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Quantitative health risk assessment of microbial hazards from water sources for community and self-supply drinking water systems

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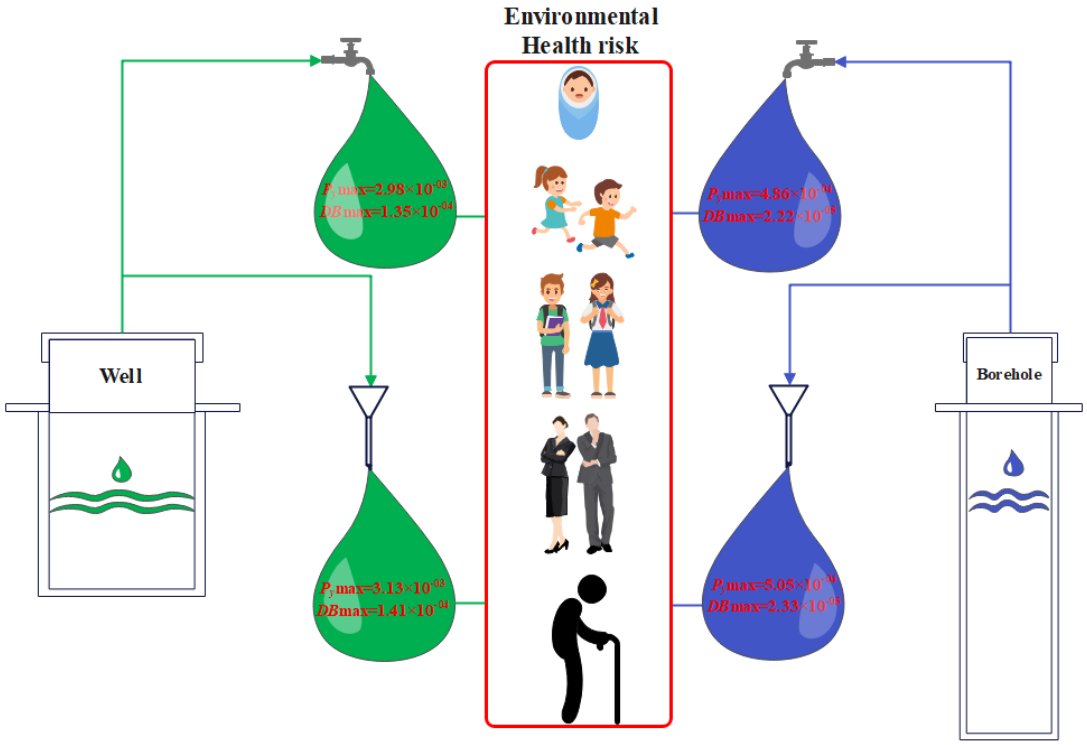
Abstract

In low- and medium-income countries (LMIC) drinking water sources (wells and boreholes) often contain a high number of pathogenic microorganisms, that can pose significant human and environmental health risks. In this study, a quantitative microbial risk assessment approach based on existing literature was conducted to evaluate and compare the quantitative health risks associated with different age groups using various drinking water supply systems. Results showed that both community-supply and self-supply modes exhibit similar levels of risk. However, the self-supply water source consistently showed higher risks compared to the community-supply one. Borehole water was found to be a more suitable option than well water, consistently showing between 5 and 8 lower health risks for *E. coli* and faecal coliform levels, respectively. The sensitivity analysis further showed the importance of prioritizing the reduction of *E. coli* concentration in well water and faecal coliform concentration in borehole water. This study offers a fresh perception on quantifying the impact of exposure concentration and age groups, shedding light on how they affect environmental health risks. These findings provide valuable insights for stakeholders involved in the management and protection of water sources.

Keywords: Quantitative microbial risk assessment; Drinking water; Well and borehole water; Drinking water supply systems; Sensitivity analysis



Environmental implication

Wells and boreholes are commonly utilized as drinking water sources but contain significant amounts of pathogenic microorganisms, posing significant environmental health risks. This study focuses on a comprehensive assessment to compare the quantitative health risks associated with two drinking water supply systems for various age groups. The analysis involves conducting quantitative microbial risk assessments regarding the concentrations of *E. coli* and faecal coliform. This study employs quantitative microbial risk assessment to reveal disparities in health risks across age groups and water supply systems in areas with high pathogenic microorganism contamination. It emphasizes the priority of addressing *E. coli* and faecal coliform concentrations for improved environmental health. Findings will assist stakeholders in effectively managing microbial hazards in drinking water sources.

1. Introduction

Water is an essential element for sustaining life (Mohammadi et al., 2019; Qasemi et al., 2018). However, the availability of safe drinking water sources is decreasing globally due to intensified human activities (WHO, 2022). Ensuring the microbiological quality of drinking water is crucial (Amatobi & Agunwamba, 2022). The World Health Organization (WHO) reports that approximately 1.7 billion cases of childhood diarrhea occur each year, resulting to the death of approximately 525,000 children below the age of five. These alarming statistics are attributed to inadequate water supply, poor sanitation, and hygiene practices. The presence of hazardous pathogenic microorganisms in drinking water pose significant environmental health risks, underscoring the necessity of assessing the microbiological quality of drinking water, particularly for the presence of *E. coli*, which serves as an indicator of fecal contamination (WHO, 2017).

Access to safe and healthy drinking water sources remains a significant challenge in low and medium income countries (LMICs), primarily due to the inability of governments to provide piped water infrastructure in impoverished and rural areas (Bain et al., 2012; Ngoran et al., 2015; WHO, 2019). Groundwater is often a viable alternative to meet the drinking water needs of the majority of rural individuals without access to basic water services (United Nations, 2022; Xie et al. 2023). Consequently, people extract water from underground sources using either manually constructed or mechanized wells (Omole, 2013; Barrow, 2016; Ngasala et al., 2018; Yu et al., 2019). However, such drinking water extraction methods are susceptible to contamination because they are often exposed to high levels of fecal contamination resulting from human activities (Mato, 2002). Shallow wells, which are commonly hand-dug and

typically range from 5 to 30 meters deep, are popular LMICs (Odey et al., 2018). These open water sources, lacking protective structures, are susceptible to contamination from sources such as animal waste, leading to environmental health risks associated with microbial pollution (Pang et al., 2021). On the other hand, boreholes, created using machinery, are deep wells ranging from 40 to 400 meters deep, providing access to groundwater (Grönwall et al., 2010). Borehole water is also susceptible to microbial pollution, due to subsurface infiltration of water, especially during rainy seasons (Palamuleni & Akoth, 2015; Lukubye & Andama, 2017;). In addition, other studies have suggested that factors, such as well depth and various adjacent land uses, also play a role in the risk (Li et al. 2015; De Giglio et al. 2016).

Due to inadequate protection measures around well and borehole water sources, they often fail to provide water free from microbial contamination hazards (Pantaleo, et al., 2018), thus posing serious environmental health risks to communities consuming the water directly (referred to as the community-supply mode of drinking water) (Taylor et al., 2009; Gwimbi, 2011). To tackle this issue, some households employ cost-effective and simple water purification methods such as plain sedimentation and filters to reduce presence of pollutants and impurities, particularly in cases of turbid water containing inorganic impurities. For example, it uses sand or a piece of cloth as the filtering medium to purify turbid water (Wu et al., 2020). However, these treatments have limited effectiveness against pathogenic microorganisms such as *E. coli* and faecal coliforms. This limitation results in unsatisfactory bacterial water quality of the treated water. This is primarily due to the ad-hoc and experiential nature of these measures, the lack of professional guidance, and the absence of systematic monitoring or detection, as highlighted by Charles, (2020). Additionally, individuals living outside community water supply areas may need to purchase treated water representing the self-supply

mode of drinking water as described by Marobhe, (2008).

To compare different water sources and drinking modes across various age groups, it is necessary to assess the associated environmental health risks. These risks are typically quantified using annual probability of infection ($P_{(y)}$) and disease burden (DB) through quantitative microbiological risk assessment (QMRA) (Haas et al., 2014). QMRA is a framework designed to quantitatively assess health risks in environmental exposure scenarios (Haas et al., 2017; Seis et al., 2020). The U.S. Environmental Protection Agency (U.S. EPA) approves a $P_{(y)}$ benchmark of 10^{-4} pppy, which is set as the level of acceptable infection risk from pathogenic microorganisms in drinking water. While the World Health Organization (WHO) endorses a DB benchmark of 10^{-6} disability-adjusted years of life (DALYs pppy), which is the tolerable burden of waterborne diseases (Lim et al., 2015; Fuhrimann et al., 2016; Shi et al., 2018; WHO, 2022). Sensitivity analysis helps identify prioritized control points in exposure scenarios (WHO, 2016).

