Advanced Review

Human and environmental health risks and benefits associated with use of urban stormwater

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For stormwater harvesting to achieve its full potential in mitigating water scarcity problems and restoring stream health, it is necessary to evaluate the human and environmental health risks and benefits associated with it. Stormwater harbors large amounts of pollutants and has traditionally been viewed as a leading cause of water-quality degradation of receiving waters. Harvesting stormwater for household use raises questions of human exposure to pollutants, especially human pathogens, which have the potential to cause large-scale disease outbreaks. These issues are compounded by uncertainties relating to the performance of stormwater treatment technologies in pathogen removal. Quantitative microbial risk assessment provides an objective risk estimate based on scientific data and the best assumptions, which can be used to educate and instil confidence in stakeholders of the practice. Although limited, human health risk studies have positively supported the use of minimally treated rainwater and stormwater for some non-potable applications. In addition to the well-known benefit of preserving the stream hydrology and ecology, wetlands used for harvesting stormwater can also provide new habitats for wildlife that benefit environmental health. A fundamental change from viewing stormwater as waste to resource requires the coordinated efforts in research, education, and effective communication.

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INTRODUCTION

Population growth, rapid urbanization, and climate change have been straining our traditional water resources and degrading the environment. Several recent studies and reviews have analyzed the impact of urban development on natural hydrological system and coined the term 'urban stream syndrome' to describe the complex issues related to change in land coverage and stream flow.[1–3] Efforts to prevent and reverse urban stream syndrome require harvesting a major portion of stormwater running off impervious surfaces and using the harvested water for local irrigation of landscape to improve evapotranspiration, or for other non-potable uses that involve exporting the harvested water through sewage systems.[4] This review paper uniquely focuses on the validity of use of harvested stormwater for local applications. Harvesting is hereby defined as collection of surface runoff from impervious surfaces, which is consistent with that used in the previous reviews on stream hydrology. As such, groundwater infiltration with the potential for groundwater recharge is not included in this review as harvesting. Furthermore, this paper will not duplicate the previous reviews[4] on quantity of the stormwater that should be partitioned between infiltration to recharge groundwater aquifer and harvesting for local use.

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Extending from the benefit of reversing the urban stream syndrome, an additional benefit of stormwater harvesting lies in applying the minimally treated stormwater or untreated rainwater for non-potable household applications to alleviate the pressure on drinking water resource. Stormwater harvesting presents the opportunity to shift the urban water management paradigm from the traditional view of stormwater as a pollutant and flood risk to the view of new water resource.[5] However, the quality of stormwater and potential health concern associated with household use should be evaluated. Treatment systems commonly used for improving stormwater quality (e.g., constructed wetlands, biofilters) should be examined if stormwater is used in direct human contact activities (showering, laundry, home crop gardens irrigation, etc.). Among the array of health hazards that may be carried by stormwater, microbial pathogens are the most important public health concern due to their low dose of infection, the acute nature, the secondary transmission, and the potential for large-scale disease outbreaks. There is also a lack of understanding of microbial removal efficiency because the earlier stormwater harvesting systems have focused on removal of total nitrogen, phosphorous, and other chemical constituents. This paper focuses on the potential human health risks posed by microbial contaminants during household uses of stormwater, and human and environmental health benefits beyond the well-studied stream ecology and drinking water substitution.[6–8]

MICROBIAL QUALITY OF STORMWATER

In cities of developed countries, stormwater are collected from impervious surfaces by extensive networks of engineered underground storm drainage systems[9] (Figure 1). In most cities, urban stormwater empties directly to rivers, creeks, or coastal waters without any treatment. In other cities where storm drain and sewer collection systems are combined, stormwater is piped to sewage treatment plants together with municipal sewage for treatment. These combined systems can present serious problems during wet weather, when the stormwater overwhelms the design volume of sewage treatment plants and has to be released (with raw sewage) to the receiving water without any treatment.[10] During this combined sewer and stormwater overflow (CSO) event, the receiving water is severely contaminated by raw sewage.

Source Matters

Rainwater and snowmelt are the main sources of stormwater (Figure 1). Although rainwater harvesting is an important component of stormwater harvesting, a clear distinction is made between the quality of rainwater harvested directly from rooftops in the rain tanks and precipitation collected in stormwater channels. Rooftop-harvested rainwater is less polluted with chemical and microbial contaminants than stormwater, which mobilizes accumulated pollutants from the ground (i.e., from motor vehicles, animal wastes, and lawn maintenance). In addition to precipitation, urban runoff from landscape and agriculture irrigation, car washes and wash down of grounds also contribute to stormwater in metropolitan areas (Figure 1). During dry-weather conditions, urban runoff is the main source of stormwater in storm drain system. In many cities, the underground storm channels have connectivity with groundwater through seepage. However, the contribution of the groundwater to the stormwater flow is highly variable and poorly quantified. Cross contamination of stormwater and sewage due to aging infrastructure, poor design, and poor implementation has also been reported,[11,12] where the degree of seepage and exchange vary significantly from city to city (Figure 1). The diversity of stormwater sources leads to considerable variability in both water quality and quantity.

