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Reevaluation of health risk benchmark for sustainable water practice through risk analysis of rooftop-harvested rainwater

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ABSTRACT

Health risk concerns associated with household use of rooftop-harvested rainwater (HRW) constitute one of the main impediments to exploit the benefits of rainwater harvesting in the United States. However, the benchmark based on the U.S. EPA acceptable annual infection risk level of $\leq$1 case per 10,000 persons per year ($\leq 10^{-4}$ pppy) developed to aid drinking water regulations may be unnecessarily stringent for sustainable water practice. In this study, we challenge the current risk benchmark by quantifying the potential microbial risk associated with consumption of HRW-irrigated home produce and comparing it against the current risk benchmark. Microbial pathogen data for HRW and exposure rates reported in literature are applied to assess the potential microbial risk posed to household consumers of their homegrown produce. A Quantitative Microbial Risk Assessment (QMRA) model based on worst-case scenario (e.g. overhead irrigation, no pathogen inactivation) is applied to three crops that are most popular among home gardeners (lettuce, cucumbers, and tomatoes) and commonly consumed raw. The infection risks of household consumers attributed to consumption of these home produce vary with the type of produce. The lettuce presents the highest risk, which is followed by tomato and cucumber, respectively. Results show that the 95th percentile values of infection risk per intake event of home produce are one to three orders of magnitude (10^{-7} to 10^{-5}) lower than U.S. EPA risk benchmark ($\leq 10^{-4}$ pppy). However, annual infection risks under the same scenario (multiple intake events in a year) are very likely to exceed the risk benchmark by one order of magnitude in some cases. Estimated 95th percentile values of the annual risk are in the 10^{-4} to 10^{-3} pppy range, which are still lower than the 10^{-3} to 10^{-1} pppy risk range of reclaimed water irrigated produce estimated in comparable studies. We further discuss the desirability of HRW for irrigating home produce based on the relative risk of HRW to reclaimed wastewater for irrigation of food crops. The appropriateness of the $\leq 10^{-4}$ pppy risk benchmark for assessing safety level of HRW-irrigated fresh produce is questioned by considering the assumptions made for the QMRA model. Consequently, the need of an updated approach to assess appropriateness of sustainable water practice for making guidelines and policies is proposed.

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1. Introduction

Increasing scarcity of readily available water and energy resources, population growth, aging water infrastructures, and extreme weather phenomena have presented daunting challenges to global water securities in recent years (Grant et al., 2012; Vorosmarty et al., 2010). Sustainable water resource management, such as wide-scale adoption of low-impact development (LID) and green infrastructures, could be one of the key solutions to alleviate these heavy burdens (Roy et al., 2008). LIDs, for example, rain gardens, vegetated rooftops, permeable pavements, and rainwater tanks, are decentralized, onsite stormwater management tools which can be applied to both existing developments and new ones for preserving and/or restoring pre-development hydrological features and reducing pollution loads to aquatic environments. In other cases, the collection of rainwater using LIDs as an additional water resource has been a partial solution to alleviate water supply burdens in arid countries like Jordan and Tunisia (Abu-Zreig et al. 2013). Harvesting rainwater from rooftops to supplement household or local water needs represents one of the simplest, yet effective LIDs that define sustainable practice suitably. Here, a distinction is made between harvested rainwater (HRW) and stormwater. HRW is rainwater that falls onto rooftop of buildings and is collected directly into a rain storage tank. Stormwater, on the other hand, is rainwater that falls onto catchment areas such as roads and pavements, and therefore collects many more pollutants before discharge into any stream or stormwater collection system. Extensive use of HRW as alternative water supplies is not only limited to arid countries, but has been a common trend in cities of many developed countries such as Australia, Germany, and Japan. For example, many urban regions in Australia harvest rainwater from rooftop for both potable (less common) and non-potable purposes (Sinclair et al., 2005).

However, adoption and scale of rainwater harvesting practice vary from place to place, and are dependent on the awareness of the public as well as legislative, financial, and technical support programs towards the practice (Abu-Zreig et al., 2013; Ward et al., 2013). Ward et al. (2013) studied the water-user perceptions towards rainwater harvesting in UK, where water users expressed an overall positive receptivity of using HRW for a wide range of uses (but less positive receptivity towards water use of more personal contact). They concluded that the receptivity of water users towards HRW in developed countries is high in places with persistent water issues (e.g. limited water resources), where water reuse is becoming an accepted and normal part of everyday life.

In the United States, health risks associated with using HRW represent one of the greatest concerns for the public, who have accustomed to using potable water for every end-use and deemed any lesser quality water unsafe. Skeptical city officials who adopt rainwater tanks do not recommend the use of stored rainwater for household purposes, opting to discharge them after storm events as a mean to manage/reduce stormwater pollution (City of Los Angeles, 2011). Lack of governmental guidelines for safe usage of HRW is a main contributing factor for varying perspectives across different agencies in the nation regarding the best practice to utilize their stored rainwater (Kloss, 2008). As of the end of 2012, only 12 out of 50 states in the U.S. have their own rainwater-harvesting laws (National Conference of State Legislature, 2013) that deal with different aspects of the practice (encouraging or prohibiting the practice, and/or restrict HRW usage options, etc). More recently, there are also a number of local governments in the cities of Atlanta, Portland, and Cincinnati who changed their local codes to allow for rainwater uses. These changes were met by resistance from government-run drinking water providers in fear that wide-scale adoption of rainwater harvesting practice will result in community revenue loss on their part. This trend shows the diverse opinions at both state and local level regarding rainwater harvesting and also the lack of scientific studies to support the practice (Roy et al. 2008).

It is apparent that the current water policy or lack of an adequate water policy in the U.S. has obstructed the progress of sustainable water practices. Transition of water management have been slow due to the lack of support for adopting new standards that conflict against existing (but often outdated) standards, which were established decades ago. Sustainable water practices such as application of HRW for various end-uses often find themselves disadvantaged to be benchmarked against stringent standards such as the safe drinking water standards. The science behind the establishment of the latter was based on risk assessment paradigms, but this risk-based approach has seldom been applied to other sustainable water practices for non-potable uses in the U.S. It is therefore proposed to guide sustainable water practices using the same strategy, where risk assessment serves as the main tool to answer the appropriateness of each practice (Fewtrell and Kay, 2007).

Putting this into context, urban agriculture in densely populated cities such as New York City is rapidly growing due to the adoption of LIDs to manage stormwater, and the recognition of the long forgotten idea of using HRW for irrigating crops (Design Trust for Public Space, 2013). However, most HRW quality reported in literature did not comply with the U.S. EPA safe drinking water standards (Abbasi and Abbasi, 2011). HRW collects chemical pollutants from dry deposits, microbial pathogens from feces of birds, rats and other wild animals resting/nesting on the rooftops (Simmons et al. 2001). These pathogens washed into the storage tank by rain could survive in the tank and potentially transmitted to the HRW end-users. Thus, using HRW for irrigating crops could result in (chemical and microbial) contamination of the crops. Epidemiological data have indicated that foodborne disease outbreaks are most prominent where there are continuing sources of infection, for example, serving of contaminated food in restaurants (Todd et al., 2007). If restaurants in New York City decided to use their city-grown HRW-irrigated crops for preparation of raw salads, there exist risks of foodborne disease outbreak. Nevertheless, in a comparative analysis, prior to the rise of urban agriculture in New York City, people may be eating raw vegetables irrigated with secondary-treated effluents imported from countries with uncertain sanitary practices (Beuchat, 2002). Such dichotomy argues for reevaluation of heath risk benchmark for sustainable water practice.