Microbes in well or borehole water have been partially investigated in previous studies. For example, Bakalli et al. (2019) presented 5 years microbiological data for the quality of well water from different areas of Albania, showed that 100% of wells were contaminated and not recommended for consumption. In another study, Marras et al. (2020) conducted a continuous sampling analysis of microbes for private wells in south-central Sardinia from 2014 to 2018 and found that only 36% of them met minimum drinking water standards, and some were even not suitable for irrigation. Baia et al. (2022) studied well and borehole in the Western Amazonian city of Porto Velho, found that total coliforms were detected in 96% and 74% of wells and boreholes samples, respectively, and obtained that shallow wells were more susceptible to environmental factors. For health risk of well and borehole water, studies are rare on the microbial

side. Naik et al. (2021) have investigated the concentration of F^- in groundwater of Angul district (India) and found that nearly 28% and 58% of the samples pose a non-carcinogenic health risk for all age groups. Li et al. (2023) have studied quality characteristics and health risk assessment of water supply for domestic wells in residential areas considering that health risk of nitrate and arsenic are unacceptable for children and adults. Nevertheless, these studies often provided limited insights into the risks posed by the presence of pathogenic microorganisms. Therefore, the main objective of this research is to assess and compare the quantitative environmental health risks associated with different water sources (wells and boreholes) and two drinking water types (per capita intake rates and consumer-only intake) across various age groups.

Field sampling, groundwater testing, and analysis are demanding tasks. The continuous monitoring and updating of a vast groundwater database are often hindered by limited human and material resources, as highlighted by the United Nations in 2022. However, historical literature data can offer a valuable means to gain insights into the environmental characteristics and properties of groundwater (Fienen and Arshad, 2016; Dong et al., 2023). This data can be used to support new research agenda and providing timely practical guidance to address current challenges (Easterdayet al., 2018).

In this study, an investigation using existing literature is carried out to examine various human exposure scenarios to pathogenic microorganisms, specifically *E. coli* and faecal coliform, which are commonly found in wells and boreholes. The analysis utilizes QMRA to determine $P_{(y)}$ and DB, considering the concentrations of hazards pathogenic microorganisms *E. coli* and faecal coliforms. Additionally, the study quantifies the contributions of exposure concentration and drinking water volume to DB through sensitivity analysis using Monte Carlo simulation. This study offers a fresh perspective

into the human health risks associated with the exposure to pathogenic microorganism in drinking water sources in LMICs.

2. Materials and methods

2.1 Literature data research method

Through a desk work, the present study has identified literature that relevant to the purpose and scope of the current work, which is conducted using three databases, namely ScienceDirect, Web of Science, and Google Scholar. Additional information regarding the review process can be found in Supplementary Materials Figure 1.

According to the guideline of the WHO, *E. coli* and faecal coliforms are regarded as indicator bacteria for water quality because of their constant presence in the gastrointestinal tract, and they are a significant cause of gastrointestinal illness (Kolarević et al., 2011; Jahne et al., 2015). The concentration of pathogenic microorganisms can be found in Supplementary Materials Table 1. According to the guideline of the U.S. EPA (2011), residents are characterized by various volume of water to drink depending on the age groups, exposing them to different levels of health risks. The relationship between the drinking water volume and the divided age groups has already considered the effects of weight, personal physical condition, and lifestyle factors (Moya and Goldman, 2011; U.S. EPA, 2011; Tuttle et al., 2013). This study categorizes individuals into Type I and II age levels, as presented in Table 1 (U.S. EPA, 2011; Tuttle et al., 2013). Table 2 provides information on the volumes of drinking water that consumed corresponding to these age levels, distinguishing between community-supply and self-supply modes referencing to the Table Recommended

Values for Drinking Water Ingestion in the U.S. EPA guideline (2011).

[Table 1 inserts here]

[Table 2 inserts here]

2.2 QMRA

QMRA is a procedure for estimating the risk of infection quantitatively, and it is widely applied to assess health risks associated with drinking water, recreational waters, irrigation water, and sewage (Regli et al., 1991; Haas et al., 1999; Zaneti et al. 2021). QMRA is carried out following a classical four-step framework (National Research Council, 1983; Stellacci et al., 2010; Haas et al., 2014): hazard identification (pathogens of concern), exposure assessment (dose of pathogen exposure per person per day), dose–response assessment (probabilities of risk of infection and disease burdens (DBs) of the exposed population), risk characterization (two benchmarks: $P_{(y)}$ of 10^{-4} pppy approved by the U.S. EPA and 10^{-6} DALYs pppy approved by the WHO (Regli et al., 1991; U.S. EPA, 2005; WHO, 2022;). DB considers the unique characteristics of *E. coli* and faecal coliform in terms of morbidity and mortality, meaning that pathogens with higher virulence have greater DALYs. For the annual risk of infection, by contrast, thinks all pathogens are equally important (Gibney et al., 2013). For DALYs, disease surveillance data are demanded, but these data are often regionally bounded and cannot be representative of the whole population (Lim et al., 2015). Therefore, it is necessary to analyze the relationship between different methods results and their corresponding benchmarks and complement each other to make up for the shortcomings of the methods.

The common challenge of QMRA is the limited availability of high-quality, relevant, and timely data for the input factors, and more advanced models need to be validated

against well-characterized human dataset of disease (Mok et al., 2014; Haas, 2015; Owusu-Ansah et al. 2017). Although the potential for concomitant exposure to multiple pathogens exists in realistic scenarios, dose-response models have only focused on a single pathogen (Haas, 2015).

The two key values used for pathogen dose calculation in QMRA are the pathogen concentration and daily volume of drinking water (Itoh & Zhou, 2018). The beta-Poisson model is utilized to quantify the risk associated with exposure to *E. coli* and faecal coliforms in water from boreholes and wells (Olalemi et al., 2021). For assessing the practical pathogenicity in the dose–response model (Supplementary Materials Eq. (1)), the *E. coli* dose is multiplied by 0.08 since Haas et al. (1999) reported that 8% of the *E. coli* is pathogenic. In view of the data availability, considering the worst-case condition is habitually conducted for the QMRA framework, this study supposes that all faecal coliforms are assumed to be pathogenic.

[Table 3 inserts here]

2.3 Monte Carlo simulation and sensitivity analysis

Monte Carlo simulations are utilized to estimate the probability distribution of parameters in QMRA (WHO, 2006; Pasalari et al., 2019). The input variable parameters (C: exposure concentration and V: volume of drinking water) are randomly selected from their corresponding probability distributions. Concentration data of pathogenic microorganisms are assumed to follow a unimodal log10-transformed normal distribution because most microbial data are distributed lognormally (Hirano et al., 1982; Loper et al., 1984). Then, output health risks are computed over 10,000 iterations

to reach a steady state (Shi et al., 2018). Supplementary Materials Table 2-9 shows the specific data of results.

Sensitivity analysis is usually employed in probabilistic assessments of Monte Carlo simulations to explore the possible effects of varying inputs on assessment outcomes and quantify the contributions of all QMRA inputted variable parameters (Ferson and Tucker, 2006; Helton et al., 2006; Dias et al., 2019). The magnitudes of contributions of input variables are ranked to focus future empirical studies to expend effort for the improvement of input estimates (Ferson & Tucker, 2006; Dean & Mitchell, 2020). Sensitivity percentage ratio indicates a sensitivity value between 0% and 100%, and relative importance is indicated by showing the magnitude of contribution (Haas et al., 2017; Shi et al., 2018). A higher absolute value of the sensitivity level reflects a greater contribution. Quantification contribution is calculated by Microsoft Excel 2010 coupled with Oracle Crystal Ball, and all results in figures are generated with Origin software 2018 (Haas et al., 2017; Liu et al., 2019; Xu et al., 2020).

3 Results and discussions

3.1 Health risks for adults and minors

The $P_{(y)}$ and DB of the exposed populations belonging to Type I age level (as indicated in Table 2) are presented in Figures 1 and 2, respectively. Additionally, Supplementary Materials Tables 2-5 provide specific results for these health risks.

Comparing the two drinking water types, namely consumer-only intake, and per capita intake, reveals similar trends in the variation of health risks. This similarity can be attributed to the comparable exposure routes and risk characterization methods

employed for both types of drinking water. However, the health risks associated with consumer-only intake, in general, are higher than those linked to per capita intake (approximately 1.07-1.11 times higher for $P_{(y)}$ and 1.08-1.13 times higher for DB). This outcome suggests that the potential health hazards associated with the self-supply mode are generally greater than those associated with the community-supply mode due to the higher volume of consumer-only intake in the case of the self-supply mode (refer to Table 3). The community-supply mode is characterized by per capita intake rates, which is generated by averaging consumer-only intakes over the entire population including those individuals who reported no intake (U.S. EPA, 2011). The self-supply mode is characterized by consumer-only intake, which represents the quantity of water consumed only by individuals that reported consuming water (U.S. EPA, 2011). Therefore, the consumer-only intake reflects the actual volume of water consumed by individuals; while the per capita intake represents the regional average volume. The results of Hynds et al. (2012) support this finding of variances in the volume of drinking water. They reported that drinking volume of bottled water (self-supply mode) is higher than that of rural supplies, such as hand-dug wells or boreholes (community-supply mode).