Microbial Pathogens

Stormwater quality studies have traditionally focused on physiochemical parameters, nutrients, heavy metals, and micropollutants due to their accumulative environmental damaging effects on the receiving waters. The National Stormwater Quality Database in the U.S. collected more than 10 years of stormwater monitoring data from the National Pollutant Discharge Elimination System MS4 (municipal separate storm sewer system) stormwater permit program, which includes about 9000 rain events across the U.S. with information of more than 125 different stormwater quality constituents. Fecal indicator bacteria (FIB, i.e., *Escherichia coli* and fecal coliforms also known as thermotolerant coliforms) are the only microbial data collected in the database.

MS4 stormwater permit program data from the U.S. and a large volume of international literature consistently showed very high concentrations (i.e., >10,000 CFU/100 mL) of FIB in stormwater and in surface water receiving storm runoff. FIB concentration is influenced by the intensity of watershed development, stream flow, and antecedent precipitation.[13] But the first-flush loading of FIB is not always seen, indicating that the FIB may have an ecological origin rather than a direct fecal source.[13] The adequacy of using FIB to indicate human pathogens in stormwater has been

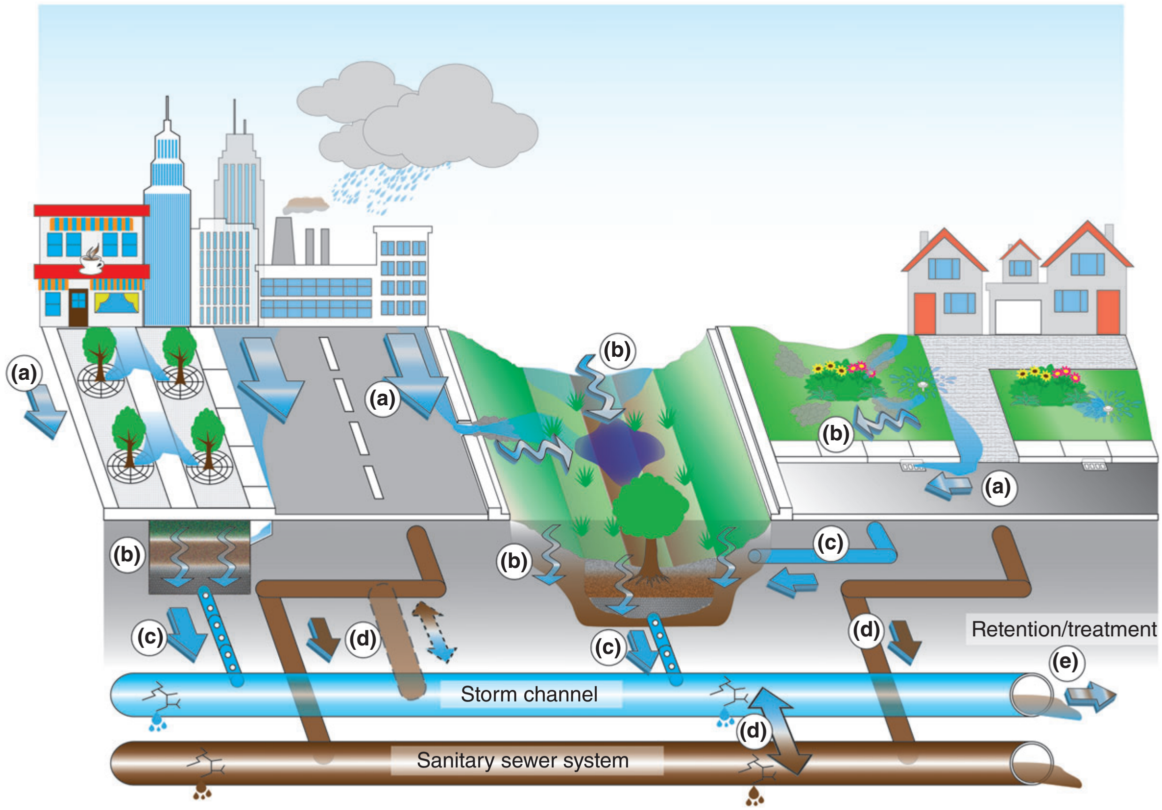

FIGURE 1 | Schematic illustration of urban stormwater generation and harvesting scenarios. Precipitation or irrigation runoff from impervious surface is collected either directly to underground storm channels through street gutters (a) or infiltrated through sandfilters/biofilters (b) and entering the channels through the perforated underdrains (c). The close approximation between sanitary sewer lines and underground storm channels may cause cross contamination of stormwater with sewage due to aging infrastructure, poor design and poor implementation (d). Stormwater harvesting is achieved by piping the stormwater from main channel (e) to retention/treatment systems such as artificial wetlands and recharge basin.

questioned.[14,15] Numerous studies have been carried out to identify the sources of fecal contamination in waters with high concentrations of FIB using microbial source-tracking technology in order to better understand the microbiological health risk associated with stormwater.[15]

The quantitative data on human pathogens in stormwater are sparse, which is largely due to the difficulties of detecting and quantifying pathogens. Pathogen detection requires concentration of large volumes of water. The presence of relatively high concentrations of suspended solids (>2000 mg/mL)[16] and grease (>1000 mg/mL)[17] in stormwater significantly challenges the technology that can be applied for concentration and recovery of pathogens. There are also large amounts of hydrocarbons and heavy metals (>5 mg/L) that inhibit the molecular detection method used to identify and quantify a specific pathogen.[16] Several reports have indicated that microbial pathogens are more frequently detected in the receiving water near storm drains than in the stormwater itself due to the technical challenges in recovering pathogens from stormwater directly (Table 1).