Here, we attempt to assess the appropriateness of using untreated HRW to water lawns and/or gardens, which is generally practiced in the United States (Kloss, 2008). The National Gardening Association (NGA) estimated in a 2008 survey that 31% of US households participated in food gardening (NGA, 2009). Produce that are eaten raw and fresh, such as salad greens, tomatoes, were recognized vectors for foodborne diseases (Berger et al., 2010; Olaimat and Holley, 2012). It is believed that home gardeners have varying knowledge in terms of how to grow their own produce as compared to the industrial standards. Specific irrigation methods and pasteurization process were usually employed by the latter based on the crops grown in order to reduce the microbial contamination of the produce. However, an average home gardener might lack such awareness and could increase the microbial risks of eating raw home produce. For example, cultivar of tomatoes grown in commercial farms usually has thicker skins to resist against fruit cracking which could create opening for pathogen intrusion (Peet, 1992). Home gardeners lacking the logic behind this might opt to grow thin-skinned tomatoes and over-irrigate them to the point of cracking and thus increase the probability of contamination.

A Quantitative Microbial Risk Assessment (QMRA) framework is applied to assess the potential microbial health risks associated with using HRW to irrigate homegrown-produce in the United States. A probabilistic-based risk model is built to estimate range and likelihood of the risk in question. Three types of produce: tomatoes, cucumber, and lettuce, which are commonly consumed raw as fresh salads, are selected for the study. They are also some of the most popular home produce in the U.S. According to NGA, 86% home gardens grow tomatoes, 47% grow cucumber, and 28% grow lettuce (NGA, 2009). The risk outcomes are then compared to the U.S. EPA risk benchmark of $\leq$1 infection case per 10,000 persons per year (hereafter, represented as: $\leq 10^{-4}$ pppy) and the relative risk is estimated using the comparative risk study of food crops irrigated using reclaimed wastewater.

This study discusses the strength of using comparative risk analysis to assess appropriateness of a water practice independently of risk benchmark set for a different water use (e.g. drinking purpose). It entails the strength (and pitfalls) of risk assessment tools for appraising sustainable water practice.

2. Materials and methods

For the purpose of relative risk estimation, we structured our QMRA risk model in a fashion similar to the risk model used by Hamilton et al. (2006), in which real measurements collected from different sources (as opposed to simplistic assumptions used in a screening-level QMRA) are used to assess the risk of reclaimed water irrigated vegetables. It should be noted that the definition of reclaimed water used in Hamilton et al. refers to non-disinfected secondary effluent of different wastewater treatment plants in Southern California. Thus, their outcomes may be regionally bound. Our risk model incorporates home produce production and consumption behavior of the U.S. population, which are based on nation-wide survey responses from home-gardeners to characterize the risk of whole population.

As with all risk assessment studies, assumptions were made based on worst-case scenarios in our risk model, which are: 1) No environmental inactivation of pathogens on food crops, 2) Overhead irrigation that maximize pathogen exposure to edible portion of the crops, 3) Intake rate of each crop is solely attributed to consumption of raw crops, and 4) Annual risk assumes that home gardeners eat homegrown produce daily (e.g. 365 exposure events annually). These assumptions are also justified through the general understanding that home gardeners would hand-irrigate their crops everyday and would harvest their crops only when they need it (i.e. for preparation of raw and fresh salads immediately after harvesting). And, as a result, the scenario maximizes the water exposure to the edible portion of the crops and minimizes any possible inactivation of pathogens attached on the crops. Considering human habits, this worst-case scenario is not far fetched. Similar assumptions were used by Hamilton et al. (2006), where differences are marked by their use of enteric viruses as the sole target pathogen, and pathogen inactivation varies by duration of environmental exposure.

2.1. *Hazard identification*

The potential microbial hazards of HRW were reported in numerous literature (Crabtree et al., 1996; Simmons et al. 2001; Lye, 2002; Albrechtsen, 2002; Sazakli et al., 2007; Ahmed et al., 2008, 2010; Schets et al., 2010; Vialle et al., 2012) based on the presence of pathogens in rainwater tanks. Pathogens including *Giardia* spp., *Cryptosporidium* spp., *Salmonella* spp., *Camplyobacter* spp., *Legionella pneumophila*, *Clostridium perfringens*, *E. coli*, and enterococci were found in rainwater tanks tested in Denmark, Netherlands, France, Greece, Australia, and USA. It is noted that the HRW sampling methods, pathogen detection and quantification methods used in each study were different from one another. Configuration details of rainwater collection systems, such as installation of first-flush diverters and filtration systems were only reported by a few studies (Gikas and Tsihrintzis, 2012). Due to the large uncertainties of these data, most of them can only serve to identify the potential risks in HRW. The study by Ahmed et al. (2010) is the only literature reporting the concentration of target pathogens in HRW stored in rainwater tanks and detailing the sampling and detection/quantification method of the target pathogens. As such, we used their pathogen concentration data as the generic surrogate for pathogen concentration in HRW.

2.2. *Potential risk*

Pathogens are known to possess different surviving mechanisms and resistance to sunlight, chlorination, etc. For example, *Camplyobacter* can be easily inactivated when exposed to the air, but if introduced into the soil (e.g. through drip irrigation) directly without sunlight exposure, they can survive in the root zone for at least a month (Lynch et al., 2009). Likewise, *Salmonella* is reported to persist up to weeks under greenhouse conditions and even replicate to high densities on the surface of tomatoes (Zhuang et al., 1995). Moreover, internalization of pathogens in fruits/vegetables through capillary action from calyx of fruits into its core, through wound or bruise on its surface was reported in literature (Tyler and Triplett, 2008). Due to the presence of pathogens in HRW, pathogens of different types could attach on the surfaces of home produce or internalize it, depending on the crop types (e.g. exposed or protected) and irrigation method (e.g. overhead irrigation, spray irrigation, drip irrigation) used. The risk is the greatest for home produce with exposed edible portion that are eaten raw as salads (e.g. tomatoes, lettuce, cucumber, etc.).

