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# An impact assessment for urban stormwater use

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## Abstract

Stormwater has the potential to provide a non-potable water supply which requires less treatment than municipal wastewaters with the added benefit of reducing pollution and erosion issues in receiving water bodies. However, the adoption of stormwater collection and use as an accepted practice requires that the perceived risks, particularly those associated with public health, are addressed. This paper considers the human health concerns associated with stormwater quality when used for a range of non-potable applications using *E. coli*, a commonly found pollutant in urban stormwater which is also widely included in human health based water quality standards and guidelines. Based on a source-pathway-receptor model, scores are allocated, on a scale of 0 to 5, to benchmark increasing the likelihoods of exposure to stormwater during different occupational and non-occupational applications and magnitude of impacts which may result. The impacts are assessed by comparing median stormwater *E. coli* levels with the reported guideline levels relating to different stormwater uses. Combination of the exposure and impact scores provides an overall risk score for each stormwater application. Low or medium risks are shown to be associated with most stormwater uses except for domestic car washing and occupational irrigation of edible raw food crops where the predicted highest levels of risk posed by median *E.coli* levels in stormwater necessitate the introduction of remedial actions.

**Keywords:** stormwater collection; non-potable uses; water quality; risk-rating; public health; *E. coli*.

## Introduction

Since 1900, it is estimated that in excess of 11 million people have died from drought and the livelihoods of over 2 billion people have been affected by water shortages (UNISDR, 2011). By 2025, 2.4 billion people are predicted to be living in regions of physical or economic water scarcity (UNCCD, 2014), with half of the world's population expected to be living under conditions of high water stress by 2030 (UN Water, 2013). Water scarcity is a growing concern globally and is not only a feature of the arid North African and Middle Eastern countries (WBCSD, 2006) but is increasingly identified as an area of concern in the relatively wetter north western hemisphere. For example, the recent report from the UK climate change risk evidence assessment (Committee on Climate Change, 2016) identified that nationally the UK is projected to be in water deficit by 5%–16% of its total demand by the 2050s, and by 8% – 29% of its total demand by the 2080s without the implementation of additional adaptations to those currently proposed. Forecasts such as these highlight the need to reuse water from a variety of sources. Water reuse is regarded as a top priority objective to achieve long term sustainable water resources within the EU. For example, the EU Water Framework Directive (EU WFD, 2000) identifies water reuse as a key supplementary measure to be considered within the development of river basin management plans and maximisation of water reuse is identified as a specific action within the EU's communication document 'A Blueprint to Safeguard Europe's Water Resources' (European Commission, 2012). As much as 50% - 80% of average domestic water consumption does not require water to be of a potable water quality and thus the use of collected stormwater as a substitute source comprises a potentially sustainable and economic option. For example, using stormwater for toilet flushing could reduce the demand on the potable supply in the UK by 26% achieving an average daily consumption of approximately 110 litre/capita/day (EA, 2010).

The current water reuse focus within Europe is on facilitating and promoting the use of treated wastewater discharges for aquifer recharge and for agricultural irrigation applications with stormwater use not included within the scope of the recent Common Implementation Strategy (CIS) guidelines on integrating water reuse into water planning and management (CIS, 2016). Stormwater discharges are seen as being only appropriate for on-site household stormwater harvesting applications and as having limited larger catchment scale benefits (BioDeloitte, 2015). Nevertheless, stormwater use has been extensively identified as a viable and sustainable basis to conserve water resources and to reduce urban flood discharge volumes (EA, 2010; Eslamian, 2015; NSW Dept of Environment and Conservation, 2006; O'Connor et al., 2008). Stormwater use is also considered to offer cost benefits, enhanced receiving water quality, ecological improvements and to support community wellbeing (Hatt

61 et al., 2006). Irrespective of such claims, there is only relatively limited technical guidance (as well as  
 62 field data) to support and quantify the potential use risks and benefits in respect of volume reduction  
 63 and water quality (Fletcher et al., 2008). It is within this broad context of considering the potential role  
 64 of urban stormwater use in addressing water scarcity that this paper sets out to define key stormwater  
 65 use terms, and review national stormwater use experiences and water quality guidelines. In addition,  
 66 using data from the literature, an assessment of the impacts of stormwater quality (using *E.coli* as an  
 67 indicator species) on restricted and non-restricted users is undertaken.

68  
 69 **Stormwater use: key terms and definitions**

70 Considerable confusion and overlap exists regarding the descriptors used to refer to the type of water  
 71 being collected, its mode of capture and its use to meet a defined need (Amec Foster Wheeler  
 72 Environment and Infrastructure, 2016). The terminology and associated definitions are reviewed in  
 73 Table 1 and set stormwater use in context relative to water reuse applications. The definitions  
 74 provided in Table 1 identify urban stormwater use as the collection and storage of rainfall runoff which  
 75 has flowed over an urban surface to meet an identified need. Rainwater harvesting (RWH), which  
 76 involves the collection of roof runoff, is seen as a component of stormwater use and has been  
 77 extensively discussed in the research literature (e.g. Hatt et al., 2006; Kloss, 2008). Whilst not  
 78 excluding any further reference to RWH, the scope and focus of this paper is on alternative  
 79 opportunities to collect stormwater from non-roof surfaces and the impact of its use in selected  
 80 applications considered from a water quality perspective.