In spite of the lack of consistent and quantitative data, numerous studies have shown the presence of microbial pathogens, including *Giardia*, *Cryptosporidium*, toxic *E. coli*, *Salmonella*, *Campylobacter*, and human viruses, in stormwater and surface water receiving storm runoff (Table 1). Although rooftop-harvested rainwater is well recognized to have better water quality than harvested stormwater in many studies, it is not free of microbial pathogens. Pathogens including *Giardia*, *Cryptosporidium*, *Salmonella*, *Camplyobacter* and *Legionella pneumophila* were found in rainwater tanks tested in Australia, Denmark, France, New Zealand, UK, and USA (Table 1).

To embrace the concept of stormwater harvesting for human uses, it is of paramount importance to remove human pathogens in stormwater during the practice, which will prevent the potential outbreaks of infectious diseases (Figure 2).

TABLE 1 | Microbial Pathogens in Rain Tank Water, Stormwater, and Receiving Water Near Storm Drains

Pathogens	% positive (total samples) *or* concentration/L			References
	Rainwater[a]	Stormwater[a]	Receiving water[a]	
Cryptosporidium spp.	0% (20)			18
	0% (214)			19
		37% (59)		20
			77% (120), 0.04–1.5 oocysts	21
	35% (17)			22
	4% (125)			23
		40% (20), 0.07–0.31 oocysts		24
Giardia spp.	19% (21)			25
	8% (214), 0.6–3.6 cysts			19
	13% (24), 120–580 cysts			26
	0% (20)			18
		19% (59)		20
	0% (17)			22
	7% (14)			27
	0% (125)			23
		40% (20), 0.05–3.77 cysts		24
	50% (2)			28
Camplyobacter spp.	4% (27)			25
	0% (214)			19
	17% (23), 5–110 cells			26
	1.5% (67)			29
	13% (42)			18
		3% (59)		20
		94% (54), <1–43 MPNIU[b]		30
			96% (23)	12
	12% (17)			22
	0% (142)			31
	37% (24)			32
	0% (125)			23
Legionella spp.	27% (27)			25
	4% (214), 60–170 cells			19
	15% (67)			29
		2% (54), 10,000 cells		30
	71% (7)			22
	7% (14)			27
	0% (418)			31
Salmonella spp.	11% (27)			25

TABLE 1 | Continued

Pathogens	% positive (total samples) *or* concentration/L			References
	Rainwater[a]	Stormwater[a]	Receiving water[a]	
	7% (214), 65–380 cells			19
	4% (24), 7300 cells			26
	3% (67)			29
	0% ($n > 60$)			18
			32% (22)	12
	0.1% (798)			31
	0.9% (125)			23
Adenovirus			65% (23)	12
		3% (59)		20
		91% (23)		33
			61% (18), 4100–38,000 gc[c]	34
			42% (52), 250–7000 gc	35
			29% (14), 1500–6500 gc	36
			290–400 gc	37
			9240–12,400 gc	38
			33% (12), 880–7500 gc	14
			52% (21)	39
			16% (114), 220–60,000 gc	40
		2% (61), 30–8430[d] gc		41
Norovirus			75% (52), 135–19,000 gc	35
			1270–147,000 gc	42

[a] Rainwater represents rooftop-harvested rainwater stored in rainwater tank. Stormwater represents stormwater runoff collected from storm drains, ditches, or stormwater outfall. Receiving water represents water samples collected from surface water that are affected (or potentially affected) by stormwater discharges.
[b] MPNIU is most probable number of infectious units. The range is reported as lower detection limit value and maximum observed value.
[c] gc is genome copy.
[d] Represents range of detection limits for the 60 non-detected samples. The only positive sample is within this range.

MICROBIAL REMOVAL DURING STORMWATER HARVESTING

Treated stormwater is suitable for various purposes depending on the treatment technology applied. Non-potable applications such as landscape irrigation, car washing, and toilet flushing (Figure 2) are the most common type of end-uses practiced in different countries.[20,43] Applications that involve much closer contact with the water, such as showering and swimming pool filling, are theoretically possible if the stormwater is treated adequately to ensure human safety.

The concept of utilizing stormwater as non-potable water supply is not new but has only recently received appreciable attention.[43] For example, the Santa Monica Urban Run-off Facility (SMURF) in California, USA, has been harvesting/treating urban runoff from its main stormwater drains for landscape irrigation and toilet flushing since 2001. Rainwater and stormwater have been used in various places in Australia for various non-potable purposes for decades but are not well documented or studied. Chlorination and UV disinfection are often used for disinfection to ensure the safety of stormwater applications.[20] The

