) and reverse (AQ2: 5′-GCCCCAGTGG TCTTACATGCACATC-3′) primer, 0.3 μM AdenoTaqman probe (5′-FAM-TGCACCAGACCCGGGCTCAGGTACTCC GA-BHQ1–3′) and 1 μL of DNA sample, in a total volume of 25 μL. Taq DNA polymerase activation was performed at 95 °C for 10 minutes, followed by 40 cycles of 94 °C for 5 seconds, 59 °C for 20 seconds, and 72 °C for 10 seconds. Amplification signal was collected at the end of the annealing step using the Green (FAM) channel. Positive control material was extracted from adenovirus type 41 (ATCC VR-930). PCRs were performed on a RotorGene 6000 (Corbett Life Sciences, Sydney, Australia) and amplification signal was detected on the Green (FAM) channel (excitation at 470 nm, detection at 510 nm). Quantification was done by using standards prepared from purified PCR fragments amplified from each specific virus. Briefly, a tenfold serial dilution was prepared in DNase and RNase free water to a final concentration ranging from 10^0 to 10^6 copies μL^{-1}, and aliquots were stored at −80 °C until use. Two microliters of template from each dilution was used to prepare a standard curve for qPCR. Quantification and DNA melting curve analysis were performed using the standard Corbett RotorGene 6000 software.

Examination for campylobacter

Campylobacter enumeration was based on Australian Standard AS/NZS 4276.19:2001 Water Microbiology Method 19: Examination for thermophilic *Campylobacter* spp.: Membrane filtration. Enumeration was based on filtration of 3 × 100 mL, 3 × 10 mL, 3 × 1 mL of sample or dilution using a 0.2 μm membrane. Typical colonies were Gram stained with Gram positive; growth in microaerophilic condition was confirmed as *Campylobacter* spp. Enumeration was based on the MPN McCrady table.

Calculation of health-based targets

The health-based targets (also known as the $\log_{10}$ treatment targets) calculations were performed as described below.

For each use, the treatment required (expressed in $\log_{10}$ removal) was calculated for each of the three reference pathogens to meet the WHO health-based target for drinking water of 1×10^{-6} DALYs/person/year (WHO 2011).

$$\text{Log}_{10}\text{ reduction} = \text{Log}_{10}(\text{number of organisms in stormwater} \times \text{exposure (L)} \times \text{frequency} \div \text{dose equivalent to } 1 \times 10^{-6}\text{DALY})$$

where the dose equivalent to 1×10^{-6} DALY used was: rotavirus $= 2.5 \times 10^{-3}$ n/year; *Cryptosporidium* $= 1.6 \times 10^{-2}$ n/year; *Campylobacter* $= 3.8 \times 10^{-2}$ n/year.

RESULTS AND DISCUSSION

Urban stormwater catchment pathogen risk assessment

Microbiological risks to human health and the quality of harvested stormwater are driven by pathogen contamination arising from untreated or partially treated sewage or animal faeces entering the stormwater system. This may occur when sewers overflow or fail and breach property boundaries or easements and enter stormwater drains, as well as septic tank leaks and overflows. Climate conditions are a key driver, as a high frequency and magnitude of storms can increase stormwater infiltration. Extended dry weather can also affect infrastructure integrity as well as age, length and condition of pipes, joints and pump stations (NWC 2008).

An analysis of the temporal distribution of sewer choke events was conducted using sewer choke data (United Water) and rainfall data from the Australian Bureau of Meteorology (BOM). Summed monthly sewer overflows for the 7 year period from 2003–2010 across the stormwater catchment areas were plotted with summed total monthly rainfall for the same period. These data are approximately linearly correlated ($R^2 > 0.60$) and indicate higher numbers of sewer overflows in wetter months (June-August). These results are similar to previously reported data on the seasonality of sewer overflows documented in the USA (Leeming *et al.* 1998) and in reports for Australian utilities (NWC 2008).