81  
 82 **Table 1. Overview and definition of commonly used water reuse terms**

Descriptor	Terms	Definition
Water type	Stormwater	Generic term referring to rainfall runoff as it flows over a surface
	Rainwater	Direct precipitation prior to reaching a surface
	Reclaimed water	Treated municipal wastewater that meets standards required for its intended reuse application*
	NEWater	Brand name for reclaimed water treated to a potable standard
Capture process	Collection	Generic term for accumulating and storing water for reuse
	Harvesting	Typically applied to water collected directly from a roof surface
	Reclamation	The process of removing pollutants to obtain water of a required standard from a contaminated source*
Use activity	Use	The application of stormwater or rainwater to meet a defined need
	Reuse	The use of reclaimed water for a further defined purpose*
	Recycling	The process of generating water of a required standard following a specified application.
	Recharge	The process through which water is infiltrated/injected to below ground storage and entry to an aquifer*

83 Key: \*term used to refer to treated municipal wastewater and associated processes (JRC, 2016).  
 84  
 85

86 **Uses of stormwater**

87 Stormwater use and implementation can be divided into restricted or unrestricted categories  
 88 depending on public exposure/access. The US EPA Guidelines for Water Reuse (CDM Smith, 2012)  
 89 define restricted use as ‘the use of reclaimed water for non-potable applications in municipal settings  
 90 where public access is controlled or restricted by physical or institutional barriers, such as fencing,  
 91 advisory signage, or temporary access restriction’. Unrestricted use is described as ‘the use of  
 92 reclaimed water for non-potable applications in municipal settings where public access is not  
 93 restricted’. These definitions specifically refer to the use of reclaimed water in urban settings rather  
 94 than collected stormwater but this approach is extended here to the categorising of stormwater use  
 95 applications to support further assessment of its water quality implications on target receptors. Table  
 96 2 identifies the range of applications for which stormwater can be used as an alternative source of  
 97 water, together with the scale at which the practice is commonly applied and an indication of key  
 98 areas of concern. Many of the uses can involve either or both non-occupational and occupational  
 99 exposure and the potential health risks associated with such uses need to be assessed to identify the  
 100 level of risk associated with the various uses/receptors. Currently, the available international  
 101 examples and case studies do not fully support the range of potential applications illustrated in Table  
 102 2, highlighting areas for further research and experiential learning.

103  
 104

105 **Table 2. Potential applications for collected stormwater, common scale of application and key**  
 106 **limitations/concerns for water quality**

Land Use	Application	Household (site) scale	Sub-catchment (neighbourhood) scale	Catchment (district) scale	Limitations / concerns
Urban (non - irrigation)	Toilet flushing (R; <b>NO</b> ) Firefighting (U; <b>O/NO</b> ) Vehicle washing (R: <b>O/NO</b> ) Street Cleaning (U; <b>O/NO</b> ) Dust control (U; <b>NO</b> ) Water features (U; O/NO)	√ √ √  √	√ √ √ √ √		Dual distribution and costs of dual plumbing in domestic environments; problems due to cross-connections; public health risks; lack of relevant legislation
Irrigation	Lawns, flowers/shrubs (U; O/NO) Parks, playgrounds, public open space (U; <b>O/NO</b> ) Sports grounds, golf courses etc. (R; <b>O/NO</b> ) Nurseries (R; <b>O/NO</b> ) Agricultural crops* (R; <b>O/NO</b> ) Orchards* (R; <b>O/NO</b> ) Allotments* (U; O/NO)	√	√ √ √ √ √ √	√  √	Variation in seasonal demands; adverse impacts on plants / crops; public health risks; lack of relevant legislation
Habitat, aesthetics and recreation	Ornamental / recreational waterbodies (U; O/NO) Detention/retention basins (U; N/NO) Wetlands (U; O/NO)	√	√ √ √	√ √ √	Occurrence of algal growths; adverse ecological impacts; public health risks; lack of relevant legislation
Water supply/ recharge	Surface reservoirs Groundwater recharge	√	√ √	√ √	Potential impact on and prejudice to groundwater

107 Key: R=restricted/controlled access; U=unrestricted/open access; O= occupational exposure; NO=non-  
 108 occupational exposure [where both occupational and non-occupational exposure are indicated, bold type  
 109 indicates where a predominant exposure route exists]  
 110 \* food products may or may not be processed prior to human consumption.  
 111  
 112