2.3. *Target pathogens*

Salmonella spp. and *Giardia lamblia* (syn. *Giardia duodenalis*, *Giardia intestinalis)* were used as target pathogens for the analysis due to the availability of data and their importance in waterborne/foodborne human health risk. *Salmonella* and *Giardia* are known to cause gastroenteritis with varying symptoms and are well-recognized to be transmitted through ingestion of contaminated food and water (Haas et al. 1999). Symptoms associated with Salmonellosis are characterized by the abrupt onset of diarrhea, abdominal pain, prostration, chills, fever, and vomiting (Kanarat, 2004). *Salmonella* spp. is also known to cause reactive arthritis and inflammatory bowel disease (Kemmeren et al. 2006). Giardiasis is characterized by abrupt onset of self-limiting, foul-smelling, watery diarrhea, along with abdominal cramps, flatulence, and steatorrhoea (Kanarat, 2004). The abundance of *Salmonella* spp., and *Giardia lamblia* as reported by Ahmed et al. (2010) were first collected using binary PCR assay for the presence of the target pathogens and followed by quantitative PCR (qPCR) for pathogen quantification in positive binary PCR samples. Target genes used for detecting/quantifying *Salmonella* spp. was *Salmonella invA* gene and for *Giardia*, the *Giardia* β-giardin gene, which are known markers for human-pathogenic *Salmonella* and *Giardia*, respectively. *Salmonella invA* gene is essential for the invasion of epithelial cells (pathogenesis mechanism) by *Salmonella* spp. (Galan and Curtis, 1989, 1991; Jepson and Clark, 2001), and also contains sequence unique to *Salmonella* (Rahn et al. 1992). A study by Swamy et al. (1996) tested the presence of *invA* gene in *Salmonella* isolates from different sources, including wastewater and human sources, which were all positive ($n = 245$). β-giardin gene is a conventional target for genotyping *G. lamblia*, which is able to define the genotype A and genotype B found in humans and a wide variety of mammals, and are associated with human infection (Lalle et al. 2005a,b).

Both *Salmonella invA* gene and *Giardia* β-giardin gene were identified in feces of various domestic and wild animals, such as dogs, cats, ferrets, snakes, birds, and possums (Abe et al., 2005; Lalle et al. 2005a,b; Bermis et al. 2007; Volotão et al. 2007; Ahmed et al. 2010). A separate study by Ahmed et al. (2012) had validated the presence of *Giardia* and *Salmonella* (using the two target genes as mentioned) in wild animals that are likely dwelling around rooftops of houses in Australia, including brushtail possums, crows, seagulls, magpies, topknot pigeons, etc. Some of these wild animals are also commonly found in the United States. In the context of Southern California, raccoons, skunks, crows, and seagulls can be sighted dwelling at elevated places, such as trees and rooftops.

As such, the binary PCR and qPCR data from Ahmed et al. provide solid evidence of potential human-infectious pathogens in rainwater. However, the caveats associated with their data were made up by the uncertainties related to the ratio of viable or dead cells/cysts to the total cells/cysts count, and also the ratio of human-infectious cells/cysts to total cells/cysts counts. The viability data require extensive monetary and time resources to collect and are currently unavailable for HRW. It might also be inappropriate to extrapolate pathogen data of other environmental waters (which is focused on contaminated surface water or groundwater). The types of animals dwelling around/on rooftops are different from those that live on the ground surface, (such as cattle, pigs, dogs, and cats). Due to these knowledge gaps and uncertainties, we assumed that all the target pathogens as quantified are viable and human-infectious in order to serve as a worst-case-scenario estimate and abide by good risk assessment principles (Haas et al. 1999).

A total of 214 samples were tested using binary PCR, which provide good statistical confidence in terms of the sample size. The lower qPCR detection limit of each target pathogen was also reported, and is used to represent the upper range of binary PCR with negative outcome. Details of the data treatment are described in the Monte-Carlo simulation in Section 2.8.

2.4. *Pathogen transfer to home produce*

The transfer of pathogens to home produce is modeled based on the amount of water that is absorbed by home produce upon irrigation. Water retention rate varies among different types of crops, which could be a function of crop geometry, surface area properties (e.g. charge, smoothness, etc.), crop type (root, exposed, or protected), and irrigation method (e.g. surface- or subsurface-irrigation). Shuval et al. (1997) conducted a laboratory test to measure the amount of water that can be absorbed by cucumber and lettuce. The experiment measured the increase in weight of the vegetable after submerging them in water for varying period of time. The weight increase of crops translated to an average of 0.36 ± 0.12 mL water absorbed by 100 g of cucumber ($n = 26$), and an average of 10.8 ± 1.9 mL water per 100 g lettuce ($n = 12$). Likewise, the water retention rate of tomato were converted from the relative weight increase of tomato submerged in packinghouse flumes and dump tanks, which ranged from 0.04 to 1.66 mL of water per 100 g of tomato (Bartz, 1988).

2.5. *Intake rate of home produce*

The best available consumer-only intake rate of home produce by home gardeners was estimated based on the 1987–1988 Nationwide Food Consumption Survey (NFCS) by Moya and Phillips (2001) (U.S.EPA, 2011). In their study, they estimated the distributions for unadjusted intake rate of individual home-produced food items (e.g. lettuce, tomato, and cucumber). The term “unadjusted” does not account for food-preparation and post-cooking losses, and therefore, serve as a maximum estimate. This assumption closely represents crops eaten in its raw form, such as tomatoes and lettuce, which are usually sliced for salad preparation with relatively negligible discarded portion.

The intake rate of home produce is adjusted based on body weight and expressed as grams of home produce per kg body weight per day (g HP·kg BW^{-1}·day^{-1}). Empirical distributions of each home produce intake rate were generated from percentile values of the data reported. As the intake rate of home produce is adjusted according to body weight, the distributions of body weight of US population were referred to based on a study by Kahn and Stralka (2008). Empirical distributions of the overall US population's body weight were generated from the data reported, which are based on the USDA's 1994–1996, 1998 CSFII (Continuing Survey of Food Intake by Individuals).

2.6. *Dose of pathogens ingested*

Pathogen ingestion is estimated using pathogen concentration in HRW, intake rate, body weight, and volume of HRW retained per mass of produce (Hamilton et al. 2006). Each of the parameter is assumed to be independent of each other. It is expressed as:

$$d = \mathrm{PConc}\cdot\mathrm{Intake}\cdot\mathrm{BodyWeight}\cdot V \tag{1}$$

where:

d = Dose of pathogens ingested (# pathogens·day^{-1})
PConc = Pathogen concentration in HRW (# pathogens·mL $water^{-1}$)
Intake = Intake rate of home produce by home gardeners (g HP·kg BW^{-1}·day^{-1})
Body weight = Body weight of US population (kg BW)
V = Volume of water absorbed per unit mass of home produce (mL water·g HP^{-1})

Steady state distribution of *d* is obtained by 10,000 or more iterations of Equation (1) using Monte-Carlo method.

2.7. *Infection risk per day*

The infection risk, P_{inf}, is quantified as estimated infection case per person per day (or per event if assuming a single consumption event in a day). Different target pathogens have different virulence and infectious dose. Thus, dose–response models are developed for specific target pathogens. Dose-response model uses dose of target pathogens taken in as an input parameter and return a probability of infection. It should be noted that infection can be characterized as either symptomatic (showing clinical signs of illness) or asymptomatic (not showing clinical signs of illness). The probability of developing a symptomatic infection is equivalent to the illness risk, which is dependent on a number of factors such as age, immune state, nutritional status, etc. In general, infection rate is greater than illness rate unless specified.