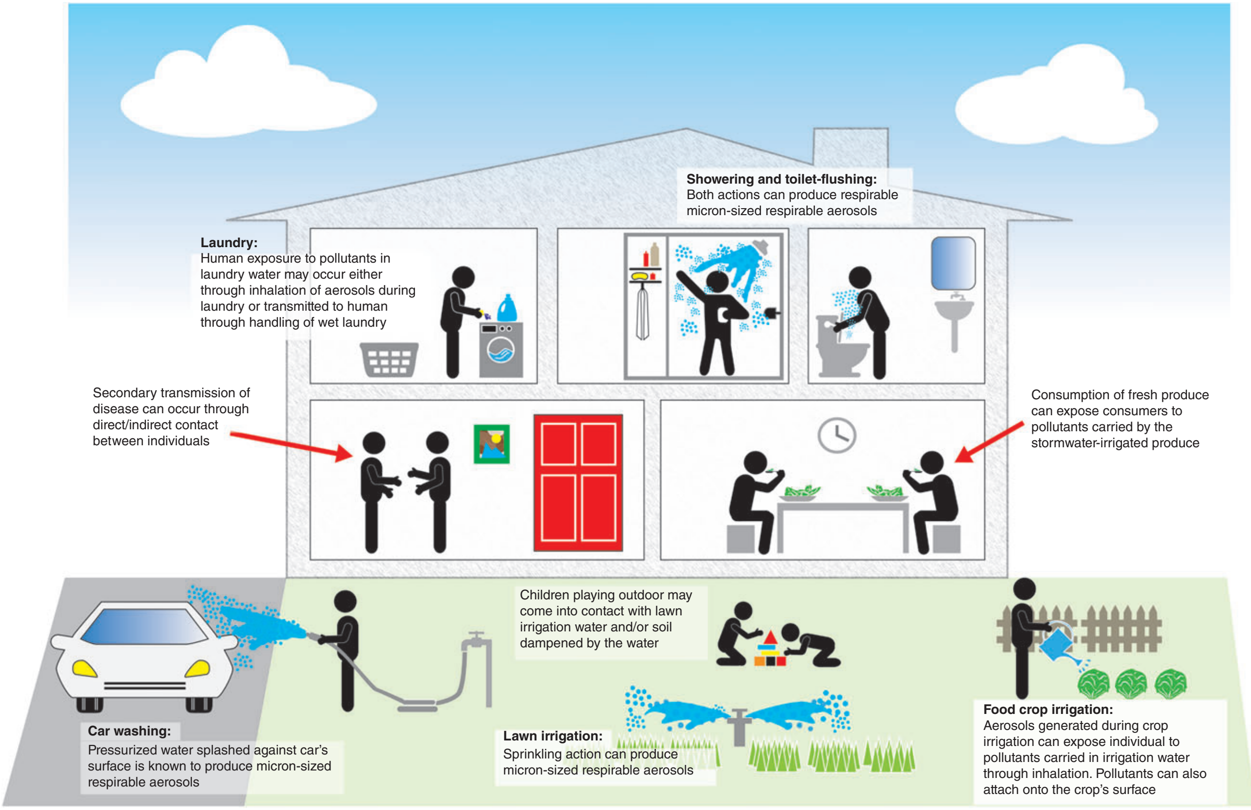

FIGURE 2 | Schematic illustration of route of human exposure to stormwater pollutants during different stormwater use. Inhalation of aerosols during laundering, showering, toilet flushing, car washing, lawn and home garden irrigation represents the major route of human exposure to pollutants carried in the stormwater, while consumption of fresh produce irrigated by stormwater exposes human to pollutants through ingestion. Secondary transmission during person-to-person contact also contributes to an important portion of human exposure.

modern stormwater harvesting practice focuses on using low-impact development (LID), natural systems, or green engineering for treatment. With subtle differences, all three terms describe similar approaches for managing stormwater. The U.S. EPA defines LID as 'an approach to land development (or re-development) that works with nature to manage stormwater as close to its source as possible'.[44] This differs from the traditional engineering practice of harvesting stormwater using constructed pipes, tanks and concrete structures because LID adds the direct benefits of environmental preservation. Rain tanks, artificial wetlands, biofilters/bioswales are some examples of the LID systems.

There have been a number of reviews focusing on stormwater treatment technologies, costs, and economical trade-offs.[45,46] These previous reviews summarized the state of technology at the time for removal of nutrients and chemical contaminants in stormwater treatment systems and pointed out that there was a lack of information on removal of microbial pathogens.

Rainwater Harvesting System

Rain tank is the earliest LID system used to capture rainwater for later use and has been reviewed extensively elsewhere.[29,47,48] While many variations of rainwater harvesting systems have been developed, all are made up of the same basic components, which include a collection area, a conveyance system, a first-flush diversion/screening system, and a storage system. Rainwater is most commonly collected from the rooftop of buildings before it reaches the ground. While rooftops and rain gutters are less contaminated (at least for most cases where atmosphere deposition is not the major contributor of pollutants), they are subjected to the accumulation of tree litters, atmospheric deposits, animal feces (e.g., birds, squirrels), and traces of weathered roofing materials (e.g., heavy metals).[47] Immediately after a rain event, these contaminants are rinsed off in large amount, producing a rather polluted initial runoff from the first 0.25 cm of rain. These 'first flushes' are usually discarded in the modern design of rain tanks using diverters to reduce pollutants in the collection tank. In addition, leaf screens and mesh filters are usually employed before the storage tanks to prevent introduction of debris and pests (e.g., mosquitoes) into the tank. Intuitively, the water quality of harvested rainwater is highly variable. There is essentially no direct engineering measure for the reduction of microbial pathogens in the rain tank. The fate of the microbial pathogens and FIB in rain tank involves both natural decay and regrowth due to complicated environmental conditions. The biofilm growth in the rain tank is controversial; some suggested the benefit of biofilm at adsorbing trace metals and other pollutants,[49] while others indicated the risk of supporting the survival and growth of human pathogens.[50] There are several reports of presence of pathogens and FIB in the rain tank water (see Section *Microbial Removal During Stormwater Harvesting*) but no report on pathogen fate in the rain tank. The Australian Guidelines 23 for stormwater harvesting and reuse relied on the ratio of FIB–to-pathogen in human sewage to determine the pathogen reduction for use of rainwater.[20] The new field data that are being collected throughout the world will likely improve our current understanding of the fate of pathogen in rain tank and the health risk associated with uses of rainwater.