[Figure 1 inserts here]

[Figure 2 inserts here]

3.1.1 Annual infection risks

Considering the medium value of Figure 1, for exposure to pathogenic microorganisms (*E. coli* and faecal coliform), the $P_{(y)}$ of drinking water from wells (8.18×10^{-4} pppy to

2.17×10^{-3} pppy for *E. coli*; 1.11×10^{-03} pppy to 2.93×10^{-3} pppy for faecal coliform) is approximately one order of magnitude higher than that of drinking water from boreholes (1.84×10^{-4} pppy to 4.77×10^{-4} pppy for *E. coli*; 1.42×10^{-4} pppy to 3.91×10^{-4} pppy for faecal coliform). This finding is in good agreement with Hynds et al. (2014) who reported similar results and predicted that drinking water from wells had a higher incidence of disease transmission than water from boreholes. This condition relates to the higher average concentrations of pathogenic microorganisms in well water (Supplementary Materials Table 1). The wells are more vulnerable to the influence of external environment (e.g., clay, silt, minute organic, inorganic particulate matter, and algae) which cause water turbidity and increase concentrations of pathogenic bacteria (Azhdarpoor et al.,2019; Bwire et al., 2020; Olalemi et al. 2020). It is in line with the current situation of findings of other literatures. Lutterodt et al. (2018) reported that under the effect of low design and construction quality, wells are more vulnerable to bacterial invasion. Sari (2018) stated that the degree of microbial contamination in well water is more severe than that in other water sources, such as springs or boreholes.

Considering the medium value of Figure 1, the $P_{(y)}$ for adults is 2.4 – 2.5 times higher than that for minors (Figure 1). This variable depends on the total daily intake drinking water volume of adults, which is greater than that of minors (Table 3). Meanwhile, the risks for adults and minors exceed the U.S. EPA benchmarks by 2.5 – 28 and 0.4 – 11 times, respectively. These findings indicate that the health risk levels associated with the direct consumption of well and borehole water are unacceptable for both adults and minors.

However, the implications of the results on health risk levels change when considering the best-case condition for the optimistic estimate. Under the best-case conditions, the risks associated with borehole water fall below the benchmark; in contrast, the risks for

295 faecal coliform and *E. coli* associated with well water are 0.7 – 4.9 and 0.2 – 2.4 times
296 higher than the benchmark, respectively. For the optimistic estimate, the risks of
297 infection in well water do not meet the U.S. EPA benchmark requirements and are
298 deemed unbearable.

299 **3.1.2 Disease burdens**

300 Under general conditions, for exposure to pathogenic microorganisms, the DB of
301 drinking water from boreholes (8.15×10^{-6} DALYs pppy to 2.23×10^{-5} DALYs pppy for
302 *E. coli*; 6.55×10^{-6} DALYs pppy to 1.80×10^{-5} DALYs pppy for faecal coliform) is about
303 one order of magnitude lower than that from wells (3.70×10^{-5} DALYs pppy to 9.96×10^{-5}
304 DALYs pppy for *E. coli*; 4.98×10^{-5} DALYs pppy to 1.35×10^{-4} DALYs pppy for fecal
305 coliform) (Figure 2). However, all of them fail to satisfy the WHO DB benchmark. Thus,
306 in general, the impact of health problems associated with the use of drinking water from
307 these types of water sources is totally unacceptable. The findings agree with the results
308 on the risk of infection (Figure 1). These results further prove that risks of infection and
309 DB are closely related. Disease surveillance data of DB show that the $P_{(y)}$ is further
310 translated into DALYs. The DALYs depends on the statistics of disease detective which
311 may not be representative of the population as a whole because it is often regionally
312 bounded, therefore DB and $P_{(y)}$ should be used as complements (Lim et al., 2015). Thus,
313 the health risks of drinking water from the two water sources all fail to meet the
314 corresponding benchmarks under general conditions, which indicates that evident risks
315 are inevitable from any perspective of risk assessment.
316 The DBs of self-supply mode of drinking water (Figures 2a and 2c) are 8.73×10^{-2} to
317 1.25×10^{-1} and 7.57×10^{-2} to 9.24×10^{-2} times higher than those of community-supply
318 mode (Figures 2b and 2d) under optimistic and conservative conditions, respectively.

This finding corresponds to the results of risk of infection (Figure 1), which indicates that self-supply mode not only fails to reduce health risks after simple treatment but also leads to higher risks due to increased volume of daily drinking water. This is because that after simple treatment, the volume of daily drinking water increases (Table 2). However, the exposure concentration does not sharply plummet, resulting in an increase in the parameter exposure dose (d) in the self-supply mode. Furthermore, all exposure scenarios all exceed the WHO benchmark except for one scenario in which minors are exposed to faecal coliform in borehole water due to their less exposure dose relating to the lower level of minimum water intake (Table 2) and the lower pathogen concentrations in borehole water (Supplementary Table 1). This suggests that using borehole water as a drinking water source is biased for minors.

[Figure 3 inserts here]

Figure 3 presents the sensitivity percentage ratio of the two primary influencing factors, namely the exposure concentration and volume of drinking water, on the disability burden (DB) for minors and adults. Both the community-supply (Figure 3a) and self-supply (Figure 3b) modes of drinking water exhibit similar outcomes. This similarity result can be attributed to the limited effectiveness of the simple treatment methods employed in the self-supply mode. But this simple treatment still reduces the psychological wariness to the treated water, prompting an increase in drinking volume (V in Table 2). Sapana et al. (2012) have studied a common simple treatment for groundwater and obtained that the number of microorganisms in groundwater is still not satisfied the WHO drinking water standards under the current situation. In sum, an increase in the volume of drinking water leads to a corresponding increase in the

number of consumed microorganisms.

Furthermore, when examining the sensitivity percentage ratio in each scenario, the rankings of the parameters are coincident between minors and adults. This finding can be attributed to the use of the same input values for the sensitivity parameter of exposure concentration. Meanwhile, the other sensitivity parameter, which is the volume of drinking water, shows minimal variation. These results imply that the age group of the population studied has little influence on the prioritization of the control measures. Both adults and minors share similar risk impact parameters that should be given priority. When dealing with faecal coliform in well water and *E. coli* in borehole water scenarios, prioritizing the volume of drinking water is essential. However, in scenarios involving faecal coliform in borehole water and *E. coli* in well water, the focus should shift to prioritizing exposure concentration as the primary risk impact parameter. Exposure concentration and volume of drinking water show alternating regularities for the two pathogenic microorganisms considered. Referring to faecal coliform, sensitivity analysis indicates that exposure concentration is more sensitive to the DB of borehole water, but the volume of drinking water contributes more to the DB of well water. With regard to borehole water, the sensitivity percentage ratio of exposure concentration is 0.3 – 0.8 times higher than that of volume of drinking water; as for well water, the volume of drinking water is 0.9 – 1.5 times higher than that of exposure concentration. However, the results for *E. coli* are the complete opposite. For well water, the sensitivity percentage ratio of exposure concentration is 0.2 – 0.7 times higher than that of the volume of drinking water. For borehole water, the value of drinking water is 0.4 – 0.9 times higher than that of exposure concentration. This result further demonstrates the substantial impact of pathogen type on health risk because of the different factors for dose–response relationships between the faecal coliform and *E. coli* (Blokker, Smeets,

& Medema, 2018). The *E. coli* dose is multiplied by 0.08 given that 8% of *E. coli* are pathogenic, but pathogenicity of faecal coliform is assumed as 1 (Haas et al., 1999; Machdar et al., 2013; Shi et al., 2018).

Treatments for exposure concentration of microorganisms in water sources should take precedence over the control of the volume of drinking water. Referring to the two pathogenic microorganisms (*E. coli* and faecal coliform), the two different sources of drinking water have various priorities for control. For well water, the sensitivity of exposure concentration of *E. coli* ranks first in the contribution to disease health risk burden, but faecal coliform exposure concentration is the priority for borehole water (Figure 3). This result is related to the degree of dispersion (standard deviation) of microorganisms' exposure concentration being more than 50% of its mean value in all exposure scenarios, which implies the various pollution levels of drinking water sources. Therefore, decreasing the exposure concentration should be one of the most significant methods for lessening the disease health risk burden of drinking water sources characterized by diverse water qualities. To reduce risks associated with the use of borehole and wells for drinking water, adequate maintenance and protection from open environment exposure are required (Olalemi et al., 2021). But in regions where water sources are heavily contaminated with microorganisms, it suggests that it should be seriously treated, such as eliminating around sources of faecal contamination. In addition, for wells, ensuring their proper design/construction to prevent pollutants from entering the wellhead or by-pass flow near the wellhead is critical (Hynds et al., 2014).