An exponential dose–response model (Equation (2)) from the literature (Rose et al., 1991) was used for estimating the infection risk due to exposure to *Giardia*. A beta-Poisson model (Equation (3)) was used for estimating the risk of exposure to *Salmonella* (Haas et al., 1999).

$$\text{Exponential model, } P_{inf} = 1 - \exp(-r \times d) \tag{2}$$

$$\text{beta} - \text{Poisson model, } P_{inf} = 1 - \left[1 + \frac{d}{\beta}\right]^{-\alpha} \tag{3}$$

The *r* in the exponential model is the best–fit parameter, which is 0.0198 for *Giardia*. The best–fit parameters ∝ and β in the beta-Poisson model are 0.3126 and 2884, respectively, for *Salmonella*.

The infection risk due to exposure to target pathogens is calculated using Monte Carlo method for 10,000 or more iterations to obtain steady state distribution of the infection risk.

2.8. *Risk characterization*

The results for infection risk per day are further adjusted to annual infection risk in order to be compared to the U.S. EPA acceptable annual infection risk associated with drinking water ($\leq 10^{-4}$ pppy), which has since been used as a benchmark for foodborne risk associated with irrigation water (Shuval et al. 1997; Petterson et al. 2001; Hamilton et al. 2006; Mara et al. 2007). The annual infection risk guideline accounts for the fact that a person engages in a scenario multiple times throughout a year (e.g. 365 exposure events in a year) and the compounded risk of multiple exposures needs to be accounted for. We estimated the annual infection risk of consuming the HRW-irrigated crops by assuming home gardeners consume their home produce daily, which is computed based on the independence theorem according to Haas et al. (1999):

$$\text{Annual infection risk} = 1 - \prod_{i=1}^{n=365}\left[1 - D(P_{inf})_i\right] \tag{4}$$

The subscript *i* represents the *i*-th iteration of Equation (4) and *n* represents the total number of iterations (the total number of exposure events in a year). $D(P_{inf})$ represents distribution of probability of infection.

Again, the distribution of the annual infection risk is computed using the Monte-Carlo method.

2.9. *Monte-Carlo simulation*

All Monte-Carlo algorithms were written and implemented using MATLAB R2010a (The Mathworks, Inc., MA). Distribution-based input parameters are randomly selected based on their corresponding probability distributions, output parameters (e.g. dose of pathogens ingested, infection risk due to certain target pathogens) are computed between 10,000 and 15,000 iterations until its distribution attained steady state. Reproducibility of the results is checked by small variation (e.g. <1%) in terms of average between replicates of distribution.

In acknowledging that samples falling below pathogen detection limit are not equivalent to absence of pathogens in the samples (Lubin et al. 2004), we used extra steps in treating the sampling of target pathogens concentration in HRW. The binary PCR (positive and negative) data of target pathogens were used to generate a *m x n* binary matrix containing "0"s and "1"s, representing negative and positive results. The percentage of "1"s in each row was selected randomly from the binomial distribution of the binary PCR result for the target pathogen, where probability of selecting a certain percentage is highest at the distribution's mode and decreasing towards its tail (95% confidence interval). Whenever a random sample of target pathogen concentration is needed, a sample will first be randomly picked from the binary matrix. If a "0" is picked, a uniformly distributed number from the interval [0 1] will be sampled and multiply by the lower qPCR detection limit of the target pathogen to represent the pathogen concentration. Otherwise, a “1” picked would lead to random sampling from the empirical distribution of the target pathogen concentration (observed samples above detection-limit). Uniform distributions (instead of point estimates or normal distribution) are used to minimize the introduction of unwanted bias into the risk model where information is lacking. A pseudo-algorithm flowchart for the generation of infection risk is shown in Fig. 1.

2.10. *Sensitivity analysis*

The uncertainty and variability propagation of each input parameters throughout the risk model is assessed using a sensitivity analysis method. Spearman’s rank correlation of the infection risk (model outputs) to each input parameters (e.g. pathogen concentration, water retention rate, etc.) were computed to assess the relative contribution of the latter to the uncertainties/variability of the infection risk. The method was chosen due to its ease of implementation and capability of showing possible strong non-linear correlation of parameters, which were used frequently in similar studies (Haas et al. 1999; Hamilton et al., 2006).

3. Results

3.1. *Infection risk per day*

The estimated infection risks per day (or per intake event) due to consumption of raw produce irrigated with HRW are presented in Table 1 and Fig. 2. The mean value and 95th percentile value of each infection risk is tabulated in Table 1. Giardiasis risks are visibly much higher by one to two order(s) of magnitude than Salmonellosis risks (for every crop considered), as shown by the right-shifting trend of the former’s cumulative distribution curve in relative to the latter in Fig. 2. Among the three crops, the ascending order of infection risk is as follows: cucumber < tomato < lettuce. However, the mean intake rate of lettuce is the lowest (0.39 g HP$\cdot$kg BW$^{-1}\cdot$day^{-1}) in comparison to that of tomato and cucumber (1.18 and 1.03 g HP$\cdot$kg BW$^{-1}\cdot$day^{-1}) (Fig. 5). The higher infection risk of consuming contaminated lettuce is due to the relatively higher water retention rate of lettuce than that of tomato and cucumber. It is also inferred that the infection risk per day (for both pathogens and all home produce) is very unlikely to exceed the propounded acceptable annual infection risk at $\leq 10^{-4}$ pppy, with the 95th percentile values of the former 1 to 3 order(s) of magnitude lower than the latter (Table 2).

3.2. *Annual infection risk*

The annual infection risks of consuming HRW-irrigated home produce are presented in Table 1 and Fig. 3. Both the mean and 95th percentile values of annual Giardiasis risk and Salmonellosis risk (for all crops) are in the range of 10^{-4} to 10^{-3} order of magnitude. Fig. 3 shows probability density (normalized histogram, in increment of $\log_{10}(0.05)$) of the annual risk associated with each crop. The lower *x*-axis limit of the graph is represented by the U.S. EPA annual infection risk benchmark ($\leq 10^{-4}$ pppy), suggesting it is unlikely to be met by all the HRW-irrigated home produce. However, a comparison of the annual infection risk of HRW-irrigated crops with that of reclaimed water irrigated crops (Hamilton et al. 2006) shows that the former is one to two orders of magnitude(s) lower than the latter.