Human pathogens generally enter stormwater through sewer overflows and leakages. At the screening level, <14 overflows per 100 km per year as an average over the five most recent years can be considered relatively low (NRMMC-EPHC-NHMRC 2009a). The number of sewer overflows per 100 km of sewer main (from 2006 to 2010) was 16.5 for Parafield and 17.5 for Cobbler Creek catchments. In the absence of pathogen data, it has been recommended in Australia that when overflow rates are moderate to high (i.e. 14.5–50 overflows/100 km sewer main/year), to allow for another 1.0 $\log_{10}$ pathogen reduction through treatment or exposure controls (NRMMC-EPHC-NHMRC 2009a).

Sewer overflows that discharge into the environment (e.g. roads, watercourses) represent the highest risk of pathogen entry into the stormwater system. Sewer overflows to the environment (those which leave dwellings and property boundaries) were assessed as extreme risks to public health (Figure 2).

Sewer overflows appear to occur more frequently in areas where there are significant changes in terrain relief (i.e. close to foothills; Figure 2). This is consistent with the hypotheses that the transition from steep to flat terrain is associated with deposition of solids due to lower flow velocities, combined with a greater likelihood of pressurisation of sewers at these locations during storm events when stormwater enters sewers high in the sewer catchment. Other factors may also affect sewer overflow frequency, for example age of pipes and time between maintenance.

Overflow of sewage pump stations within stormwater catchments, particularly when in close proximity to watercourses, presents risks of contaminating harvested water with pathogens. One near Cobbler Creek was located within 20 m of a watercourse, and presents an extreme risk if it were to break down and overflow into the stormwater network (Cobbler Creek catchment). Another three were within 35 m of a watercourse: two in Cobbler Creek, one in Parafield catchment. These were assigned a high risk rating. The remaining sewage pump stations were further than 35 m from watercourses. The potential for overflows from these to enter the stormwater system is reduced, so moderate risk ratings were applied.

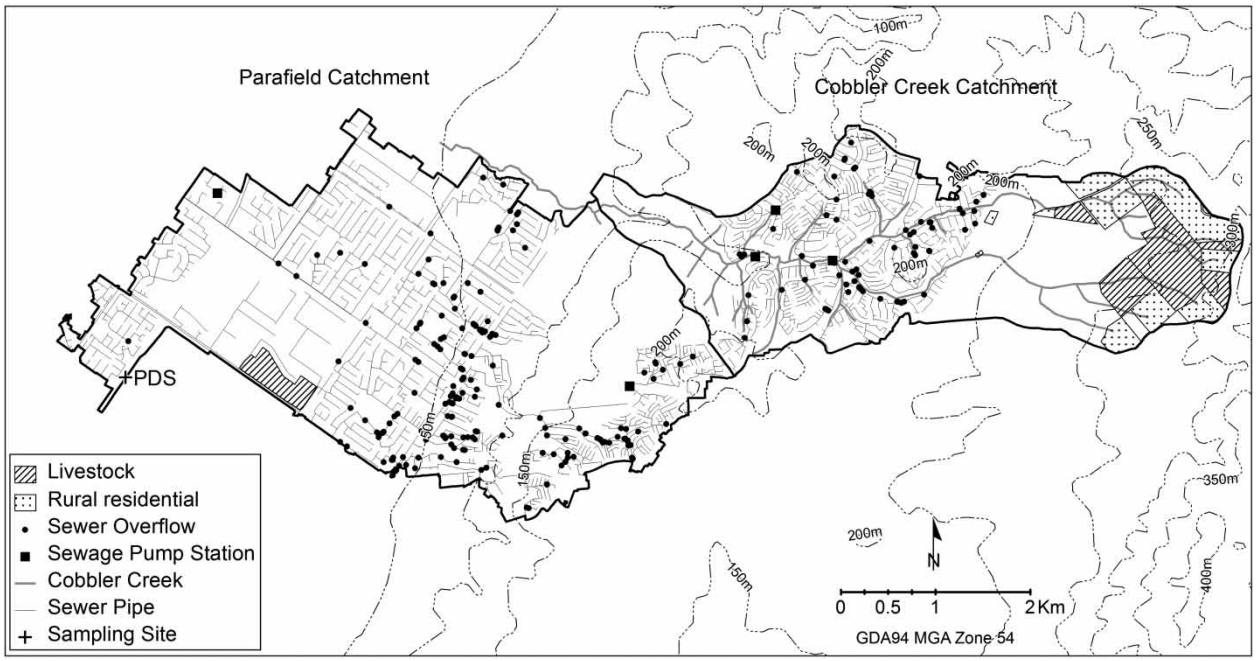

Figure 2 | Catchment pathogen risks, sewer overflow data (2003–2010), sewer pumping stations, and animal grazing.