Retention Ponds and Wetlands

Retention ponds are constructed basins that are mainly used to mitigate the peak flow during rain events. Constructed wetlands are similar to wet retention ponds that incorporate plants in shallow pools. Besides peak flow mitigation, wetlands are also used for stormwater quality control. Typical wetland designs include a deep pond at the inlet (sediment forebay) to decrease the water velocity and sediment load, followed by shallow water areas with wetland plants, and outlet structures to control the hydraulic regime of the wetland. For the proper functioning of the system, a permanent flow condition is required to support the growth of wetland plants.[51,52]

The transport and fate of microbial pathogens have been extensively studied in constructed wastewater wetlands.[53,54] However, very few (if any) similar studies have been carried out in stormwater wetlands, which is likely due to the lack of tools for detecting low concentration of human microbial pathogens in stormwater. Researchers have relied on FIB or indictor viruses to understand the fate of microbial pathogen in stormwater wetlands, in spite of all the well-recognized disadvantages of this approach, such as the regrowth of indicators under favorable conditions and the contribution of nonhuman sources.[55] Sedimentation, sunlight exposure, water temperature, and the adsorption to biofilms are considered as main factors governing the removal of microbial pathogens in wetlands. Bavor et al.[56] indicated that the establishment of vegetation could improve the removal of FIB through the enhanced sedimentation. In contrast, Hathaway et al.[57] concluded a lower plant coverage in wetland improved FIB removal due to high exposure to sunlight. The variability observed is likely caused by the size of the wetland, the residence time, the quality of influent, and local conditions. Residence time is perhaps the most important factor in controlling the removal rates of microbial pathogens in the wetland, but is ignored by many studies. Struck et al.[58] found the removal of FIB generally followed the first-order decay model as a function of time. The decay rate is significantly faster in the first 50 h over the 100-h study period. These results imply that neither sedimentation nor sunlight exposure will be sufficient to treat the rapid flow of stormwater through the wetland when the residence time is less than 50 h, especially during a heavy rain event.

According to the International Stormwater BMP Database (ISBD) 2014,[59] the average removal rate of fecal coliform, *E. coli*, and *Enterococcus* in the five wetlands investigated were 91, 53, and 61% (Table 2). Similar or slightly higher rates of removal are also reported in two Australian studies (Table 2). Based on the current data, none of the wetland effluent can meet the microbial water quality criteria for primary contact recreation (30-day geometric mean for *E. coli* <126 CFU/100 mL, *Enterococcus* < 35 CFU/100 mL), which indicates potential health risks are associated with the wetland-treated water. However, others argue that the low removal rate of FIB is due to its regrowth in wetlands. The behavior of pathogen in wetland can be significantly different than that of the FIB. So far, there is no reported study on specific pathogen removal in the stormwater wetland, which highlights the need for future field scale studies to address this gap.[20]

Biofilters

Biofilters are primarily designed to treat and attenuate stormwater runoff for a specified water volume.[44] While they provide limited flood retention capacity compared to wetlands due to their relatively smaller footprints, biofilters easily enable stormwater treatment in urban settings and established communities. The typical designs of biofilters (e.g., grassed channel, dry swale, wet swale, or bio-swale) allow stormwater to flow through the systems horizontally or vertically. Pollutants in the stormwater are removed through biological uptake by plants and biofilm, filtration through a subsoil matrix, and/or infiltration into the underlying soils. In recent years, several studies have been

TABLE 2 | Microbial Removal Efficiency of Stormwater Water Treatment Systems

Treatment	Microorganisms	Removal Efficiencies	Country of Study Sites	References
Wetland	*E. coli*	33–96%	U.S.	57
		53%	U.S.	59
	Enterococci	1 $\log_{10}$	Australia	60
		61%	U.S.	59
	Fecal coliform	56–98%	U.S.	57
		91%	U.S.	59
		0–2 $\log_{10}$	Australia	56
Wet retention pond	*E. coli*	46%	U.S.	61
	Fecal coliform	54–99.8%	Lab study	62
		84%	U.S.	59
		70%	U.S.	61
		0–0.5 $\log_{10}$	Australia	56
Biofilter	*E. coli*	79–93%	Australia	63
		3 $\log_{10}$	Israel	64
		1–2 $\log_{10}$	Lab study	65
		97%	Lab study	66
	Enterococci	79–92%	Australia	63
	Fecal coliform	2 $\log_{10}$	Israel	64
	C. perfringens	>97%	Australia	63
	F-RNA coliphage	1–5 $\log_{10}$	Lab study	65
		82%	Lab study	66
		1–3 $\log_{10}$	Australia	63
	Adenovirus	<1 $\log_{10}$	Australia	63