3.2 Health risks for various age levels

To further investigate the impact of more detailed age ranges on health risk assessment,

393 the age level has been divided into six ranges (Type II in Table 3). Figures 4-7 present
394 the risks of infection and DB for each of the six exposure scenarios, and specific results
395 can be found in Supplementary Materials Table 6-9.
396 Under general conditions, for all age ranges, the health risks exceed the corresponding
397 benchmarks (ranging from 0.2 to 30 times higher for $P_{(y)}$ and 4.3 to 140 times higher
398 for DB), aligning with the conclusions drawn for age level Type I (adults and minors).
399 This observation is consistent with the Guidelines for Drinking-water Quality (WHO,
400 2022), which states that coliform bacteria should not be detected in drinking water at
401 any level, yet the concentration of pathogenic bacteria in water ranges from 1.7 to 230
402 CFU/100 mL in this study (Supplementary Materials Table 1).
403 Furthermore, within each age range in Type II, the health risks associated with drinking
404 water type per capita intake (depicted in Figures 4 and 5) are consistently lower than
405 those linked to drinking water type consumer-only intake (shown in Figures 6 and 7).
406 This implies that households relying on self-supply mode face higher risks compared
407 to those in the current exposure scenarios. Similar findings were reported by Arévalo-
408 Pérez et al. (2014) and Galdos-Balzategui et al. (2017), suggesting that increased
409 investment in simple treatments does not always guarantee water safety in all
410 circumstances in the planned future. Thus, for newborns, the community-supply model
411 is recommended and investments in the self-supply model should be used to focus on
412 continuous management and safety monitoring of public water sources. In the self-
413 supply model, enhancing the effectiveness of simple treatment methods, such as
414 increasing the treatment duration to ensure the reduction of the microorganism
415 concentration, is seen as essential.
416
417 [Figure 4 inserts here]

[Figure 5 inserts here]

[Figure 6 inserts here]

[Figure 7 inserts here]

Under the best-case condition, the probabilities of infection during the infancy period for the community-supply mode are all within acceptable limits (Figure 4a). However, as age increases, the risks of infection gradually escalate, surpassing the U.S. EPA benchmark from the childhood period for well water (Figure 4b) and the maturity stage for borehole water (Figure 4d). The exception is for borehole water contaminated with faecal coliforms, where the infection risks consistently meet the benchmark (Figure 4). The DB results follow a similar trend, with risks increasing steadily as age advances, surpassing the WHO benchmark from the childhood period for all scenarios except borehole water (Figure 5b), which consistently fails to meet the WHO benchmark (Figure 5). The senile period exhibits the highest health risks (Figures 4e and 5e). Similar findings were reported by Buzby (2002) and Balbus and Malina (2009), suggesting that the risks of elderly individuals are higher than other age groups when exposed to microbial pathogens.

Furthermore, under the best-case condition, for all age ranges (Figures 4f and 6f), the probabilities of infection are acceptable only for borehole water. The health risks associated with borehole water was consistently lower than those of well water. This result aligns with the conclusions drawn for adults and minors, indicating that borehole water is a relatively more suitable water source compared to well water.

3.3 Limitation

Microbial concentration (C) and drinking water volume (V) were chosen as the two

main variable inputs of QMRA sensitivity analysis. Drinking water volume is influenced not only by age groups but also by gender, weight, personal physical condition, and lifestyle factors (U.S. EPA, 2011). These aspects were not considered in our study because they are already well-thought-out in the definition of the recommended factor drinking water volume.

Regarding exposure to pathogenic microorganisms, human health risk should not rely only on a single pathogen. However, due to limited data and constraints with existing dose-response models, it remains challenging to comprehensively assess the combined effects of multiple microbial pathogens on human health (Haas, 2015). To overcome these issues, the parameter volume of drinking water was derived from the Recommended Values for Drinking Water Ingestion table provided in the U.S. EPA health risk assessment guidelines (U.S. EPA, 2011; Table 2). Additionally, other parameters in the calculation were selected from well-established studies in the field of health risk assessment to ensure comparison with previous work and real-world scenarios (Table 3).

4. Conclusion

The findings of this study have important implications for the management and safety of drinking water sources. The higher health risks associated with the self-supply mode ($P_{(y)}$: 1.35×10^{-4}–3.13×10^{-3} pppy; DB: 6.12×10^{-6}–1.41×10^{-4} DALYs pppy) compared to the community-supply mode ($P_{(y)}$: 1.18×10^{-4}–2.98×10^{-3} pppy; DB: 5.31×10^{-6}–1.35×10^{-4} DALYs pppy) highlight the need for effective water treatment and management strategies for individuals relying on self-supplied water. Additionally, the consistent higher risks observed for well water compared to borehole wate ($P_{(y)}$: 4.45–4.67 times

higher for *E. coli*; 7.49–7.92 times higher for faecal coliform. DB: 4.47–4.60 times higher for *E. coli*; 7.41–7.60 times higher for faecal coliform) underscore the importance of improving monitoring and treatment practices for well water sources. The sensitivity analysis revealed that controlling the concentration of microorganisms in drinking water is crucial, emphasizing the need to prioritize reducing specific pathogens depending on the water source. Furthermore, the minor differences observed between adults and minors in terms of risk impact suggest that both age groups require similar prioritization in managing health risks. The study also highlights the need for rigorous monitoring and treatment measures for well water, as it consistently failed to meet benchmark requirements even under optimistic scenarios. Overall, these findings contribute to our understanding of risk assessment of environmental health for hazards pathogenic microorganisms in drinking water and provide valuable insights for stakeholders involved in managing and protecting drinking water sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

Cheng Yan: Conceptualization, Data curation, Writing-original draft, Writing-review & editing, Visualization, Software, Investigation, Funding acquisition, Resources, Supervision & Validation. Wei-di Wan: Conceptualization, Data curation, Writing-original draft, Writing-review & editing, Visualization, Software. Rui-ning Wang: Writing-original draft, Writing-review & editing, Visualization, Supervision & Validation. Tian-nuo Lai: Visualization, Software. Wajid Ali: Software, Supervision & Validation. Shan-shan He: Software, Supervision & Validation. Sai Liu: Visualization, Software, Supervision & Validation. Xiang Li: Visualization, Software, Supervision &

Validation. Zaheer Ahmad Nasir: Supervision & Validation. Frederic Coulon: Writing-review & editing, Visualization, Supervision & Validation.

References

Amatobi, D.A.; Agunwamba, J.C. Improved quantitative microbial risk assessment (QMRA) for drinking water sources in developing countries. Applied Water Science 2022;12

Arévalo-Pérez, E.C.; Martínez-León, A.J.; Lemus-Pérez, M.F.; Rodríguez-Susa, M.S. Aproximación a la presencia de SPD y microorganismos en agua embotellada. Tecnología y ciencias del agua 2014;5:05-18.

Azhdarpoor, A.; Salehi, N.; Heidari, H.; Sarmadipour, M.; Mahmoudian, H. Relationship between turbidity and microbial load of water in salman Farsi Dam Reservoir. J Environ Pollut Manage 2019;2:201

Baia, C.C.; Vargas, T.F.; Ribeiro, V.A.; Laureano, J.d.J.; Boyer, R.; Dórea, C.C.; Bastos, W.R. Microbiological Contamination of Urban Groundwater in the Brazilian Western Amazon. Water 2022;14:4023

Bain, R.E.; Gundry, S.W.; Wright, J.A.; Yang, H.; Pedley, S.; Bartram, J.K. Accounting for water quality in monitoring access to safe drinking-water as part of the Millennium Development Goals: lessons from five countries. Bulletin of the World Health Organization 2012;90:228-235

Bakalli, M.; Bakalli, D.; Selamaj, J. Assessment of quality of water wells in rural areas in Tirana City, Albania. AIP Conference Proceedings: AIP Publishing; 2019

Balbus, J.M.; Malina, C. Identifying vulnerable subpopulations for climate change health effects in the United States. Journal of occupational and environmental

522 medicine 2009;51:33-37
523 Barrow, C. J. 2016. Water resources and agricultural development in the tropics.
524 Routledge.Bogdanovic´ T, Ujevic I, Sedak M, Listeš E, Šimat V, Petricˇevic S, Poljak
525 V. 2014. As, Cd, Hg and Pb in four edible shellfish species from breeding and
526 harvesting areas along the eastern Adriatic Coast, Croatia. Food Chem. 146:197–203
527 Blokker M, Smeets P, Medema G. Quantitative microbial risk assessment of repairs of
528 the drinking water distribution system[J]. Microbial Risk Analysis, 2018, 8: 22-31.
529 Buzby J C. Older adults at risk of complications from microbial foodborne illness[J].
530 Food Review/National Food Review, 2002, 25(1482-2016-121529): 30-35.
531 Bwire, G.; Sack, D.A.; Kagirita, A.; Obala, T.; Debes, A.K.; Ram, M.; Komakech, H.;
532 George, C.M.; Orach, C.G. The quality of drinking and domestic water from the
533 surface water sources (lakes, rivers, irrigation canals and ponds) and springs in
534 cholera prone communities of Uganda: an analysis of vital physicochemical
535 parameters. BMC Public Health 2020;20:1-18.
536 Charles, K.J.; Nowicki, S.; Bartram, J.K. A framework for monitoring the safety of
537 water services: from measurements to security. NPJ Clean Water 2020;3:36
538 Davis. R. & Hirji. R. (Eds) (2003). Water Quality: As.sessment and Protection. Water
539 resources and environment technical note D.I. The World Bank, Washington, DC.
540 De Giglio, O.; Barbuti, G.; Trerotoli, P.; Brigida, S.; Calabrese, A.; Di Vittorio, G.;
541 Lovero, G.; Caggiano, G.; Uricchio, V.F.; Montagna, M.T. Microbiological and
542 hydrogeological assessment of groundwater in southern Italy. Environmental
543 monitoring and assessment 2016;188:1-9
544 Dean, K.; Mitchell, J. Reverse QMRA for Pseudomonas aeruginosa in premise
545 plumbing to inform risk management. Journal of Environmental Engineering
546 2020;146:04019120