Pathogens, including faecal indicators in runoff, are likely to originate from animals and humans (USEPA 2005). The origin of pathogens including protozoa (e.g. *Cryptosporidium*, *Giardia*) in runoff has been attributed to indirect faecal deposition (Graczyk *et al.* 2000; Bryan *et al.* 2009). *Cryptosporidium* is commonly found in surface runoff and is usually associated with farm animals and human sewage (Xiao *et al.* 2000). The persistence of some pathogens, particularly *E. coli* in soils in pasture lands, is evidenced to be associated with contamination of drinking water (Jones, 1999). Livestock grazing areas were assessed as a high risk to public health based on a likely occurrence of human infective pathogens.

Urban stormwater pathogen numbers

The results of the flow gauging at the Parafield Data Station as well as daily rainfall and times when samples were collected are given in Figure 3. A total of 20 samples were taken across the study period. Thirteen grab samples were collected from August 2010 to September 2012. Over this period a total of 75 rain events (with a minimum inter-event time of 24 hours) were recorded. A total of seven composite samples were collected from March 2012 to November 2012. Over this period a total of 44 rain events (with a minimum inter-event time of 24 hours) were recorded. During the study period on days of rain, daily rainfall ranged from 0.2 to 51.2 mm d^{-1} (mean 3.8 mm). Daily flow rates on days where there was flow recorded ranged from 7.2×10^{-4} to 9.8×10^{4} m^3 d^{-1} (mean 4.9×10^{4} m^3 d^{-1}).

Compiled pathogen and faecal indicator stormwater quality data for the Parafield site are reported in Table 1.

Table 1 shows the extracted pathogen data numbers used in this risk assessment, and includes the Parafield stormwater harvesting system and the compiled stormwater data from sewered catchments in Sydney with high sewer overflow frequency (>44 overflows per year per 100 km of sewer) (NRMMC-EPHC-NHMRC 2009a).

Urban stormwater treatment requirements for potable use

The pathogen data were transformed into a form suitable to support data analysis, by setting results that reported below detection limits to a value of one half the detection limit (for all relevant samples for all determinants). The results were