conducted to understand the fate of microbial pathogens in the biofilters. Using laboratory-scale biofilters, these studies showed that plants play a crucial role in the removal of microbial pathogens, yet the mechanisms of interaction between plants and the seeded indicator bacteria and viruses are still not clear.[63,65] Traditional filter media, such as sand, soil, zeolite, and anthracite, are often used for biofilter construction; improved microbial pathogen removal efficiency were observed in media incorporated with Cu and Zn compounds.[67] Studies also showed that the microbial pathogen removal efficiency is significantly affected by the dry and wet weather conditions. Adding a submerged zone at the bottom of the biofilter improves the microbial removal efficiency of biofilters because it prevents the formation of fine fissures and macro pores during extended dry period.[65,68] Overall, these myriad designs and operational characteristics of biofilters have led to inconsistent pathogen removal efficiencies as reported across the literature (Table 2). Human viral pathogen was only tested once in a biofiltration laboratory-scale study and showed less than one log removal through the system.[69] It should be cautioned that most of these conclusions are based on laboratory-scale studies due to the lack of field studies.

Cost and Water Quality

The cost of water treatment often increases with improvement in microbial quality of the finished water. Additional treatments including microfiltration, UV radiation, and chlorine disinfection can be included to further reduce pathogen loads in finishing water. Most of the current cost estimates for stormwater treatment, however, do not include the cost of disinfection. Among 12 stormwater harvesting cases studied in New South Wales (NSW), Australia, only two included disinfection processes into the cost estimation. The cost structure of stormwater harvesting is highly complex and variable, which includes capital costs, recurrent costs, and water quality benefits unit costs. Although it is difficult to compare between countries and regions, recent studies in NSW have indicated that the average levelized cost for treated stormwater is higher than the mains water prices in the Sydney Greater Metropolitan Area in 2005–2006.[70] An evaluation of the water supply options for Melbourne that compares traditional supply sources and alternative sources indicates stormwater harvesting as the lowest cost option for greenfield development among options including wastewater recycling and rainwater harvesting.[71] However, the finishing stormwater quality is not intended for direct human contact and did not include the cost of additional treatment beyond wetland treatment. Dandy et al.[72] used City of Salisbury, South Australia, as a case study to demonstrate the framework and tools needed for estimating a number of stormwater harvesting options. The report emphasized the importance of incorporating a broader multi-criteria analysis to economic, environmental, and social criteria.

RISKS OF USING STORMWATER

Human Health Risk

It is important to recognize that all human activities involve risk. It is appropriate to compare the risk of a new water practice with existing standards or water supplies. In terms of the risk associated with human use of harvested stormwater, health risk can be defined as actual risk, perceived risk, and estimated risk. Through analyses of these risks, decisions on water uses can be made to advance and refine the practice.

Actual Risk

The actual risk of stormwater use can be expressed as the number of people whose health statuses are compromised (i.e., hospitalized) through using treated stormwater. While epidemiological studies may offer a glimpse into the actual risk of such practice, the results can be compromised by manifold of uncertainties. For example, people who use treated stormwater can get ill from many different sources of contamination, such as eating contaminated food in a restaurant or through secondary infection from another person. There are also challenges in conducting ethical experiments that can validate the actual risk. Moreover, stormwater harvesting practice is still in its early development and collection of the relevant epidemiological data is inevitably difficult, if not impossible.

Perceived Risk

Perceived risk of stormwater varies widely from person to person due to the lack of understanding of stormwater harvesting and effective public education.[73,74] This has resulted in conservative stormwater applications that are familiar to and more acceptable to the public (e.g., irrigation). This also compares with the public's perception of wastewater reuse, where indirect potable reuse of recycled wastewater is usually fervently opposed by the public when essential information about the safety of the water is not communicated effectively.[75] However, the situation can be the opposite if the risks are communicated transparently with all the stakeholders involved, which was the case for the renowned Orange County Water District's indirect potable use of treated wastewater.[76]

Estimated Risk

Most often, the variation of perceived risks among individuals can be reduced through estimating and communicating the risk objectively. Estimated risk is a technical assessment of risk through the collection and application of scientific facts that are relevant to the risk. For example, the potential risk of stormwater use is first identified by an understanding of the hazards in stormwater. The degree of exposure to these hazards can differ from one type of water application to another, marked by the different levels of water contact (i.e., toilet-flushing vs. showering), frequency of the water application (i.e., daily vs. weekly), and also disease transmission routes (i.e., breathing contaminated aerosols vs. ingesting contaminated water/food, see Figure 2). Finally, the risk is determined by the pathogen's ability to reach infection site in human body, the pathogen's potency to induce an infection, and an individual's immunity against the pathogen.

The quantitative microbial risk assessment (QMRA) has been adopted to provide a scientific basis to model these risks.[73] Estimated risks of water applications are generally compared to the acceptable drinking water risk benchmarks recommended by U.S. EPA and WHO for safety assurance. These benchmarks are set at threshold of ≤1 infection case/10,000 persons-year by U.S. EPA and ≤1 DALY/1,000,000 persons-year by WHO.[77,78] Table 3 shows a summary of risk estimates associated with the applications of untreated rooftop-harvested rainwater and treated urban stormwater from four QMRA studies. Based on these risk estimates, harvested stormwater is only suitable for toilet flushing, whereas rooftop-harvested rainwater is suitable for various applications including toilet flushing, showering, and garden hosing. While the absolute risk of using rainwater for food-crop irrigation is questionable, a comparative risk analysis has shown that rainwater-irrigated food-crops present risks that are at least 10-fold lower than food-crops irrigated using reclaimed wastewater, which is a common agricultural practice.[80,82] Overall, these risk assessments indicate