113 Figure 1 illustrates stormwater use applications identified from a review of Australian and United  
 114 States schemes indicating the similarities in sectoral distributions, apart from toilet flushing, which  
 115 clearly reflects public resistance to potential exposure risks in the US (Alan Plummer Associates Inc.,  
 116 2010). Firefighting and industrial applications each consistently represent less than 10% of the total  
 117 stormwater use indicating a resistance to use for these purposes with very few examples cited in the  
 118 literature. The Australian data refers to end-use applications within 17 selected municipalities, which  
 119 show outdoor irrigation, water feature supplementation and aquifer recharge to be the most common  
 120 end-uses comprising nearly 70% of all applications (Hatt et al., 2006). There does not appear to be  
 121 any significant influence of site, sub-catchment or catchment scale of application on the reported end-  
 122 use type, although it is notable that the large majority of end-uses were restricted to site scale and  
 123 mainly applied for purposes having a low potential for direct human contact.  
 124

125 INSERT FIGURE 1 HERE

126  
 127 It is also notable that most end-use schemes reviewed by Hatt et al., (2006) used the same drainage  
 128 design controls developed for sustainable drainage system (SuDS) controls i.e. primarily focussed on  
 129 achieving water quantity objectives as opposed to prioritising the need to produce the highest quality  
 130 water outputs. Furthermore, where SuDS design did include water quality control as a design  
 131 parameter, its primary intention was to protect receiving water ecosystems rather than public health.  
 132

133 There is evidence that stormwater use in a variety of urban applications is becoming more acceptable  
134 to the public. A recent national Australian report suggested that as many as 90% of both public and  
135 industrial customers now regard the application of urban stormwater for potable uses as a justifiable  
136 and viable alternative option to conserve future water resources (Arup, 2016). However, only a small  
137 proportion of stormwater runoff is currently used in any substantial way. Although Australia is widely  
138 regarded as possessing an advanced and integrated stormwater and wastewater reuse policy, this  
139 still only amounts to some 3% of the total supply output (Fletcher et al., 2008).

140

#### 141 **Stormwater use: national experiences**

142 Over the last decade, several countries (including Germany, Japan and Australia) have referred to  
143 RWH within pertinent legislation and developed a range of initiatives and guidance to encourage its  
144 uptake (Environment Protection and Heritage Council, 2009; German Federal Water Act, 2010;  
145 Ogoshi et al., 2001). However, as identified earlier, RWH is only one component of stormwater use,  
146 with other opportunities to collect, store and use stormwater at a variety of scales yet to receive the  
147 same support in legislation or practice. Generic stormwater collection relates to the use of bulk  
148 rainfall-runoff discharges from non-roof impervious surfaces which are relevant to end-of-pipe sub-  
149 catchment (neighbourhood) and catchment (district) source control. Relevant management  
150 approaches include a range of SuDS collection and storage technologies such as detention/retention  
151 basins and wetlands, which are often incorporated into Low Impact Development (LID) designs (in the  
152 US) and Water Sensitive Urban Design (WSUD) approaches (in Australia). Such SuDS controls can  
153 offer a range of non-potable reuse opportunities including ornamental and water features, irrigation,  
154 firefighting etc. Highway and other stormwater discharges to porous paving, filter drains and infiltration  
155 trenches/basins also represent a recharge function and therefore an indirect water use application.  
156 However, large catchment and neighbourhood scale recharge applications have a long and  
157 acknowledged history in practice in some locations. For example, stormwater infiltration basins have  
158 been used for groundwater augmentation in Long Island, New York since 1935 (Aronson, 1979) and  
159 there are now over 3000 such facilities in place in New York state. Many county authorities across the  
160 United States have local legislative mandates for managed aquifer recharge (MAR) and recovery of  
161 stormwater discharges which date back some 40 – 50 years (Aronson et al., 1979). Soakaway  
162 infiltration of stormwater runoff at site, neighbourhood and catchment scales has long been practiced  
163 throughout the UK and Europe and recharge studies have demonstrated their satisfactory long term  
164 hydraulic performance efficiency with little evidence of any significant impacts on groundwater quality  
165 (Chen et al., 2008; Edwards et al., 2016). The EU Demeau project ([www.demeau-fp7.eu](http://www.demeau-fp7.eu)) has  
166 highlighted the role of stormwater recharge at 270 locations across Europe with storage and  
167 attenuation of infiltrated or injected stormwater to the shallow sub-surface zone leading to a safe and  
168 sustainable option for augmenting scarce water resources. Whilst such infiltration practices are  
169 usually covered by well-defined legislative requirements (e.g. EU Water Framework Directive (WFD),  
170 2000; EU Groundwater Directive (GWD), 2006) and normally associated with formal design and  
171 construction guidelines with compliance specified by both performance criteria and water quality  
172 standards, this is not the case for other stormwater end use applications involving bulk collection of  
173 stormwater from non-roof surfaces.