3.3. *Sensitivity analysis*

The relative contribution of each input parameters to the uncertainties/variability of infection risks are summarized in Figs. 4 and 5. Significance of each parameter is characterized by its Spearman’s rank correlation coefficient with infection risk, $|r_s|$, where a higher value indicates greater contribution to the uncertainties/variability of infection risk and vice versa. In general, consumption rate of home produce ($|r_s| > 0.60$) accounts for most of infection risk’s uncertainties/variability. It should, however, be noted that consumption rate is a product of intake rate (body weight adjusted) and body weight. Separate consideration of intake rate and body weight shows that intake rate still accounts for a large share ($|r_s| > 0.52$) of infection risk’s uncertainties/variability whereas body weight shows a lesser contribution ($|r_s| < 0.34$). Pathogen concentration in HRW is another large contributor of infection risk’s uncertainties/variability ($|r_s| > 0.53$). Although water retention rate of lettuce and cucumber ($|r_s| < 0.11$) represents a minor contributor to the uncertainties/variability of the infection, the same is not observed for tomato’s ($|r_s| > 0.38$). This observation is explained by the wide variation of water retention rate of tomato (0.04–1.63 ml per 100 g tomato). Not much difference in terms of parameter sensitivity is observed for the prediction of Giardiasis and Salmonellosis risk.

4. Discussion

Emerging water and energy issues have heightened people’s awareness to conserve and use their water wisely. HRW represents an easy source of relatively clean water that most average households can harvest and benefit from. However, the lack of uniform guidelines across the nation for safe usage of HRW has hampered the wide adoption of the rainwater harvesting practice (Kloss, 2008). QMRA was the main driving force for the development of the Surface Water Treatment Rule established by U.S. EPA in 1989 for guiding the safe treatment of drinking water (US EPA, 1989a, 1989b). The same approach should, in principle, be used for establishing safety guidelines of HRW usage.

4.1. *Benchmarking risk with U.S. EPA annual infection risk*

U.S. EPA drinking water annual infection risk benchmark of 10^{-4} pppy has been widely treated as a benchmark for foodborne risk related to irrigation water due to the lack of specific risk benchmark for non-potable water applications. In this study, the annual infection risk associated with consumption

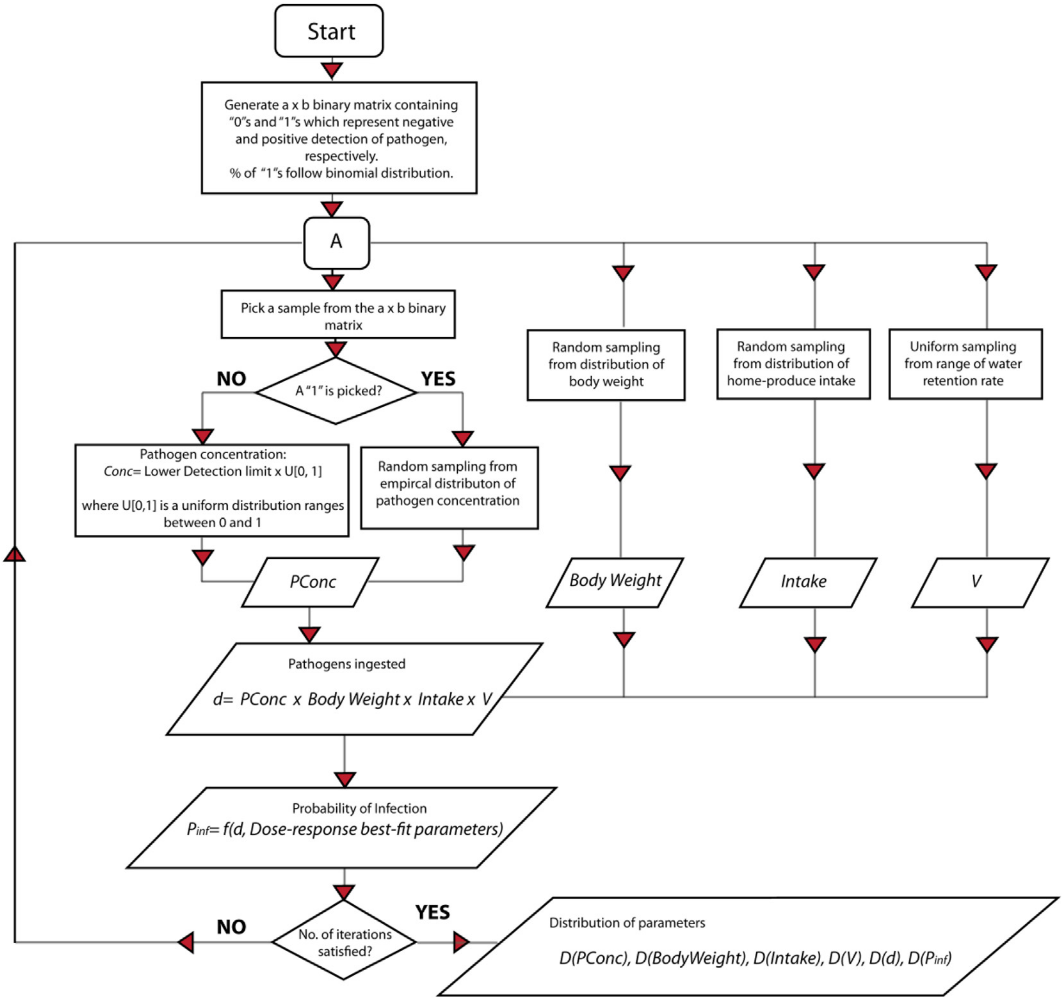


Fig. 1 – Pseudo-algorithm flowchart for estimating illness risk due to consumption of HRW-irrigated home produce. Node A represents the starting point for each iteration after the first one.

of raw crops irrigated using untreated HRW exceeds the commonly accepted U.S. EPA annual infection risk benchmark, implying potential human health concerns. However, the validity of this benchmark should be questioned. In fact, Haas (1996) discussed that a more practical annual infection risk level people accept unknowingly for food is at 10^{-3} pppy. Petterson et al. (2001) continued the discussion by reiterating the need for considerable advancement for assessing public health risks from food crops, in which screening-level QMRA result for salad crops irrigated with secondary-treated wastewater significantly exceeds human health risk benchmark (based on the 10^{-4} pppy). The comparison with U.S. EPA annual infection benchmark is also complicated by the annual consumption rates based on human habits. The drinking water standards are based on the daily consumption of 2 L of water by a person for 365 days (e.g. 365 exposure events in a year). While this is a justifiable assumption for drinking water consumption, the eating habit of people can vary on a day-to-day basis (e.g. most people probably would not eat the same food every day). The annual infection risk for food consumption would need to consider such variation to yield a more reasonable annual consumption rate for the specific produce, at least for food crops eaten raw.

4.2. *Benchmarking risk with WHO guidelines for drinking water quality*

Aside from the annual infection risk benchmark set by the U.S. EPA, WHO has recommended the use of DALYs (Disability-Adjusted Life Years) to set health based targets for drinking water, in which a tolerable disease burden of less than 10^{-6} DALYs pppy is recommended (WHO, 2004). The use of DALYs accounts for the unique morbidity and mortality characteristics caused by different pathogens, such that a certain pathogen which causes greater impacts than other pathogens (due to a longer or more severe clinical symptoms the former caused to an infected person) will have a greater DALY per illness case. This is in stark contrast of the U.S. EPA annual infection risk benchmark approach, which treats all pathogens as equally important (Gibney et al. 2013). Moreover, the DALYs approach possess the flexibility to aggregate all the risks presented by different pathogens into one single DALYs

Table 1 – Descriptions of parameters used in the risk model.