TABLE 3 | Quantitative Microbial Risk Assessment of Human Health Risks Associated with Use of Rooftop-Harvested Rainwater and Stormwater

Type of Water	Applications	Target Pathogen	Exposure Route	Risk Estimate: Infection cases/10,000 persons-year[a]	Risk Estimate: DALYs/1,000,000 persons-year[a]	Frequency of Applications Considered	References
Rainwater	Toilet flushing	*Camploybacter* spp.	Aerosol ingestion	0.00004–1 (0.2)	0.01–400 (70)	Applications are engaged six times per day, but exposure events per year varies from 0–219 times. (based on 0–30% pathogen detection).	79
	Drinking	*Salmonella* spp.	Liquid ingestion	10–53		Applications are engaged daily, but only 18 exposure events per year (based on 5% pathogen detection).	19
		Giardia lamblia		20–130			
	Showering	*Salmonella* spp.	Aerosol ingestion	0.02–0.1			
		Giardia lamblia		0.04–0.2			
		L. pneumophila	Aerosol inhalation	0.003–0.007			
	Garden hosing	*Salmonella* spp.	Liquid ingestion	0.01–0.08		Applications are engaged biweekly, but only five exposure events per year (based on 5% pathogen detection).	
		Giardia lamblia		0.03–0.2			
		L. pneumophila	Aerosol inhalation	0.002–0.006			
	Foodcrop irrigation (including tomatoes, lettuce, and cucumber)	*Salmonella* spp.	Ingestion of contaminated foodcrop	0.3–27 (1–11)	0.2–16 (0.9–7)	Food crops are consumed daily. Every infection case is an illness case.	80
		Giardia lamblia		3–77 (6–55)	0.8–21 (1–4)		
Stormwater[b]	Toilet flushing	Adenovirus[a]	Aerosol inhalation	0.0002–0.01 (0.001–0.002)	0.001–0.03 (0.003–0.005)	Applications are engaged four times daily, totaling up to 1460 exposure events per year.	81
		Norovirus[c]	Aerosol ingestion	0.003–2 (0.005–0.3)	$0–5 \times 10^{-9}$ ($0–1 \times 10^{-16}$)		
	Showering	Adenovirus[a]	Aerosol inhalation	0.0006–21 (0.004–0.6)	0.002–56 (0.01–2)	Applications are engaged daily. Each event lasted for 20 min. Aerosol distributions of hot and cold shower were considered.	
		Norovirus[c]	Aerosol ingestion	1–6,954 (3–430)	($4 \times 10^{-9}–6 \times 10^{-5}$)		
	Foodcrop irrigation (lettuce only)	Norovirus[c]	Ingestion of contaminated foodcrop	1961–9998 (6810–9730)	0.002–140 (0.1–51)	Food crops are consumed 90, 180, or 270 times per year.	

[a] Unbracketed values represent the minimum and maximum of each risk estimate. Bracketed values represent the mean or median values (a range of mean/median is given for risk estimates that covered different scenarios).
[b] Virus concentration for stormwater were inferred from data for receiving waters affected by stormwater discharge due to the lack of reliable virus quantification method for stormwater.
[c] Norovirus is assumed to be in monodispersed form.

that potable uses of rainwater, and more so for stormwater, are not advisable unless adequate risk management strategies (e.g., additional water treatment) are undertaken. The outcome of QMRA can also be presented in a more practical format, such as 'tolerable pathogen concentration in stormwater' and/or 'treatment technologies/log removal required' for each specific stormwater application (i.e., as used in the Australian Guideline 23).[20] These formats are calculated based on a desired health baseline, such as the WHO's $\leq 10^{-6}$ DALYs threshold. It should also be noted that these risk estimates contain caveats and data gaps that are intrinsic to most QMRA models. Furthermore, water systems fed by stormwater are also prone to harbor opportunistic pathogens such as *Legionella spp*. (as found in rainwater tanks). The health risks of opportunistic pathogens have not been evaluated. The QMRA process thus helps to guide additional research and data collection to further improve the risk estimates.

Ultimately, perhaps the most significant contribution of QMRA is not the quantified risk value but the linking of relevant sciences together during the risk modeling process to gain a better conceptual understanding of the risk.[83] This also empowers the stakeholders with confidence in using stormwater and the knowledge to troubleshoot issues related to stormwater harvesting systems.

Environmental Health Risk

Many aspects of environmental health risks have been addressed in the previous reviews. The negative impact of over-harvesting of stormwater that results in reduction of stream baseflow[84] is well documented. For that matter, the Australian guidelines for stormwater harvesting have suggested for a tiered approach to investigate the risk of overextracting stormwater.[20] Based on the guidelines, any stormwater harvesting schemes that extract more than 10% of the annual runoff within their catchment area are required to conduct detailed investigation for reducing any potential environmental risks. Urban landscape, golf course and home garden irrigation using stormwater may also negatively impact soil salinity, chemical composition, and plant health (i.e., chlorine). These impacts tend to be chronic and accumulative and will require additional years of experience to collect additional data.[70]

Another potential environmental health risk that has not been well recognized may be caused by the harvesting infrastructure (i.e., stormwater harvesting wetlands). These wetlands were constructed to trap toxic chemicals, heavy metals, and pharmaceuticals in the stormwater. The long-term accumulation of these chemicals and toxins in the wetland can pose hazards to wildlife.[85] There is also anecdotal evidence suggesting that stormwater harvesting wetlands can become a breeding ground for pathogenic microbes that infect waterfowls and other wetland residents.[86] The highly eutrophic stormwater wetland may also encourage the growth of weeds, pests and invasive species, negatively impact local biodiversity.[87] Little data have been collected in this aspect of research since stormwater harvesting wetlands are still at their infancy. The risk of creating an ecological trap, where wildlife is attracted to a potentially dangerous situation, may also have legal implications. Many countries have laws which confer liability on individuals or organizations who act to the detriment of waterbirds, whether intended or not (e.g., the USA's Migratory Bird Treaty Act of 1918 [amended 1974]).