547 Dias, E.; Ebdon, J.; Taylor, H. Estimating the concentration of viral pathogens and
548 indicator organisms in the final effluent of wastewater treatment processes using
549 stochastic modelling. Microbial Risk Analysis 2019;11:47-56
550 Dong, Y.; Jiang, Z.; Hu, Y.; Jiang, Y.; Tong, L.; Yu, Y.; Cheng, J.; He, Y.; Shi, J.; Wang,
551 Y. Pathogen contamination of groundwater systems and health risks. Critical
552 Reviews in Environmental Science and Technology 2023:1-23
553 Dyussenbayev, A. Age Periods Of Human Life. Advances in Social Sciences Research
554 Journal 2017;4
555 Easterday, K.; Paulson, T.; DasMohapatra, P.; Alagona, P.; Feirer, S.; Kelly, M. From
556 the field to the cloud: A review of three approaches to sharing historical data from
557 field stations using principles from data science. Frontiers in Environmental Science
558 2018;6:88
559 Ferson, S.; Tucker, W.T. Sensitivity analysis using probability bounding. Reliability
560 Engineering & System Safety 2006;91:1435-1442
561 Fienen, M.N.; Arshad, M. The international scale of the groundwater issue. Integrated
562 groundwater management: concepts, approaches and challenges 2016:21-48
563 Fuhrimann, S.; Winkler, M.S.; Stalder, M.; Niwagaba, C.B.; Babu, M.; Kabatereine,
564 N.B.; Halage, A.A.; Utzinger, J.; Cissé, G.; Nauta, M. Disease burden due to
565 gastrointestinal pathogens in a wastewater system in Kampala, Uganda. Microbial
566 Risk Analysis 2016;4:16-28
567 Galdos-Balzategui, A.; Carmona de la Torre, J.; Sánchez-Pérez, H.J.; Morales-López,
568 J.J.; Torres-Dosal, A.; Gómez-Urbina, S. Evaluación cuantitativa del riesgo
569 microbiológico por consumo de agua en San Cristóbal de Las Casas, Chiapas,
570 México. Tecnología y ciencias del agua 2017;8:133-153
571 Gibney, K.; Sinclair, M.; O'toole, J.; Leder, K. Using disability-adjusted life years to set

572 health-based targets: a novel use of an established burden of disease metric. Journal
573 of public health policy 2013;34:439-446
574 Grönwall, J. T., Mulenga, M., McGranahan, G. 2010. Groundwater, self-supply and
575 poor urban dwellers: A review with case studies of Bangalore and Lusaka: IIED.
576 Gwimbi, P. The microbial quality of drinking water in Manonyane community: Maseru
577 District (Lesotho). African health sciences 2011;11
578 Haas, C.; Rose, J.; Gerba, C. Quantitative microbial risk assessment. JW Wiley. Inc:
579 New York 1999:464
580 Haas, C.N. Microbial dose response modeling: past, present, and future. Environmental
581 science & technology 2015;49:1245-1259
582 Haas, C.N.; Rose, J.B.; Gerba, C.P. Quantitative microbial risk assessment ed^eds: John
583 Wiley & Sons; 2014
584 Haas, C.N.; Rycroft, T.; Bibby, K.; Casson, L. Risks from ebolavirus discharge from
585 hospitals to sewer workers. Water Environment Research 2017;89:357-368
586 Havelaar, A.H.; Kirk, M.; Torgerson, P.R.; Gibb, H.J.; Devleesschauwer, B. World
587 Health Organization Global Estimates and Regional Comparisons of the Burden of
588 Foodborne Disease in 2010. Plos Medicine 2015;12:e1001923
589 Helton, J.C.; Johnson, J.D.; Sallaberry, C.J.; Storlie, C.B. Survey of sampling-based
590 methods for uncertainty and sensitivity analysis. Reliability Engineering & System
591 Safety 2006;91:1175-1209
592 Hirano, S.S.; Nordheim, E.V.; Arny, D.C.; Upper, C.D. Lognormal distribution of
593 epiphytic bacterial populations on leaf surfaces. Applied and Environmental
594 Microbiology 1982;44:695-700
595 Hynds, P.D.; Gill, L.W.; Misstear, B.D. A quantitative risk assessment of verotoxigenic
596 E. coli (VTEC) in private groundwater sources in the Republic of Ireland. Human

and Ecological Risk Assessment: An International Journal 2014;20:1446-1468

Hynds, P.D.; Misstear, B.D.; Gill, L.W. Investigation of water consumption patterns among Irish adults for waterborne quantitative microbial risk assessment (QMRA). Journal of water and health 2012;10:453-464

Irda Sari, S. Y., Sunjaya, D. K., Shimizu-Furusawa, H., Watanabe, C., & Raksanagara, A. S. (2018). Water Sources Quality in Urban Slum Settlement along the Contaminated River Basin in Indonesia: Application of Quantitative Microbial Risk Assessment. *Journal of environmental and public health, 2018*, 3806537. Retrieved from https://doi.org/10.1155/2018/3806537. doi:10.1155/2018/3806537

Irda Sari; Zhou, L. Effect of unboiled water consumption data on sensitivity analysis in quantitative microbial risk assessment. NPJ Clean Water 2018;1:18

Jahne, M.A.; Rogers, S.W.; Holsen, T.M.; Grimberg, S.J.; Ramler, I.P. Emission and dispersion of bioaerosols from dairy manure application sites: human health risk assessment. Environmental science & technology 2015;49:9842-9849

Kolarević, S.; Knežević-Vukčević, J.; Paunović, M.; Gačić, Z.; Vuković-Gačić, B. Assessment of the microbiological quality of the river Tisa in Serbia. Water Research and Management 2011;1:57-61

Kundu, A.; Wuertz, S.; Smith, W.A. Quantitative microbial risk assessment to estimate the risk of diarrheal diseases from fresh produce consumption in India. Food Microbiology 2018;75:95-102

Li, Q.; Kang, X.; Lin, G.; Yang, G.; Wu, P.; Zuo, W.; Xie, T.; Liu, Y. Groundwater quality characteristics and health risk assessment in the valley plain area of the western Qinghai–Tibet plateau. Journal of Contaminant Hydrology 2023;257:104221

Li, X.; Atwill, E.R.; Antaki, E.; Applegate, O.; Bergamaschi, B.; Bond, R.F.; Chase, J.;

622 Ransom, K.M.; Samuels, W.; Watanabe, N. Fecal indicator and pathogenic bacteria
623 and their antibiotic resistance in alluvial groundwater of an irrigated agricultural
624 region with dairies. Journal of environmental quality 2015;44:1435-1447
625 Lim, K.-Y.; Hamilton, A.J.; Jiang, S.C. Assessment of public health risk associated with
626 viral contamination in harvested urban stormwater for domestic applications. Science
627 of the Total Environment 2015;523:95-108
628 Liu, Y.; Lu, W.; Wang, H.; Gao, X.; Huang, Q. Improved impact assessment of odorous
629 compounds from landfills using Monte Carlo simulation. Science of the total
630 environment 2019;648:805-810
631 Loper, J.; Suslow, T.; Schroth, M. Lognormal distribution of bacterial populations in
632 the rhizosphere. Phytopathology 1984;74:1454-1460
633 Lukubye, B.; Andama, M. Bacterial analysis of selected drinking water sources in
634 Mbarara Municipality, Uganda. Journal of Water Resource and Protection
635 2017;9:999-1013
636 Lutterodt, G.; Van de Vossenberg, J.; Hoiting, Y.; Kamara, A.K.; Oduro-Kwarteng, S.;
637 Foppen, J.W.A. Microbial groundwater quality status of hand-dug wells and
638 boreholes in the Dodowa area of Ghana. International Journal of Environmental
639 Research and Public Health 2018;15:730.
640 Machdar, E.; Van Der Steen, N.; Raschid-Sally, L.; Lens, P. Application of quantitative
641 microbial risk assessment to analyze the public health risk from poor drinking water
642 quality in a low income area in Accra, Ghana. Science of the Total Environment
643 2013;449:134-142
644 Mangale Sapana, M.; Chonde Sonal, G.; Raut, P. Use of Moringa oleifera (drumstick)
645 seed as natural absorbent and an antimicrobial agent for ground water treatment.
646 Research Journal of Recent Sciences. ISSN 2012;2277:2502

Marobhe, N.J. Critical review of water supply services in urban and rural areas of Tanzania. Water policy 2008;10:57-71

Marras, L.; Bertolino, G.; Sanna, A.; Pinna, A.; Carraro, V.; Schintu, M.; Coroneo, V. Potential issues of well water in domestic use in a retrospective study from 2014 to 2018. Environmental Monitoring and Assessment 2020;192:1-8

Mato, R. Groundwater pollution in urban Dar es Salaam. Tanzania: Assessing Vulnerability and Protection Priorities, Department of Chemical Engineering and Chemistry, Technische Universiteit Eindhoven, Eindhoven, Netherlands 2002:194

Mohammadi, A.A.; Zarei, A.; Majidi, S.; Ghaderpoury, A.; Hashempour, Y.; Saghi, M.H.; Alinejad, A.; Yousefi, M.; Hosseingholizadeh, N.; Ghaderpoori, M. Carcinogenic and non-carcinogenic health risk assessment of heavy metals in drinking water of Khorramabad, Iran. MethodsX 2019;6:1642-1651

Mok, H.-F.; Barker, S.F.; Hamilton, A.J. A probabilistic quantitative microbial risk assessment model of norovirus disease burden from wastewater irrigation of vegetables in Shepparton, Australia. Water research 2014;54:347-362

Moya, J.; Goldman, L.R. Children's Exposure to Environmental Agents, Editor(s): Jerome Nriagu, Encyclopedia of Environmental Health (Second Edition), Elsevier, 2011, Pages 603-609,

Naik, M.R.; Barik, M.; Jha, V.; Sahoo, S.K.; Sahoo, N.K. Spatial distribution and probabilistic health risk assessment of fluoride in groundwater of Angul district, Odisha, India. Groundwater for Sustainable Development 2021;14:100604

National Research Council, 1983. Risk Assessment in the Federal Government: Managing the Process. The National Academies Press.