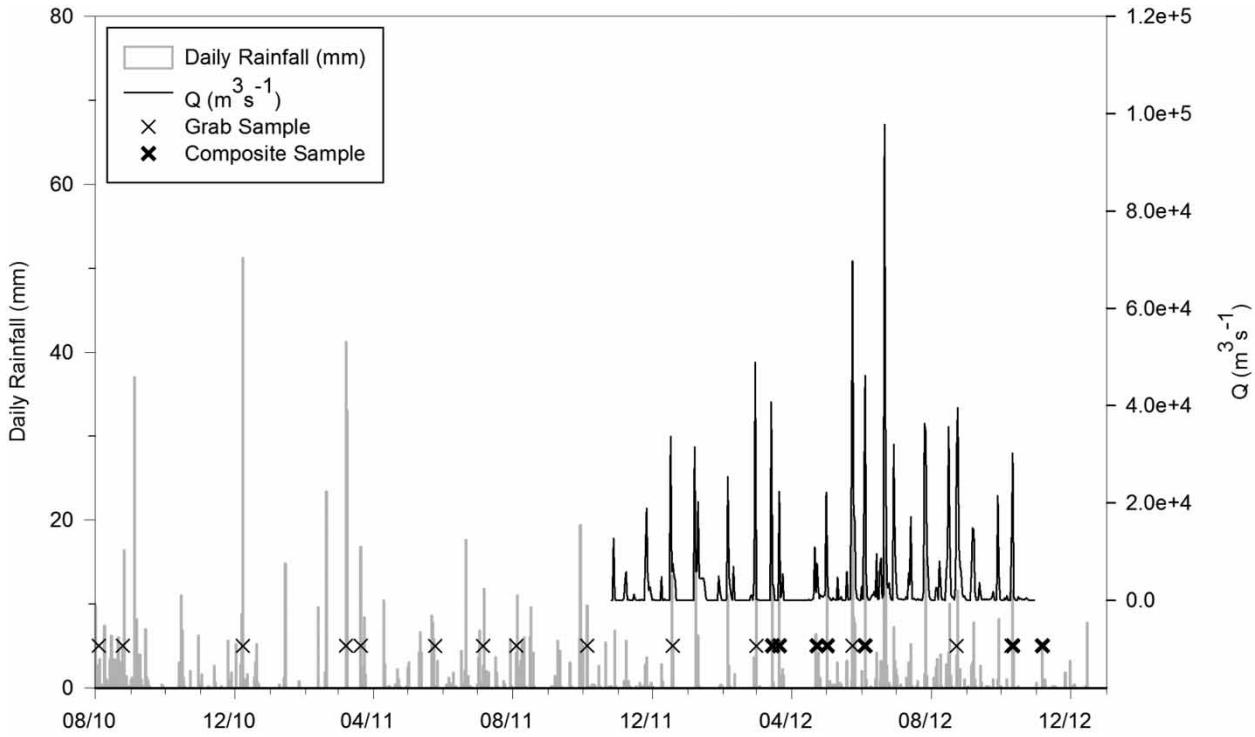

Figure 3 | Hydrograph including all event-based samples for pathogens.

Table 1 | Summary of pathogen and faecal indicators from urban stormwater data

	Default values for reference pathogens (raw stormwater)[a]	Parafield stormwater harvesting system (PDS untreated stormwater only)[b]				Stormwater quality summary statistics from untreated sewered urban catchments in Sydney[c]			
	Log normal 95th percentile	Number of samples	Detects (%)	Median	Log normal 95th percentile	Number of samples	Detects (%)	Median	Log normal 95th percentile
Adenovirus (n/L)	1	18	28	<1	2	NR	0	<1	1
Cryptosporidium (n/10L)	18 (=1.8/L)	18	50	4	14	59	37	<13	102
Campylobacter (n/L)	15	19	26	2	11	59	3	<2	<2
Giardia (n/10L)		18	50	12	83	59	19	<25	220
E. coli (n/100 mL)		21	95	9,600	64,000	58	100	1,700	240,000
Enterococci (n/100 mL)		1	100	2,900		59	100	740	12,100
Bacteriophage (n/10 mL)		20	100	140	1,800				

NR, not recorded, PDS, Parafield Data Station.
[a]Default values recommended for non-potable use risk assessment after Table A3.1 from NRMMC-EPHC-NHMRC (2009b).
[b]Data set only includes sampling of untreated stormwater from the Parafield Data Station to 30/11/2012.
[c]Derived from Table A2.4, NRMMC-EPHC-NHMRC (2009b).

also corrected for the recovery efficiency of the methodology used for analysis (for protozoan parasite oocysts counts). An interpolated 95th percentile was carried forward based on a fitted log normal distribution to provide the summary statistic for the drinking water human health risk assessment. The root mean square error for the lognormal fits for the Parafield catchment pathogen data were 0.006438 for viruses, 0.004094 for protozoa and 0.03265 for bacteria.

This approach was previously adopted for deriving the *Cryptosporidium* protozoan reference pathogen numbers in stormwater based on the interpolated 95th percentile of the confirmed oocyst counts in samples containing either *C. parvum* or *C. hominis*: 18 oocysts per 10 L (NRMMC-EPHC-NHMRC 2009a). The 95th percentile numbers of confirmed oocysts from the Parafield Data Station was lower, at 14 oocysts per 10 L (Table 1). The maximum observed value for *Cryptosporidium* at the Parafield Data Station was 19 per 10 L. However, in urban stormwater there is evidence that most samples do not contain human infectious oocyst genotypes; rather, they contain genotypes that infect other animals. For example, Jiang (2004) reported that in sewered urban stormwater systems only about 5% of around 100 *Cryptosporidium* oocyst types characterised were infective for humans.