BENEFITS OF USING STORMWATER

Human Health Benefits

The most direct human health benefit from stormwater harvesting for local use is to reduce the pollutant loads to the receiving water that is used for human recreation. The impact of stormwater runoff to coastal water quality degradation is well documented.[88] In fact, the California Department of Public Health advises beach users to avoid contact with ocean and bay waters for a period of 3 days (72 h) after rainfall ends due to contamination of ocean and bay water by urban runoff.[89] Elevated health risks were found among beachgoers recreating at sites polluted by stormwater runoff in comparison with those away from the storm drains.[90] QMRA also indicates elevated human health risks from exposure to stormwater-affected receiving waters.[91–93] Stormwater harvesting will reduce the loading of pollutants to the recreation water and effectively avert these hazards.

Stormwater harvesting infrastructures, i.e., rain garden, wetlands, also provide indirect human health benefit by providing new relaxation and recreational sites, which have well-documented benefit for both human body and minds.[94] The third human health benefit of using harvested stormwater to supplement the traditional water supplies in household is the reduction of human stress on water shortage and the improvement of livability of the home environment.[95,96]

Environmental Health Benefits

The best-known environmental benefits of stormwater harvesting are for stream hydrology and ecology restoration. Since both subjects have been discussed extensively in the literature, they are not reiterated in this paper. Another benefit that has been largely ignored but equally important is the direct benefit from construction of new wetlands for stormwater treatment. This is non-trivial, particularly with the backdrop of global wetland decimation. Roughly half of the world's wetlands have disappeared since 1900.[97–99]

Intuitively, it may seem unlikely that stormwater treatment wetlands could make an impact on a global scale. Nonetheless, their potential contribution may be surprisingly significant in certain areas. This is perhaps best illustrated by the situation in Melbourne, Australia. By 2013 there were about 435 constructed wetland systems used in Melbourne for treating stormwater and many more have been slated for construction.[100,101] The number of individual ponds comprising a system varies but is generally in the order of 3–10, with the average pond covering about half a hectare.[102] This clearly represents a large amount of wetland reconstruction for a city that has drained most of its natural wetlands for development.

These stormwater wetlands constructed for water treatment are not substitutes for natural wetlands, although habitat considerations are often incorporated into the design.[103–105] The location of the wetlands in a landscape context—for example, with respect to the movement of migratory species—is also likely to be a relevant factor in assessing their biodiversity value. In sum, despite the fact that wildlife habitat is often promoted as a benefit of stormwater treatment wetlands,[85] there have been very few attempts to date to determine their broader involvement in biodiversity conservation even at reasonably local spatial scales.

A recent study on waterbird use of Melbourne's stormwater treatment wetlands[102] found that on a per-area basis these wetlands tend to support more individual birds as well as species than natural wetlands in south-eastern Australia.[106] In addition, they are located in areas where wetlands are critically needed for many species. Numerous Australian duck species, for example, breed on ephemeral inland wetlands and use permanent coastal wetlands as non-breeding refuges,[107–110] but many of these wetlands have been drained. There is more to wetland biodiversity than avifauna, Jenkins et al.[111] have shown that stormwater wetlands can support diverse aquatic macroinvertebrate and vegetative communities. Herbaceous vegetative communities harvested from stormwater wetlands also hold potential as sources of energy, fiber, and other commodities.[112] The ecological roles and benefits of stormwater wetland will always be regionally specific, but the existing examples around the world suggest that these systems at least have the potential to be of direct worth from a biodiversity conservation perspective.

CONCLUSION

Stormwater has the potential to be used as a new water resource to meet human demand. The suitability of its application depends on the treatment technologies employed, the concentration and type of contaminants carried in the stormwater, and the designated use. Microbial pathogens are of the most concern when water comes in direct contact with humans through showering, toilet flushing, and consumption of stormwater-irrigated food-crops. The disease risks of using treated stormwater can be assessed through QMRA. The current risk estimates suggest that the passive stormwater treatment provided by LIDs is not adequate to support applications of stormwater beyond lawn irrigation and toilet-flushing. Adoption of the QMRA approach can assist with decision making and risk management. This may offer degrees of confidence for stakeholders to adopt the stormwater harvesting practice.

Pollution mitigation through harvesting stormwater can benefit human health by reducing human exposure to pollutants during water recreation, and benefit environmental health through preventing urban stream syndrome. Stormwater harvesting wetlands also offer new habitats for birds and other wildlife. Poor management of stormwater harvesting, however, can result in overdrawing of natural baseflow and may also endanger wildlife that gather at regions of treatment wetlands with concentrated pollutants.

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