Ngasala, T.M.; Masten, S.J.; Phanikumar, M.S.; Mwita, E.J. Analysis of water security and source preferences in rural Tanzania. Journal of Water, Sanitation and Hygiene

for Development 2018;8:439-448

Ngoran, S.D.; Dogah, K.E.; Xue, X. Assessing the impacts of climate change on water resources: The Sub-Saharan Africa perspective. Journal of Economics and Sustainable Development 2015;6:185-193

Odey, M.O.; Ibor, O.R.; Andem, A.B.; Ettah, I.; Chukwuka, A.V. Drinking water quality and risk implications for community health: A case study of shallow water wells and boreholes in three major communities in Northern Cross-River, Southern Nigeria. Human and Ecological Risk Assessment: An International Journal 2018;24:427-444

Olalemi, A.; Ogundare, O.; Yusuff, A.; Ajibola, N. Risk assessment of traditional faecal pollution markers in three streams in Akure, Nigeria. Jordan Journal of Earth and Environmental Sciences 2020;11:93-97

Olalemi, A.O.; Ige, O.M.; James, G.A.; Obasoro, F.I.; Okoko, F.O.; Ogunleye, C.O. Detection of enteric bacteria in two groundwater sources and associated microbial health risks. Journal of Water and Health 2021;19:322-335

Omole, D.O. Sustainable groundwater exploitation in Nigeria. Journal of Water Resources and Ocean Science 2013;2:9-14

Owusu-Ansah, E.d.-G.J.; Sampson, A.; Amponsah, S.K.; Abaidoo, R.C.; Dalsgaard, A.; Hald, T. Probabilistic quantitative microbial risk assessment model of norovirus from wastewater irrigated vegetables in Ghana using genome copies and fecal indicator ratio conversion for estimating exposure dose. Science of the Total Environment 2017;601:1712-1719

Palamuleni, L.; Akoth, M. Physico-chemical and microbial analysis of selected borehole water in Mahikeng, South Africa. International journal of environmental research and public health 2015;12:8619-8630

Pang, X.; Gao, T.; Qiu, Y.; Caffrey, N.; Popadynetz, J.; Younger, J.; Lee, B.E.; Neumann,

N.; Checkley, S. The prevalence and levels of enteric viruses in groundwater of private wells in rural Alberta, Canada. Water Research 2021;202:117425

Pantaleo, P.; Komakech, H.C.; Mtei, K.M.; Njau, K.N. Contamination of groundwater sources in emerging African towns: The case of Babati town, Tanzania. Water Practice & Technology 2018;13:980-990

Pasalari, H.; Ataei-Pirkooh, A.; Aminikhah, M.; Jafari, A.J.; Farzadkia, M. Assessment of airborne enteric viruses emitted from wastewater treatment plant: atmospheric dispersion model, quantitative microbial risk assessment, disease burden. Environmental Pollution 2019;253:464-473

Qasemi, M.; Farhang, M.; Biglari, H.; Afsharnia, M.; Ojrati, A.; Khani, F.; Samiee, M.; Zarei, A. Health risk assessments due to nitrate levels in drinking water in villages of Azadshahr, northeastern Iran. Environmental Earth Sciences 2018;77:1-9

Regli, S.; Rose, J.B.; Haas, C.N.; Gerba, C.P. Modeling the risk from Giardia and viruses in drinking water. Journal - American Water Works Association 1991;83:76-84

Seis, W.; Rouault, P.; Medema, G. Addressing and reducing parameter uncertainty in quantitative microbial risk assessment by incorporating external information via Bayesian hierarchical modeling. Water Research 2020;185:116202

Shi, K.-W.; Wang, C.-W.; Jiang, S.C. Quantitative microbial risk assessment of Greywater on-site reuse. Science of the Total Environment 2018;635:1507-1519

Stellacci, P.; Liberti, L.; Notarnicola, M.; Haas, C.N. Hygienic sustainability of site location of wastewater treatment plants: A case study. I. Estimating odour emission impact. Desalination 2010;253:51-56

Taylor, R.; Miret-Gaspa, M.; Tumwine, J.; Mileham, L.; Flynn, R.; Howard, G.;

721 Kulabako, R. Increased risk of diarrhoeal diseases from climate change: evidence
722 from urban communities supplied by groundwater in Uganda. Groundwater and
723 climate in Africa Proceedings of the Kampala Conference, Uganda, 24-28 June 2008:
724 IAHS Press; 2009
725 Tuttle L, Meng Q, Moya J, Johns DO. Consideration of age-related changes in behavior
726 trends in older adults in assessing risks of environmental exposures. J Aging Health.
727 2013 Mar;25(2):243-73. doi: 10.1177/0898264312468032. Epub 2012 Dec 6. PMID:
728 23223208.
729 U. Water. World Water Development Report 2020. United Nation: New York, NY, USA
730 2020;
731 U.S. EPA, 2005. Occurrence and Exposure Assessment for the Final Long Term 2
732 Enhanced Surface Water Treatment Rule. Office of Water. United States
733 Environmental Protection Agency, Washington, DC. EPA 815-R-06-002.
734 U.S. EPA. (2011) Exposure Factors Handbook: 2011 Edition. National Center for
735 Environmental Assessment, Washington, DC; EPA/600/R-09/052F. Available from
736 the National Technical Information Service, Springfield, VA, and online at
737 http://www.epa.gov/ncea/efh.
738 United Nations, The United Nations World Water Development Report 2022:
739 Groundwater: Making the invisible visible. UNESCO, Paris
740 W.H.O Progress on household drinking water, sanitation and hygiene 2000-2017:
741 special focus on inequalities ed^eds: World Health Organization; 2019
742 World Health Organization (2006) Guidelines for the safe use of wastewater, excreta
743 and greywater in agriculture and aquaculture. WHO Press, Geneva
744 World Health Organization (2019) Drinking-water. https://www.who.int/news-
745 room/fact-sheets/detail/drinking-water.

World Health Organization (2022). *Guidelines for drinking-water quality: incorporating the first and second addenda*: World Health Organization.

World Health Organization, 2017. Diarrhoeal Disease. WHO, Geneva, Switzerland. Health topics. [online] (accessed 10 February 2019). https://www.who.int/water-sanitation-health/diseases-risks/diseases/diarrhoea/en/.

World Health Organization. Quantitative Microbial Risk Assessment: Application for Water Safety Management. (World Health Organization, Geneva, Switzerland, 2016; 187).

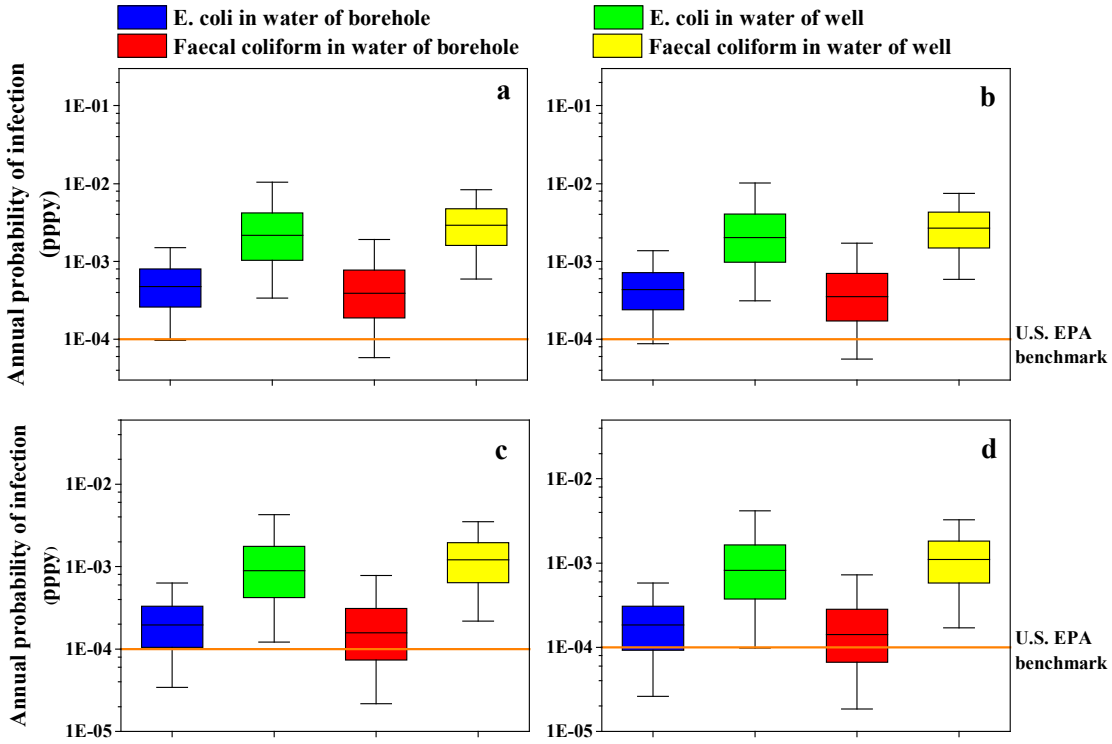
Wu, C.-F.; Piedra, L.M.; Matthew, L.E.; Rhodes, E.C.; Nguyen, T.H. Water treatment in rural Guatemala: factors associated with the use of biosand water filters. Journal of Water, Sanitation and Hygiene for Development 2020;10:286-297.