174

#### 175 **Stormwater water quality use concerns**

176 Perhaps the principal water quality concern for stormwater use application is related to public health  
177 risks particularly in respect of potential microbial contamination (Davies et al., 2008) associated with  
178 unrestricted access uses. Such applications carry the expectation (Kloss, 2008) of a tertiary level  
179 pathogenic reduction with the collected water being fully compliant with various water quality  
180 guidelines. Although water quality guidelines are available for total and faecal coliforms and  
181 enterococci in a variety of contexts (e.g. California 22, 2014; CDM Smith, 2012; EU Bathing Water  
182 Directive, 2006, Fewtrell and Bartrum, 2001) those quoted for *E. coli* are currently the most adaptable  
183 to the different applications for stormwater use and additionally this microbial parameter is often  
184 reported in stormwater data sets. Guideline standards, as a measure of public health risk, have been  
185 developed for different types of treated wastewaters but only Australian guidelines (NSW Department  
186 of Environment and Conservation, 2006) apply specifically to stormwater use (Table 3). However, a  
187 problem which exists with both stormwater and treated wastewater is that even when acceptable  
188 water quality levels originally exist (at point of discharge), the presence of nutrients may encourage  
189 both algal growth and bacterial proliferation during subsequent storage. In domestic applications, the  
190 possibility of cross-connections to the potable water supply is frequently cited as a barrier to greater  
191 stormwater use. For example, some 87 properties (17% of the residential site) on an eco-housing  
192 development at Upton, Northampton (UK) were found to be contaminated by *E. coli* (>100CFU/100ml)

193 following cross-connection of the mains supply to the domestic RWH system (DWI, 2010). A further  
 194 134 properties were found to have labelling infringements on their RWH systems. Cross-connections  
 195 and back siphonage on domestic RWH systems have also been identified in properties within the  
 196 Anglian region of the UK (EA, 2010).

197  
 198 There is currently uncertainty associated with either the lack of water quality standards for stormwater  
 199 use or the differing guideline standards that have been proposed by different agencies. These are  
 200 often based on whether the stormwater use is to be restricted or unrestricted or whether it will be  
 201 subjected to occupational or non-occupational exposure (CDM Smith Inc., 2012; NSW Department of  
 202 Environment and Conservation, 2006). However, there can be differences of one or two orders of  
 203 magnitude in the recommended values. For example, the existing bacterial guidelines for domestic  
 204 uses of collected stormwater in the UK are inconsistent with total coliform counts varying from  $\leq 10$   
 205 CFU/100ml for pressure washers/garden sprinklers up to  $\leq 1000$  cfu/100ml for garden watering/WC  
 206 flushing (EA 2010; MTP 2007). Comparable *E. coli* values are  $\leq 1$  cfu/100ml according to Australian  
 207 guidelines (NSW Department of Environment and Conservation, 2006). The existence of different  
 208 regulatory, organisational and operational agencies and public consumers in any stormwater  
 209 collection and use system requires a balance to be achieved between them when establishing  
 210 appropriate end-use water quality standards. In addition, the guideline standards need to be  
 211 supported by evidence-based epidemiology in relation to the different stormwater source types and  
 212 end-uses. The available *E. coli* standards (Table 3) are up to several orders of magnitude lower than  
 213 the levels typically found in stormwater depending on the intended use. Measured *E. coli* median  
 214 levels in urban stormwater from non-industrial catchments in Australia, USA and UK have been  
 215 quoted in the range from 290 to 19,496 cfu/100ml with a calculated median value of 3037 cfu/100ml  
 216 (Ellis and Mitchell, 2006; ISBMPD, 2014; McCarthy et al., 2012).

217  
 218 **Table 3. *E. coli* guideline values associated with different occupational and non-occupational**  
 219 **stormwater uses.**

Application category		Median <i>E. coli</i> guideline values (cfu/100ml)
Residential /Commercial activities	Toilet flushing	$\leq 1^a$
	Garden watering	
	Car washing	
Open access urban exposure	Firefighting	$\leq 10^a$
	Dust control; street cleaning; irrigation of public open spaces / parks	
	Ornamental water bodies	
Controlled access urban exposure	Irrigation of sports grounds and nurseries	$\leq 100^a$
Agricultural irrigation (including allotments)	Raw foods	$\leq 1^b$
	Processed foods	$\leq 100^b$
	Non-food crops	$\leq 1000^b$
Potable water supply	Surface reservoirs	$0^c$
	Aquifer recharge (via surface spreading or direct injection)	Below the limit of detection <sup>c</sup>

221 <sup>a</sup> NSW Department of Environment and Conservation, 2006; <sup>b</sup> JRC, 2016; <sup>c</sup> EU Drinking Water  
 222 Directive