Where there were insufficient numerical data to derive an interpolated 95th percentile (where a lognormal curve could not be fitted), or where the interpolated 95th percentile was below the detection limit, the maximum observed value was carried forward to provide the summary statistic for the health risk assessment. This approach was adopted for deriving the *Campylobacter* bacterial reference pathogen numbers in the guidelines, which was based on the maximum observed value: 15 n/L (Table 1). The maximum observed value previously applied for *Campylobacter* at the Parafield system was also 15 n/L (Page *et al.* 2010a), but greater numbers of detections in this current study allowed for an interpolated 95th percentile to be carried forward, based on a fitted log normal distribution, to provide the summary statistic for the human health risk assessment of 11 n/L.

Where no numerical data were reported because all samples were reported as 'none detected', 10 times the detection limit (1 per 10 L) for viruses was considered to represent a conservative summary statistic for the health risk assessment. This approach has been previously adopted in Australia for deriving the infectious adenovirus viral reference pathogen concentration in stormwater (1 n/L). For the Parafield system, the maximum detected number of viruses was 420 n/L using a PCR-based technique. A greater number of detections allowed for an interpolated 95th percentile to be carried forward, based on a fitted log normal distribution, to provide the summary statistic for the human health risk assessment of 194 n/L.

However, the PCR-based techniques used in the current study detect all viral DNA and make no distinction between infectious and non-infectious viruses and thereby tend to greatly over estimate risk. For example, Choi & Jiang (2005) reported 7% detection of adenoviruses by real-time PCR, with numbers ranging from 10^2 to 10^4 viruses per litre from 114 environmental samples. However, a plaque assay using two human tissue culture cell lines yielded negative results, suggesting that adenoviruses detected by real-time PCR are likely non-infectious. Similarly He & Jiang (2005) reported that for adenovirus numbers of 10^5 /L only 0.1% were infectious. In the current study, a conservative number of 1% infectious viruses has been applied, yielding a final 95th percentile of 2 viruses/L.

Previously, in the absence of site-specific data, the default numbers for pathogens have been selected for use in quantitative risk assessment for all non-potable uses. The new data collected from the Parafield Data Station allows for revised pathogen numbers to be utilised for the stormwater drinking water risk assessment which follows.

Treatment performance targets can be expressed in terms of minimum required $\log_{10}$ reductions to meet WHO drinking water health-based targets of 1×10^{-6} DALYs per person per year. The two parameters required for calculation of performance targets are pathogen numbers in urban stormwater (Table 1) and exposures associated with identified uses of urban stormwater.

As shown in Table 1, pathogen and indicator numbers can vary over a wide range. There was no observable direct correlation between pathogen and indicator numbers for the Parafield catchment. For the Parafield stormwater harvesting system, the catchment-specific assumption that urban stormwater contains 1.4 *Cryptosporidium*, 2 virus and 11 *Campylobacter* per litre (95th percentile) was used.

These values were then used to determine the microbial performance targets shown in Table 2. Specific exposure data can also be used as an alternative to the defaults shown in Table 2.

As presented in Table 2, there are considerable differences in treatment removal requirements for different uses of stormwater. As expected, drinking water has the highest requirements; all uses required some form of treatment or exposure control.

Table 2 shows that viruses require the highest $\log_{10}$ reductions, ranging from 5.8 $\log_{10}$ for drinking water to

Table 2 | Log_{10} reductions for end uses from the Parafield stormwater harvesting system

Option	Route of exposure	Exposure/ event (L)[a]	Frequency (events/yr)[a]	Log_{10} reduction targets[b]		
				Rotavirus	*Cryptosporidium*	*Campylobacter*
Restricted open space irrigation	Ingestion of sprays	0.001	50	1.6	0.6	1.2
Non-potable domestic use and unrestricted irrigation	Ingestion of water and sprays	0.67	1	2.7	1.8	2.3
Drinking	Ingestion of water	2	365	5.8	4.8	5.3

[a]Default assumptions (after NRMMC-EPHC-AHMC 2006).
[b]Total residential use (garden plus internal) after NRMMC-EPHC-AHMC (2006). Total consumption is assumed to be 2 litres per day, of which 1 litre is consumed cold. Affected individuals may consume water 365 days per year. A conservative estimate of 1 in 1,000 houses with cross-connections has been considered (NRMMC-EPHC-AHMC 2006).