Parameters	Units	Point estimates	Range and distribution type	Reference
Target pathogen binary PCR detection				
Salmonella	% Positive		*Binomial* ($n = 214$, $p = 0.107$)	
G. Lamblia	% Positive		*Binomial* ($n = 214$, $p = 0.098$)	
Target pathogen lower detection limits				
Salmonella	Cells/1000 mL	5		Ahmed et al. (2010)
G. Lamblia	Cysts/1000 mL	0.4375		
Target pathogen quantitative PCR concentration				
Salmonella	Cells/1000 mL		$P(PConc = 65, \ldots, 380)$[a]	
G. Lamblia	Cysts/1000 mL		$P(PConc = 9, \ldots, 57)$[a]	
Exposure assessment for home produce intake				
Water retention rate of home produce				
Tomatoes	mL water/100 g produce		$U(0.04, 1.63)$[b,c]	Bartz (1988)
Lettuce	mL water/100 g produce		$U(8.9, 12.7)$[c]	
Cucumber	mL water/100 g produce		$U(0.24, 0.48)$[c]	Shuval et al. (1997)
Body weight of human	kg body weight		Empirical distribution of body weight from populations of all age-groups[a]	Kahn and Stralka (2009)
Home produce intake				
Tomatoes	g produce/kg body weight			
Lettuce	g produce/kg body weight			
Cucumber	g produce/kg body weight		Empirical distribution of consumer-only intake for all age-groups[a,d]	U.S. EPA (2011)
Dose-response assessment				
Salmonella beta-Poisson model				
α	–	0.3126		
β	–	2884	Best-fit parameter	Haas et al. (1999)
G. lamblia Exponential model				
r	–	0.01982	Best-fit parameter	Rose et al. (1991)

[a] Empirical distribution from data reported in corresponding literature.
[b] Converted from % relative weight increase of submerged tomatoes.
[c] A uniform distribution is used in the absence of the distribution's descriptive statistics.
[d] Data from Table 13–39, –42, and –52 of US EPA Exposure Factors Handbook 2011

value, which can then be converted to a tolerable annual illness risk (which is similar to the annual infection risk benchmark) (Havelaar and Melse, 2003; Gibney et al. 2013). A missing link between the annual infection risk benchmark of U.S. and the tolerable annual illness risk computed from DALYs is that the former is usually higher than the latter, as illness (symptomatic infection) is only a portion of infection. DALYs only account for the impact of illness, but not for an

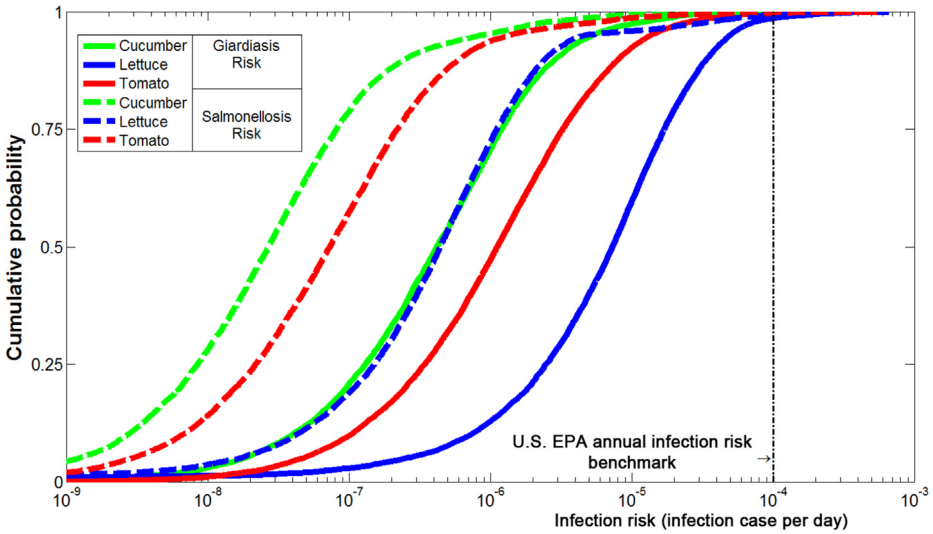
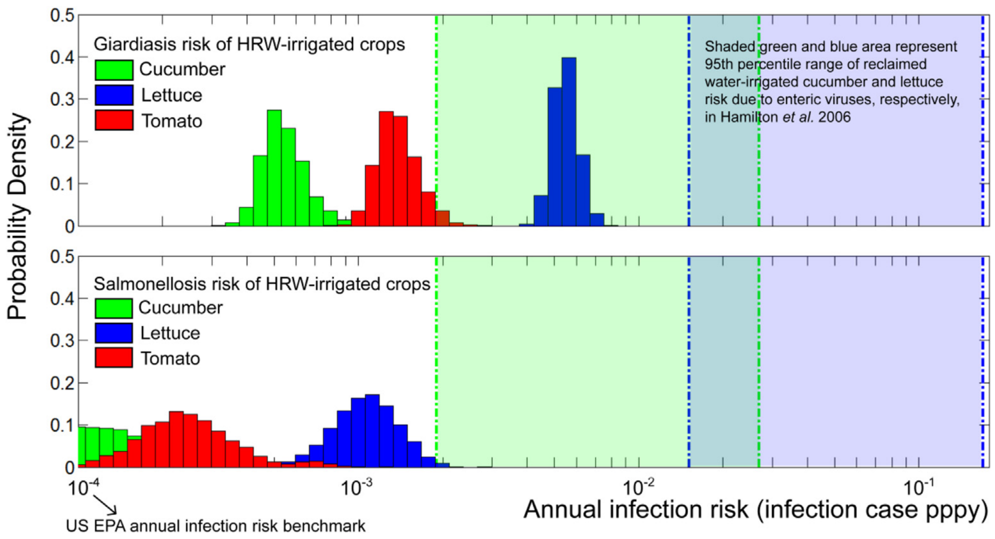


Fig. 2 – Cumulative distribution of Giardiasis risk (solid lines) and Salmonellosis risk (dashed lines) due to consumption HRW-irrigated home produce. The illness risk is expressed as likely illness case per day.



Shaded green and blue area represent 95th percentile range of reclaimed water-irrigated cucumber and lettuce risk due to enteric viruses, respectively, in Hamilton *et al.* 2006

Fig. 3 – Distribution of annual Giardiasis risk (top panel) and Salmonellosis risk (bottom panel) due to consumption HRW-irrigated home produce. The probability density is estimated as normalized histogram. The lower x-axis limit is the propounded acceptable annual risk benchmark at ≤1 illness case per 10,000 people per year. Shaded regions in the figure shows the 95th percentile range of the annual risk of reclaimed water irrigated crops estimated by Hamilton et al., 2006).

infection without clinical signs of illness (asymptomatic infection). This is an area that needs to be further addressed as probability of infection is sometimes mistaken as illness risk (unless stated explicitly).