Xie, X.; Shi, J.; Pi, K.; Deng, Y.; Yan, B.; Tong, L.; Yao, L.; Dong, Y.; Li, J.; Ma, L. Groundwater Quality and Public Health. Annual Review of Environment and Resources 2023;48

Xu, P.; Zhang, C.; Mou, X.; Wang, X.C. Bioaerosol in a typical municipal wastewater treatment plant: concentration, size distribution, and health risk assessment. Water Science and Technology 2020;82:1547-1559

Yu, W.; Wardrop, N.A.; Bain, R.E.; Alegana, V.; Graham, L.J.; Wright, J.A. Mapping access to domestic water supplies from incomplete data in developing countries: An illustrative assessment for Kenya. PloS one 2019;14:e0216923

Zaneti, R.N.; Girardi, V.; Spilki, F.R.; Mena, K.; Westphalen, A.P.C.; da Costa Colares, E.R.; Pozzebon, A.G.; Etchepare, R.G. Quantitative microbial risk assessment of SARS-CoV-2 for workers in wastewater treatment plants. Science of the Total Environment 2021;754:142163



771

772 **Figure 1** $P_{(y)}$ (pppy) of exposure populations: (a) adults in drinking water self-supply
773 mode; (b) adults in drinking water community-supply mode; (c) minors in drinking
774 water self-supply mode; (d) minors in drinking water community-supply mode. The
775 bottom and top of the box respectively represent the first and third quartiles (25th and
776 75th percentile values), and the band inside the box denotes the second quartile (general
777 condition). The bottom and top of the whiskers respectively represent the 5th (best-case
778 condition for the optimistic estimate) and 95th (worst-case condition for conservative
779 estimate) percentile values. *E. coli* = *Escherichia coli*; U.S. EPA = United States
780 Environmental Protection Agency

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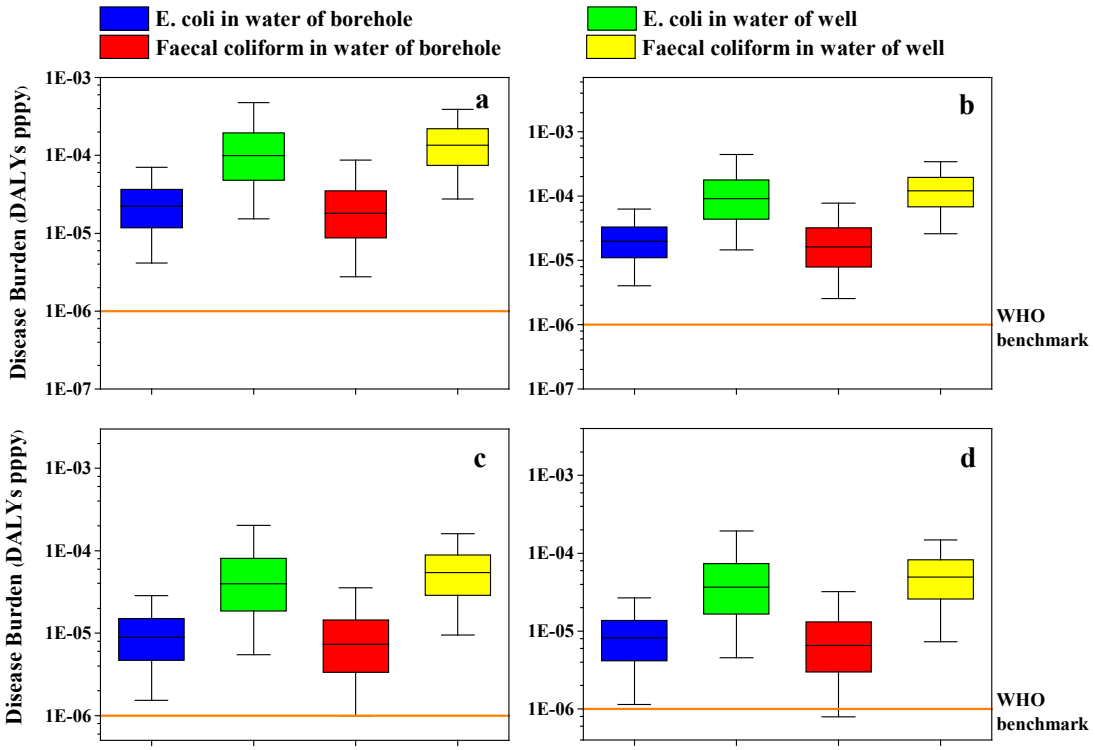


782

783 **Figure 2** DB (DALYs pppy) of exposure populations: (a) adults in self-supply mode of

784 drinking water; (b) adults in community-supply mode of drinking water; (c) minors in

785 self-supply mode of drinking water; (d) minors in community-supply mode of drinking

786 water. The bottom and top of the box respectively represent the first and third quartiles

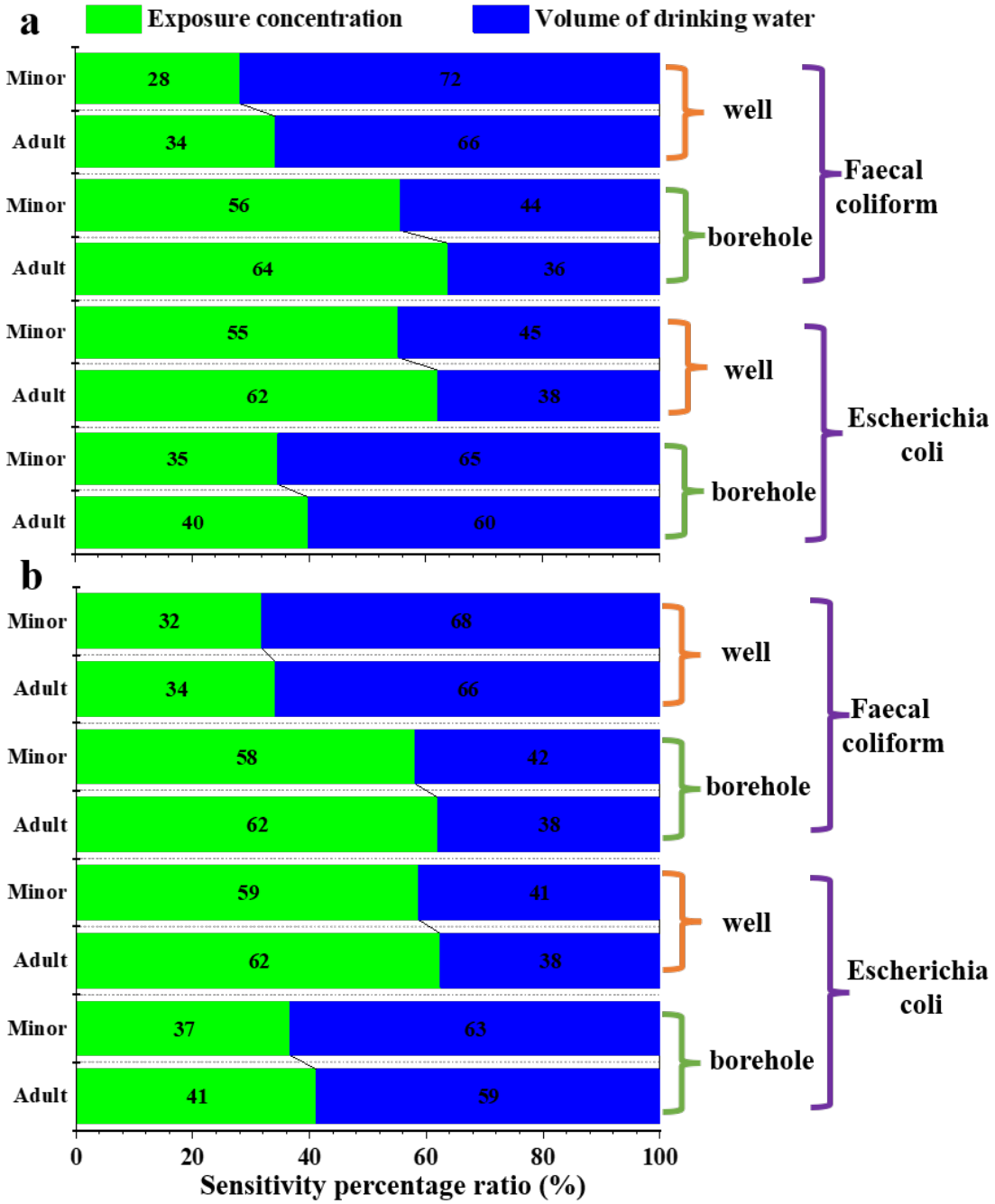
787 (25th and 75th percentile values), and the band inside the box denotes the second

788 quartile (general condition). The bottom and top of the whiskers respectively represent

789 the 5th (best-case condition for the optimistic estimate) and 95th (worst-case condition

790 for conservative estimate) percentile values.

