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

Stormwater use: key terms and definitions

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

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*

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

Uses of stormwater

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

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

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

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

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

INSERT FIGURE 1 HERE

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

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

Stormwater use: national experiences

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

Stormwater water quality use concerns

Perhaps the principal water quality concern for stormwater use application is related to public health risks particularly in respect of potential microbial contamination (Davies et al., 2008) associated with unrestricted access uses. Such applications carry the expectation (Kloss, 2008) of a tertiary level pathogenic reduction with the collected water being fully compliant with various water quality guidelines. Although water quality guidelines are available for total and faecal coliforms and enterococci in a variety of contexts (e.g. California 22, 2014; CDM Smith, 2012; EU Bathing Water Directive, 2006, Fewtrell and Bartrum, 2001) those quoted for *E. coli* are currently the most adaptable to the different applications for stormwater use and additionally this microbial parameter is often reported in stormwater data sets. Guideline standards, as a measure of public health risk, have been developed for different types of treated wastewaters but only Australian guidelines (NSW Department of Environment and Conservation, 2006) apply specifically to stormwater use (Table 3). However, a problem which exists with both stormwater and treated wastewater is that even when acceptable water quality levels originally exist (at point of discharge), the presence of nutrients may encourage both algal growth and bacterial proliferation during subsequent storage. In domestic applications, the possibility of cross-connections to the potable water supply is frequently cited as a barrier to greater stormwater use. For example, some 87 properties (17% of the residential site) on an eco-housing development at Upton, Northampton (UK) were found to be contaminated by *E. coli* (>100CFU/100ml) following cross-connection of the mains supply to the domestic RWH system (DWI, 2010). A further 134 properties were found to have labelling infringements on their RWH systems. Cross-connections and back siphonage on domestic RWH systems have also been identified in properties within the Anglian region of the UK (EA, 2010).

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

Table 3. *E. coli g*uideline values associated with different occupational and non-occupational stormwater uses.

Application category		Median E. coli guideline values (cfu/100ml)
Residential /Commercial activities	Toilet flushing	≤ 1[a]
	Garden watering	
	Car washing	
Open access urban exposure	Firefighting	≤ 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	≤ 100[a]
Agricultural irrigation (including allotments)	Raw foods	≤ 1[b]
	Processed foods	≤ 100[b]
	Non-food crops	≤ 1000[b]
Potable water supply	Surface reservoirs	0[c]
	Aquifer recharge (via surface spreading or direct injection)	Below the limit of detection[c]

[a] NSW Department of Environment and Conservation, 2006; [b] JRC, 2016; [c] EU Drinking Water Directive

It is known from the RWH literature that small tanks can support long-lasting bacterial populations and it is highly likely that a significant proportion of domestic RWH tanks would be unable to be consistently compliant with these standards (Ahmed et al., 2011). A decrease in RWH tank microbiological quality often follows storm events and may be related to a flushing of nutrients, algae and bird faeces from roofs and gutters (Charlesworth et al., 2014). The lack of detailed field studies on pathogenic prevalence in stormwater collection systems predicates a reliable quantification of actual health risks for such applications. Mosquito breeding is a potential concern whenever standing water (especially for longer than 72 hours) occurs and stormwater tanks require appropriate and regular operational procedures to ensure a safe water reuse supply for any intended end uses. Gutter guards, first flush diverters and screening (>1mm mesh) of roof flows into a storage tank are commonly included installation guidance. The use of mosquito “dunks” (soil bacterial larvicide), floating vegetable oil and occasional bleach cleaning of the tank/barrel will also help to maintain a satisfactory and safe water quality. However, even well protected and maintained tanks can still be subject to contamination (Moglia et al., 2016), which emphasises the need for careful and systematic installation and monitoring of reuse systems involving stored stormwater. The same concerns about maintenance and systematic monitoring for mosquito occurrence applies to bulk stored stormwater collection facilities.

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

Stormwater Generation for Reuse

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

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

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

Impact Assessment for Stormwater Reuse

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

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

INSERT FIGURE 2 HERE

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

Median stormwater level/ guideline level	Score
≥ 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

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

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

Consideration of risk scores

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

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

Conclusions

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

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