In our preliminary attempt (See Supplementary Table 1) in using DALYs, we equaled infection risk from QMRA to illness risk to represent a worst-case scenario, such that every infected person will develop clinical signs of illness. We calculated the tolerable annual illness risk of *Salmonella* spp. and *Giardia lamblia* to be at 0.000373 pppy and 0.000163 pppy, respectively (converted from a tolerable disease burden of 10^{-6} DALYs pppy). The aggregate tolerable annual illness risk due to the two target pathogens is calculated at 0.000113 pppy, which is comparable to the annual infection risk benchmark of U.S. EPA at 0.0001 pppy for any single target pathogen. While the data we use for calculating the tolerable annual illness risk is based on epidemiological and health data of Netherlands (Kemmeren et al. 2006; Vijgen et al. 2007), we think it is a good representation of a developed nation (e.g. U.S.). Although a number of issues related to DALYs are to be resolved, the result points to the potential of exploring DALYs as an alternative approach for developing health risk benchmark for sustainable water practice.

4.3. *Relative risk of HRW to reclaimed water*

A comparison of the estimated annual infection risk between untreated HRW irrigated crops and reclaimed water irrigated crops (Hamilton et al. 2006) shows that the former is one to two order(s) of magnitude lower than the latter. Only additional treatment, such as withholding reclaimed water for a week for environmental degradation of pathogens before irrigation of the crops, is able to reduce the annual risk of reclaimed water irrigated crop to the same level as that of

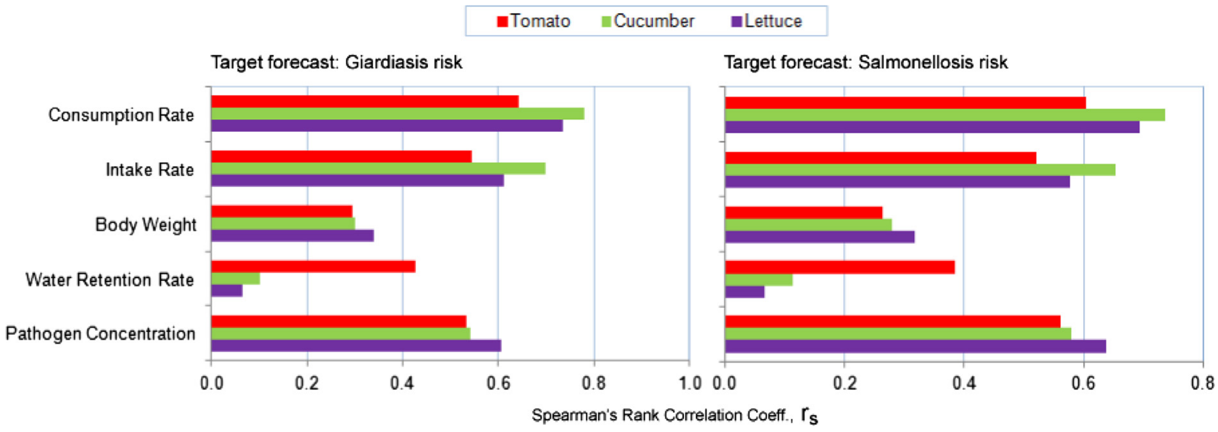


Fig. 4 – Sensitivity analysis chart of input parameters for estimating Giardiasis risk per day (Left panel) and Salmonellosis risk per day (Right panel). Consumption rate = Intake rate × Body weight.

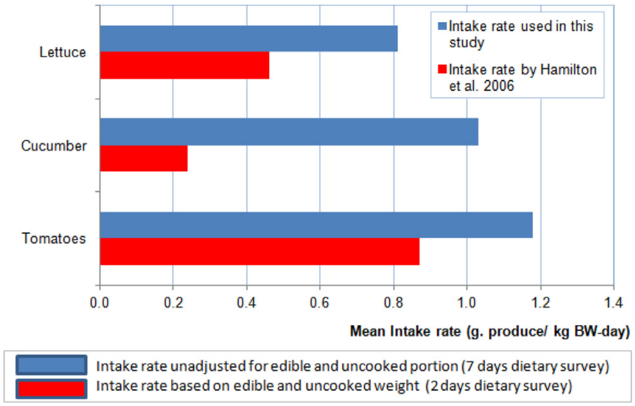


Fig. 5 – Comparison of the mean intake rate used by Hamilton et al. (2006) in their QMRA with the mean intake rate used in this study. Notice that the latter is unadjusted for edible and uncooked weight, but is based on a longer survey period. The former reports more specific intake rate, but were based on two non-consecutive days of survey.

HRW-irrigated crops. Moreover, non-disinfected secondary effluent is known to contain human-infectious pathogens such as *Giardia* and *Cryptosporidium* at much higher detection level (detection frequency of *Giardia* and *Cryptosporidium* in reclaimed water is ≥83% and ≥42% vs HRW of 9.8% and 0.4%, respectively) and concentration than HRW (Rose et al. 1996; Harwood et al., 2005). As such, inclusion of these pathogens in Hamilton et al.'s QMRA would likely elevate their estimated annual risks. Although this trend supports the idea of using untreated HRW for irrigating home produce, the 95th percentile values for annual risk of HRW-irrigated crops are not able to meet the annual risk benchmark of $\leq 10^{-4}$ pppy by far, which ranges from high 10^{-4} to low 10^{-3} pppy. The annual risk associated with consumption of HRW-irrigated lettuce (95th percentile = 1.6×10^{-3} for Salmonellosis and 6.5×10^{-3} for Giardiasis) is, in fact, considered to be highly unsafe if measured against the $\leq 10^{-4}$ pppy infection risk benchmark.

4.4. *Inferences from sensitivity analysis*

Sensitive model parameters can be used as inferences for decision-making. For example, reducing the uncertainties of a sensitive input parameter (e.g. through experiment refinement) can improve risk prediction, and/or derive risk management/mitigation strategies by controlling the phenomenon characterized by a sensitive parameter (Hamby, 1994; Haas et al. 1999; Frey and Patil, 2002; Mokhtari et al., 2006).

Our sensitivity analysis showed that variations in consumption rate of crops and pathogen concentration are equally significant in predicting infection risk. Variation of water retention rate of lettuce and cucumbers are not as significant as that of tomato in predicting infection risk. While the sensitivity analysis results of Hamilton et al. (2006) also showed the significance of consumption rate in predicting infection risk ($|r_s| > 0.49$), it was not the case for virus (pathogen) concentration in water ($|r_s| < 0.22$). Nevertheless, consumption rate of crops is deemed as a very sensitive input parameter in both models.

One of the risk management strategies that can be derived from the knowledge of high sensitivity of consumption rate is to reduce consumption of raw crops. In the event that the proposed strategy is impractical (considering the broad health benefit of fresh produce), other sensitive parameters should be explored for solutions. Pathogen concentration in HRW, another highly sensitive parameter to predict infection risk, implies that disinfecting HRW through targeting high-risk pathogens can reduce foodborne risk. Certainly, the examples above are oversimplified, but it showed how our understanding of risk management can be validated and justified by statistical method.