223  
 224 It is known from the RWH literature that small tanks can support long-lasting bacterial populations and  
 225 it is highly likely that a significant proportion of domestic RWH tanks would be unable to be  
 226 consistently compliant with these standards (Ahmed et al., 2011). A decrease in RWH tank  
 227 microbiological quality often follows storm events and may be related to a flushing of nutrients, algae  
 228 and bird faeces from roofs and gutters (Charlesworth et al., 2014). The lack of detailed field studies  
 229 on pathogenic prevalence in stormwater collection systems predicated a reliable quantification of  
 230 actual health risks for such applications. Mosquito breeding is a potential concern whenever standing  
 231 water (especially for longer than 72 hours) occurs and stormwater tanks require appropriate and

232 regular operational procedures to ensure a safe water reuse supply for any intended end uses. Gutter  
233 guards, first flush diverters and screening (>1mm mesh) of roof flows into a storage tank are  
234 commonly included installation guidance. The use of mosquito “dunks” (soil bacterial larvicide),  
235 floating vegetable oil and occasional bleach cleaning of the tank/barrel will also help to maintain a  
236 satisfactory and safe water quality. However, even well protected and maintained tanks can still be  
237 subject to contamination (Moglia et al., 2016), which emphasises the need for careful and systematic  
238 installation and monitoring of reuse systems involving stored stormwater. The same concerns about  
239 maintenance and systematic monitoring for mosquito occurrence applies to bulk stored stormwater  
240 collection facilities.

241  
242 In addition to the possibility of microbiological contamination, there are also concerns regarding the  
243 occurrence of soluble metals, hydrocarbons and other volatile organic compounds in stormwater  
244 storage systems. However, field results suggest that such toxic contamination is very location- and  
245 event-specific (Mendez, et al., 2010; Ward et al., 2010). Potentially high dissolved organic carbon  
246 concentrations in bulk stormwater storage facilities might present a problem for further use if subject  
247 to chlorination due to production of harmful by-products and slow sand filtration offers a better tertiary  
248 level treatment alternative for the achievement of a reliable and acceptable water quality standard  
249 (Avellaneda et al., 2010). However, UV disinfection and membrane filtration (1 - 5µm) appear the  
250 most cost-effective tertiary level options for small-scale domestic stormwater systems (Lainé, 2010)  
251 but there are technical issues in scaling up such systems for application to bulk stormwater treatment.  
252 In these situations, conventional SuDS treatment can be utilised but is unlikely to reduce the level of  
253 reference pathogens to consistently safe levels of public risk exposure. The application of any  
254 treatment option is complicated by the fact that the majority of stormwater use schemes will not be  
255 operated and managed by water utilities, are likely to be accessible to non-specialist users/members  
256 of the public and ideally therefore should be limited to non-potable end-uses only. However, the same  
257 technical assessment procedures are applied to such recycled waters as to treated wastewater  
258 effluents in most national guidelines.

## 259 **Stormwater Generation for Reuse**

261  
262 There are substantial difficulties associated with quantifying the potential stormwater volumes that  
263 might be available for further use applications at both local and district scales in comparison to those  
264 associated with greywater or treated wastewater. Total discharge volumes will be dependent on the  
265 occurrence and timing of rainfall-runoff in relation to local demands as well as the ability to collect and  
266 store stormwater and to coordinate this alternative water supply with other water sources. The total  
267 amount of stormwater is also a function of contributing catchment area with highest stormwater  
268 capture levels (>50%) being at site scales. In addition, as rainfall intensity, duration and depths  
269 increase, a higher percentage of the rainfall will occur as effective runoff with the consequence that  
270 at-source SuDS such as raingardens, bioretention or filter drains (and water butts/tanks) are  
271 overwhelmed at an early stage of large storm event discharges, thus requiring the inclusion of some  
272 type of overflow or bypass to surface water or piped system to avoid surface water flooding. GIS  
273 scenario analysis of the Greater London metropolitan region suggested that some 70% of rainfall  
274 associated with the 30 year storm event might be captured by all types of at-source SUDS devices,  
275 but that this decreased to below 50% if on-site water butts/tanks and raingardens were removed from  
276 the scenario (Todorovic and Breton, 2016). The ability of SuDS to capture and attenuate storm runoff  
277 from high frequency, low magnitude rainfall events is complemented by pollutant loading reductions  
278 due to sedimentation, filtration and degradation processes. However, efficient treatment requires  
279 ongoing management, monitoring and maintenance to ensure effective and safe further use practices  
280 at neighbourhood and catchment scales.