1.6 log_{10} for open space irrigation. Log_{10} reductions for bacteria were next highest, followed by protozoa. Included in the calculations is the possibility of cross-connections between the recycled water and drinking water systems, which represents a significant proportion of the exposure associated with dual-reticulation systems. The current risk assessment assumes a default cross-connection rate of 1 in 1,000. If the likelihood of cross-connections was demonstrated to be less, this would further reduce the required log_{10} reductions.

The Australian Drinking Water Guidelines (ADWG) (NHMRC-NRMMC 2011) specifies the indicative log_{10} reductions of treatment processes for enteric pathogens. Other specific treatments such as use of stormwater harvesting wetlands, bioretention basins (e.g. Zhang *et al.* 2014), elements of water sensitive urban design and natural treatment systems such as aquifers (e.g. Page *et al.* 2015b), require a case-by-case validation of the treatment efficacy which needs to be demonstrated by water quality monitoring.

Employing on-site controls to reduce exposure augments or reduces the focus on more expensive treatment. Exposure controls for irrigation such as use of a withholding period (e.g. Page *et al.* 2015a) or buffer distances, can be used in combination with treatment processes to meet the required log_{10} reduction targets calculated in Table 2. For example, a withholding period, which is currently used for public open space irrigation, would meet the required health-based targets.

Treatment processes can be used alone or in combination with on-site preventative measures to meet the minimum health-based log_{10} reduction targets. The required log_{10} reductions can be accumulated over sequential treatments and control measures. It is noted that a single treatment process (barrier) is usually not attributed a value >4.0 log_{10}. This is because validation of treatment barriers becomes problematic at >4.0 log_{10} due to a lack of available surrogates for monitoring with sufficiently low detection levels. In general, the following assessments of risk can be determined for the different stormwater use options.

Open space irrigation requires 1.3 log_{10} using the default stormwater harvesting guidelines (or >1.6 log_{10} using the Parafield specific data from Table 1) for reduction of viruses and *Cryptosporidium*, and can potentially be managed using chlorination or UV disinfection and/or exposure controls.

Toilet flushing and washing machine water requires 2.7 log_{10} for viruses and aquifer treatment, and chlorination would be sufficient. However, cross-connections are the largest risk in dual reticulation systems. Exposure can be reduced using additional preventative measures such as certified plumbing schemes, staged inspections, and audits.

Drinking water use requires the highest microbial health-based targets, which would involve significant treatment: 5.5 log_{10} for viruses using the default values from the guidelines or 5.8 log_{10} using the Parafield data. The different potential end uses for stormwater harvesting and reuse are presented along with the associated microbial health-based targets in Table 2. An example treatment train to produce the required pathogen inactivation credits for drinking water would include filtration for turbidity removal followed by UV and chlorine disinfection. Other treatment combinations are equally valid (e.g. use of ozonation or reverse osmosis membranes for pathogen removal or even aquifer treatment if validated); the selection of

treatments to meet health, economic and environmental targets should be considered to optimise the treatment train for each option.

CONCLUSIONS

A targeted event-based monitoring program of pathogens (adenovirus, *Cryptosporidium* and *Campylobacter*) in stormwater was undertaken to allow a quantitative microbial risk assessment of urban stormwater for drinking. The untreated stormwater quality was found to have 95th percentile numbers for pathogens of 2 n/L for viruses, 1.4 n/L for *Cryptosporidium* and 11 n/L for *Campylobacter*. This allowed the determination of health-based targets for drinking water end uses, and the suggestion of suitable water treatment technologies for each of the options. For open space irrigation, exposure controls such as restricted access during irrigation is sufficient to meet the 1.6 $\log_{10}$ health-based target of viruses for municipal irrigation. For third pipe systems and blending with reclaimed wastewater, a 2.7 $\log_{10}$ health-based target for viruses was required. This could be met using chlorination. For drinking water, a 5.8 $\log_{10}$ health-based target for viruses is required. This could be achieved through a mixture of treatments including filtration, UV and chlorine disinfection. Regardless of treatment technology employed, it would need to be validated to the satisfaction of regulatory agencies.

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