A comparison of the mean intake of each home produce used for our QMRA to the corresponding mean edible and intake of raw crops from all sources (i.e. home-produced or not) used by Hamilton et al. (2006) shows that the former is marginally higher than the latter (Fig. 5). The annual risk estimated for HRW-irrigated home produce is also based on daily consumption of the crops throughout the years (i.e. 365 exposure events), which may

Table 2 – Summary descriptors for the annual infection risk associated with consumption of each HRW-irrigated crops. A comparison between the 95th percentile value of annual infection risk of HRW-irrigated crops and that of reclaimed water-irrigated crops is also shown.

		Infection risk per day		Annual infection risk		
		Mean	95th percentile	Mean	95th percentile	95th percentile range for reclaimed water-irrigated crops (Hamilton et al. 2006)[a]
Giardiasis	Cucumber	1.52×10^{-6}	5.37×10^{-6}	5.53×10^{-4}	7.58×10^{-4}	$1.9 \times 10^{-3} \sim 2.7 \times 10^{-2}$
	Lettuce	1.51×10^{-5}	4.96×10^{-5}	5.49×10^{-3}	6.50×10^{-3}	$1.5 \times 10^{-2} \sim 1.7 \times 10^{-1}$
	Tomato	3.84×10^{-6}	1.37×10^{-5}	1.40×10^{-3}	1.87×10^{-3}	–
Salmonellosis	Cucumber	3.76×10^{-7}	8.60×10^{-7}	1.39×10^{-4}	2.80×10^{-4}	$1.9 \times 10^{-3} \sim 2.7 \times 10^{-2}$
	Lettuce	3.01×10^{-6}	4.63×10^{-6}	1.09×10^{-3}	1.62×10^{-3}	$1.5 \times 10^{-2} \sim 1.7 \times 10^{-1}$
	Tomato	7.35×10^{-7}	1.38×10^{-6}	2.67×10^{-4}	4.95×10^{-4}	–

[a] Result for annual infection risk of enteric virus infection based on secondary effluent of four different wastewater treatment plants in Southern California, environmental exposure of 1 day, and viral kinetic decay of 0.69 day^{-1}. Please also note the difference between human waste origin of reclaimed water in this study and pathogens of animal origin in HRW.

be improbable given the different growing season of each crop (although some crops can be grown throughout the year depending on its cultivar and/or where it is grown) and the actual amount of crops that can be grown. This substantiates the possibility that the annual infection risk of HRW irrigated crop may be overestimated due to the uncertainties of estimates for home produce annual intake rate. Indeed, the annual risk can be refined by using alternate days of intake (one intake event per two or more days). However, as with all health risk assessment, any lack of information should be replaced with cautious estimate to assure that the worst-case risk is addressed. The daily intake rate used in this study has included some seasonal variability by averaging the USDA 1987–1988 NFCS data from all seasons from all regions of the country. Consequently, the risk estimates presented here represent the best state of knowledge.

4.5. *Interpretation of QMRA*

QMRA model structure, its risk outcomes, and sensitivity test should be used as a tool integrally for decision-making because risk model is constructed based on the best knowledge and available information (parameters and data) at the time of development. There are at times that certain parameters for modeling a phenomenon is challenging due to difficulties and lack of methods to characterize it and modelers have to compromise with a surrogate parameter. A very classic example is the water retention rate by crops, which are used in this study and in many QMRA of crop contamination by irrigation water (Petterson et al. 2001; Hamilton et al. 2006; Mara et al. 2007). The water retention rate is simulated by prolonged water submergence test on the crops to represent a “worst-case scenario”. This is, at best, appropriate for predicting the risk of crops whose edible portion are exposed to contaminated water (e.g. through overhead irrigation). However, this can be considered for risk management strategies by changing the irrigation method from surface irrigation to subsurface irrigation. Additional studies will have to be conducted to substantiate the conclusion, but several studies have already shown that drip irrigation can reduce pathogen exposure to edible portion of above-ground crops (e.g. tomatoes, cucumbers, lettuce) from a detected level to 10 times less or non-detect level in relative to surface irrigation (Alum, 2001; Stine et al. 2005).

Another caveat to be addressed in our QMRA is the use of microbial data of HRW collected in Southeastern Australia to represent the microbial quality of HRW in U.S. Currently, there are only a few U.S.-based studies (Crabtree et al. 1996; Jordan et al. 2008), which investigate the microbiological quality of HRW. In fact, there has been a lack of thorough investigation of microbiological quality of HRW in developed countries, at least in terms of the data quality and quantities that can be used for standards development (Fewtrell and Kay, 2007). Thus, the interpretation of QMRA and adoption of QMRA result in policy decisions should consider the limitations at the time. QMRA should continuously evolve with the advancement of microbiological measurements, human behavior changes and availability of new information. The water policy based on the QMRA should also be updated with the QMRA development as illustrated through risk analysis of HRW-irrigated home produce.

5. Conclusions

Rainwater harvesting systems represent one of the simplest green technologies which have low cost in exchange for a high return. Collection of rainwater also encourages property owners to take “ownerships” of their own water, educating them naturally of the scarcity and characteristics of different water sources. Unfortunately, the benefits of rainwater harvesting in the U.S. are not fully realized due to the lack of studies and wide-scale support given to the area.

Promiscuous use of an established but inappropriate benchmark as shown in this study can significantly hinder the development of sustainable water practice. While a stringent health risk benchmark is definitely useful as a guidance for human health protection, it can also act as a double-edged sword that increase economic and resource risk of over-treating the water for minimal human benefits. Stringent standards promote the safety level of water uses, but also scare away practitioners in water-related fields who are used to following protocols and guidelines as the golden standard for every water-use. The U.S. EPA annual infection risk for safe drinking water is not appropriate as a singular benchmark for assessing the safety level of different water end-uses, particularly when sustainable water practice is considered. In supporting this claim, the U.S. EPA had set an acceptable swimming-associated gastrointestinal illness rate of 7 illness case per 1000 swimmers per day, which is significantly less stringent than the allowable drinking water risk level (U.S. EPA, 2004, 2012). While there are big differences between recreational water and drinking water, in terms of their purposes and controllability over their water quality, the same can be argued for HRW or any sustainable water practices versus drinking water.

As shown in this study, the risk assessment result could be impacted heavily by the quality of data used. Relative risk study of appropriate end-uses of different source water can provide another perspective of the risk and benefits appraisal, and for development of risk benchmark. Perhaps, as discussed by Haas (1996), an annual infection risk of $\leq 10^{-3}$ pppy for foodborne risk is more recommendable than the annual infection risk benchmark $\leq 10^{-4}$ pppy. Alternatively, the use of a different risk benchmark, such as DALYs, should be explored as a potential solution to the issue. It is hoped that this study will serve as a platform to drive research needed in the area, provide insights to the establishment of new standards and guidelines for sustainable water practice such as using untreated or treated HRW or other lesser-quality water, such as captured stormwater, for toilet flushing, laundry, and gardening in the near future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2013.09.059.

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