281  
282 Resilience analysis by Mugume et al., (2016) predicted that decentralised RWH systems within  
283 between 1 in 5 to 1 in 11 households might reduce catchment peak flood volumes by 25% - 30% and  
284 additionally offer alternative water supply support. Such dual-function roles for stormwater collection  
285 have also been demonstrated by other workers (Burns et al., 2015; DeBusk et al., 2013). Scenario  
286 analysis by Melville-Shreve et al., (2016) at the sub-catchment (neighbourhood) scale in the San  
287 Francisco Bay area in Western USA, estimated that between 75-80% of all domestic household water  
288 demand could be met from on-site RWH. However, even given such high reuse application, the  
289 overall larger catchment scale water demand reduction was estimated to be only between 15-20%.  
290 Another relevant US modelling study came to broadly similar conclusions with neighbourhood and  
291 catchment scale reuse applications only meeting a small proportion of outdoor water demands

292 (National Academies of Sciences, Engineering, Medicine, 2016). The major barriers to large scale  
293 applications were seen as being the need for extensive infrastructure for large scale collection,  
294 transport, storage and treatment of stormwater with supplementation through greywater and  
295 wastewater reuse being considered to be the most effective solution to cover extended periods of dry  
296 weather.

297

## 298 **Impact Assessment for Stormwater Reuse**

299

300 Jiang *et al.*, (2015) have reviewed the health hazards associated with the use of both harvested  
301 rainwater and stormwater and have identified microbial pathogens as posing the greatest public  
302 health concerns. The US methodological approach to risk assessment for water reuse assumes a  
303 potable end-use and a 5% probability of the source water being contaminated by discharged treated  
304 wastewater (National Academies of Sciences, Engineering, Medicine, 2016). The risks posed by  
305 defacto reuse for four pathogens following soil-aquifer infiltration and advanced treatment are  
306 considered on a log reduction scale. The assessment methodology suggests that the level of risk  
307 exposure from these two reuse scenarios is basically equivalent to that for existing drinking water  
308 treatment systems. This approach based on strict public health exposure criteria is essentially similar  
309 to that of the WHO for domestic water reuse which considers microtoxicological data and infectious  
310 dose rates (WHO, 2006). Quantitative microbial risk assessment (QMRA) is a recognised technique  
311 which has been applied to the estimation of risks associated with the reuse of harvested stormwater  
312 (Dobbie and Brown, 2012). Both approaches stipulate minimal treatment levels and retention times  
313 with standards applied for surface water infiltrated to ground. System safety assessment is now  
314 intruding on quantitative risk assessment which evaluates barrier efficiencies and subsequent  
315 intentional and unintentional public/worker exposure. The Australian water recycling guidelines offer  
316 perhaps the best practice examples translating this system safety methodology to a range of potential  
317 reuse applications (NSW Department of Environment and Conservation, 2006), with fit-for-purpose  
318 guidelines based on local exposure data and specified performance monitoring requirements. Safety  
319 in this context is based on an understanding and control of hazards and the water system which  
320 translates the quantitative data to practical requirements for the design and operation of a reuse  
321 system. Water Safety Plans (WSPs) represent such an applied risk management process which  
322 attempts to operationalise the risk management framework in a consistent and transparent way as  
323 developed in terms of reuse for drinking water supply in the UK (Goodwin *et al.*, 2015).

324

325 To assist in the development of an impact assessment for stormwater use, a diagrammatic source-  
326 pathway-receptor model is presented in Figure 2. In addition to direct human interactions the main  
327 receptors are identified as plants, soil and receiving waters all of which can have indirect impacts on  
328 human health. Plants for human consumption can be contaminated by direct contact with irrigating  
329 waters as well as through uptake from soils. Surface reservoirs (through direct inflow) and aquifers  
330 (through recharge following surface spreading or direct injection) are examples of receiving waters  
331 which may be affected although in both cases there will be dilution followed by water treatment prior  
332 to achieving potable water of a standard fit for human consumption. The direct human interaction with  
333 stormwater will be influenced by whether this involves occupational or non-occupational exposure and  
334 whether the use relates to a residential/commercial activity, to an open access urban activity  
335 (unrestricted) or to a controlled access urban activity (restricted). These categories have been used in  
336 the development of risk-rating framework to support an impact assessment as shown in Table 4.

337

338 INSERT FIGURE 2 HERE

339

340 In theory, the level of risk can be determined from consideration of the likelihood of exposure to occur  
341 and the magnitude of impact following exposure. The allocation of scores (in the range of 0 to 5) to  
342 each of these parameters together with an explanation of their relative meanings is shown in Table 4.  
343 The maximum score of 5 in both cases indicates the highest likelihood of occurrence and magnitude  
344 of impact. The lowest score of 0 suggest that exposure is not feasible and that no impact would be  
345 expected as compliance with the guideline standard exists. The likelihood of exposure is independent  
346 of the pollutant type and is influenced solely by the contact between the stormwater and the human  
347 receptor. The magnitude of impact following exposure is entirely dependent on the nature of the  
348 pollutant and in the case of *E. coli* is determined by the relative magnitude of the median stormwater  
349 level (3037 cfu/100ml) to the guideline standards for the different uses of stormwater. The greater the  
350 exceedance the higher the score as shown below according to a logarithmic-linear relationship:

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<u>Median stormwater level/ guideline level</u>	<u>Score</u>
≥ 10000	5
≥ 1000	4
≥ 100	3
≥ 10	2
≥ 1	1
≤ 1	0

**Table 4. Example descriptors of incrementing likelihood of occurrence and magnitude of impact**

Score	Likelihood of exposure to occur	Magnitude of impact following exposure
5	Highly likely to occur	Highly likely to exert an impact
4	Likely to occur	Likely to exert an impact
3	Possible (may occur sometimes)	Possible impact (may occur sometimes)
2	Unlikely (uncommon but known to be possible)	Unlikely (uncommon but impact may occur)
1	Rare (lack of evidence for exposure occurring)	Rare (little possibility of impact)
0	Exposure not feasible	No impact expected following comparison with guideline values

The overall level of risk is the product of the likelihood of exposure to occur multiplied by magnitude of impact following exposure, where a value of 1-4 = low risk (acceptable); 5-14 = medium risk; 15-25 = high risk (unacceptable; needs to be managed). Applying this approach to the different stormwater uses identified in Table 3 produces the risk-rating matrix shown in Table 5. The overall risk score compartments are coloured according to the derived level of risk with green indicating that only a low risk is predicted whereas red identifies situations where the level of risk is unacceptable and if the associated practices are unavoidable, actions should be instigated to reduce the overall level of risk. In contrast to the impact magnitude scores which are based on quantitative values, the likelihood of exposure scores are evaluated from a consideration of the potential for human contact to be made with used stormwater and may, to some extent, be subjective. Potential routes for the exposure of humans to stormwater during its use include inhalation, ingestion and dermal contact (Sinclair et al., 2016; WHO, 2006). Thus in the residential/commercial activity category it is postulated that exposure as a consequence of toilet flushing will be limited to occasional spray inhalation with a lesser chance of skin contact and therefore exposure would be unlikely (score:2). Aerosol production will be dependent on flush energy but QMRA results for viral infections have identified a risk value below the US EPA annual risk benchmark of  $\leq 10^{-4}$  per-person-per-year for toilet flushing using treated stormwater (Lim et al., 2015). In contrast, garden watering (occupational and non-occupational) and car washing render operatives more susceptible to spray inhalation/ingestion and skin contact (where full protective clothing is not used) leading to the possibility of exposure (score: 3). Using a chemical tracer in simulated high pressure spray car washing experiments, Sinclair et al. (2016) demonstrated that the predominant intake role was through ingestion/inhalation with negligible skin absorption. The increased direct dermal contact experienced by private car washers (non-occupational) would also make exposure likely to occur (score 4).

In both open access and controlled access environments the likelihood of exposure is considered to be higher in occupational situations due to the use of pressurised spray systems during firefighting, street cleaning, dust control and irrigation of parks and sports grounds etc. leading to elevated inhalation risks and the possibility of skin contact (scores: 4 or 3). The presence of fountains in ornamental water bodies can lead to spray inhalation and limited skin contact for both directly involved workers and the general public (score:3). The irrigation of food crops presents an elevated exposure at the occupational level as a consequence of both inhalation and skin contact as well as the potential for ingestion of freshly picked raw foods (score:5). The retention of water on crop surfaces during irrigation enhances the potential for contamination when freshly eaten (Hamilton et al., 2006). The general public will also be exposed through the intake of raw foods but the delay between irrigation and eating would be expected to lead to a decrease in *E. coli* levels (score:3). In the case of processed food the likelihood of exposure to *E. coli*, both occupationally and non-occupationally, will be reduced and are hence allocated scores of 3 and 1, respectively. Exposure through water supply sources will be rare for the general public (score:1) with occupational exposure limited to possible skin

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**Table 5. Risk matrix developed showing scores associated with stormwater use in a range of occupational and non-occupational contexts**

Application category		Score relating to magnitude of impact	Scores relating to likelihood of exposure		Risk score	
			Occupational	Non-occupational	Occupational	Non-occupational
Residential /Commercial activities	Toilet flushing	4	-	2		8
	Garden watering		3	3	12	12
	Car washing		3	4	12	16
Open access urban exposure	Firefighting	3	4	1	12	3
	Dust control; street cleaning; irrigation of public open spaces / parks		3	2	9	6
	Ornamental water bodies		3	3	9	9
Controlled access urban exposure	Irrigation of sports grounds and nurseries	2	3	1	6	2
Agricultural irrigation (including allotments)	Raw foods	4	5	3	20	12
	Processed foods	2	3	1	6	2
	Non-food crops	1	3	1	3	1
Potable water supply	Surface reservoirs	4*	2	1	8	4
	Aquifer recharge (via surface spreading or direct injection)	4*	2	1	8	4

\* if not treated

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contact (surface reservoirs) or spray inhalation through surface spreading during aquifer recharge (score:2).

**Consideration of risk scores**

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The magnitudes of the impacts which can result from the exposure to *E. coli* in stormwater have been derived by comparing the possible levels in stormwater with the microbial guidelines which currently exist for different applications of stormwater use. Likely impacts (score:4) are predicted for residential/commercial activities (toilet flushing, garden watering, car washing), consumption of raw foods, and the ingestion of untreated waters from surface reservoirs or aquifers. However, exposure through human intake of untreated water from either of these sources is unlikely as initial dilution combined with treatment would result in a low overall risk score for the general public. This increases to a medium risk classification for occupational use due to additional exposure routes. When the high impact potential posed by car washing is combined with the relatively highest likelihood of exposure which exists with the hand washing activity practised by many car owners, an overall high risk is predicted for this non-occupational activity. Therefore as a precaution it would be advisable to recommend that untreated stormwater should not be used for this purpose. The medium risk score associated with toilet flushing is consistent with the QMRA risk estimate for harvested stormwater based on a range of pathogens, but not including *E. coli* (Lim *et al.*, 2015). The same assessment technique predicted that rainwater should additionally be considered suitable for showering and garden watering (Fewtrell and Kay, 2007; Ahmed *et al.*, 2010; Lim and Jiang, 2013). Agricultural irrigation can result in exposure for all workers directly involved in these procedures. However, the potential impact arising from exposure to stormwater containing *E. coli* at identified levels is only elevated in the situation where the workers are directly ingesting raw foods which have the possibility of being contaminated. The resulting relatively highest overall occupational risk score (score:20) would be ameliorated if the practice of directly eating the crops was avoided and reduced considerably if washing and preferably some form of processing were practised. The irrigation of food crops using harvested stormwater and subsequent ingestion of the contaminated crop has also been

435 shown to pose an unacceptable risk by conducting a QMRA study (Lim *et al.*, 2015). It is clear from  
436 the overall relative risk scores presented in Table 5 that occupational risks generally entail more risk  
437 with typically medium risk being identified. In comparison, the same stormwater use applications in a  
438 non-occupational context are predominantly associated with relatively lower risk levels when exposed  
439 to stormwater containing *E. coli* at identified levels.

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441 The impact scores resulting from the risk matrix methodology are based solely on the consequences  
442 of potential public health exposure and do not consider wider ecological or technological  
443 consequences dependent on receiving water ecology, mitigation measures or on other  
444 secondary/tertiary consequences such as commercial, policy, community interests. However, the  
445 primary health impacts are clearly of the highest priority in any decision-making water reuse schemes.  
446 It is possible that the quasi-quantitative risk characterisation presented here incorporates conservative  
447 safety margins which are commonly associated with scoring allocations of risk magnitude  
448 (Dominguez-Chicas and Scrimshaw, 2010). Nevertheless, the utility and flexibility of the risk  
449 characterisation and impact methodology serves to support the consideration of appropriate action  
450 levels and appropriate source treatment options.

## 451 452 **Conclusions**

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454 In spite of the accepted potential use of collected stormwater for a range of applications there is  
455 limited evidence of widespread implementation. Given the frequently highlighted public health  
456 concerns associated with this practice, this paper has established an impact assessment  
457 methodology in which stormwater data sets are compared to available *E. coli* standards/guidelines for  
458 different stormwater uses allowing a scoring system for different levels of impact to be developed on a  
459 scientific basis. However, by necessity, the scores allocated to increasing likelihood of exposure have  
460 a subjective basis, and there is a need for a robust epidemiological understanding of stormwater use  
461 to enable these scores to be evidence-based. The overall results identify relatively low or medium  
462 levels of impact associated with most uses of stormwater, except for domestic car washing and  
463 occupational irrigation of edible raw food crops where the predicted high risk posed by median *E. coli*  
464 levels in stormwater would necessitate the introduction of remedial actions prior to use. *E. coli* is an  
465 appropriate water quality parameter against which to consider public health but the available  
466 guidelines/standards for some applications pertain only to the safe use of treated municipal  
467 wastewaters. This is a water type with very different quality characteristics and therefore when used in  
468 a stormwater context may result in an overly conservative estimate of the level of impact. Further  
469 applied research is needed to enable the described theoretical approach to be grounded in a robust  
470 evidence base and to provide a more confident prediction of the use of collected stormwater as an  
471 alternative water resource in a range of non-potable applications. The availability of a more unified  
472 and evidence-based guidance on regulation, standards and operational implementation for  
473 stormwater reuse could help support future uptake and intensification of the practice. In addition,  
474 financial incentives and economic instruments to encourage and promote end-use uptake would also  
475 help underpin local sustainable stormwater management approaches.

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