791 *E. coli* = *Escherichia coli* ;WHO = World Health Organization



792

793 **Figure 3** Sensitivity percentage ratio of the sensitivity partitioning coefficient of each

794 sensitivity input parameter (exposure concentration and volume of drinking water) of

795 DBs of minors and adults in two drinking water supply modes: (a) community-supply;

796 (b) self-supply. Correlation coefficient values are obtained from Oracle Crystal Ball

797 sensitivity analyses and shown in the middle of each bar.

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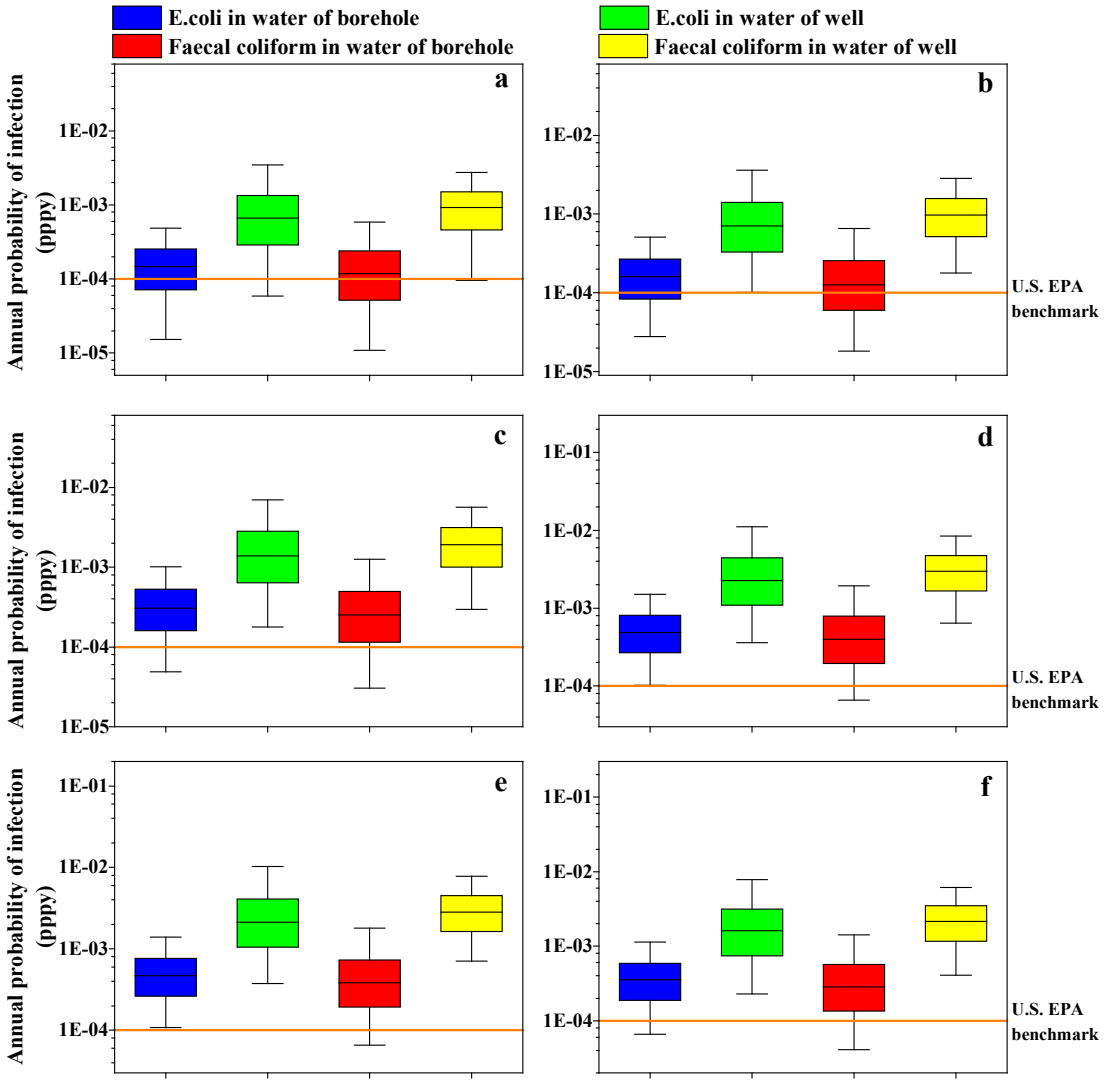

799

800 **Figure 4** $P_{(y)}$ (pppy) corresponding to the community-supply mode of drinking water
801 for six age ranges: (a) infancy period; (b) childhood period; (c) period of youth; (d)
802 maturity stage; (e) senile period; (f) all age. The bottom and top of the box respectively
803 represent the first and third quartiles (25th and 75th percentile values), and the band
804 inside the box denotes the second quartile (general condition). The bottom and top of
805 the whiskers respectively represent the 5th (best-case condition for the optimistic
806 estimate) and 95th (worst-case condition for conservative estimate) percentile values.
807 *E. coli* = *Escherichia coli*; U.S. EPA= United States Environmental Protection Agency
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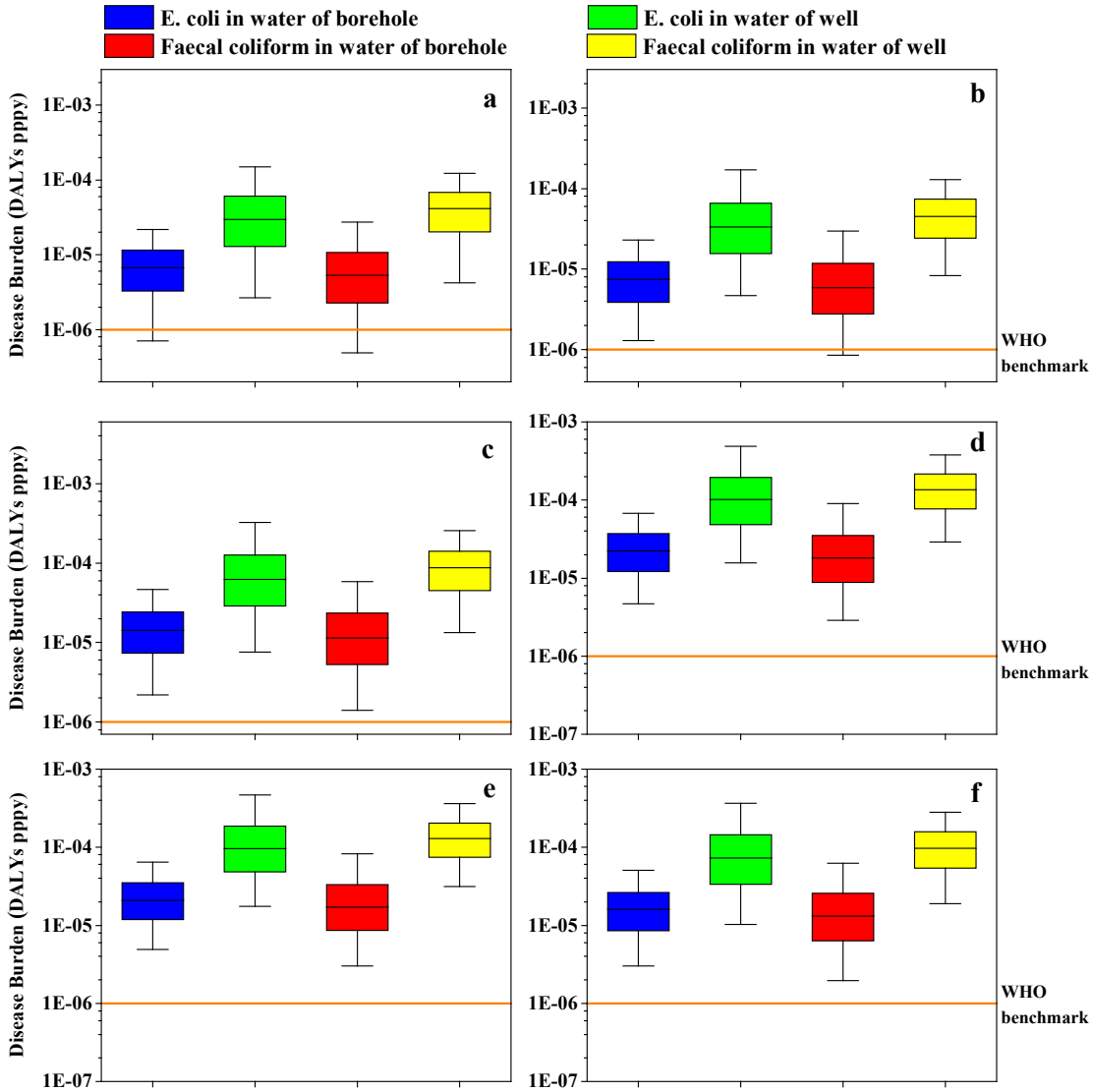


809

810 **Figure 5** DB (DALYs pppy) corresponding to the community-supply mode of drinking
811 water for six age ranges: (a) infancy period; (b) childhood period; (c) period of youth;
812 (d) maturity stage; (e) senile period; (f) all age. The bottom and top of the box
813 respectively represent the first and third quartiles (25th and 75th percentile values), and
814 the band inside the box denotes the second quartile (general condition). The bottom and
815 top of the whiskers respectively represent the 5th (best-case condition for the optimistic
816 estimate) and 95th (worst-case condition for conservative estimate) percentile values.
817 *E. coli* = *Escherichia coli*; WHO = World Health Organization

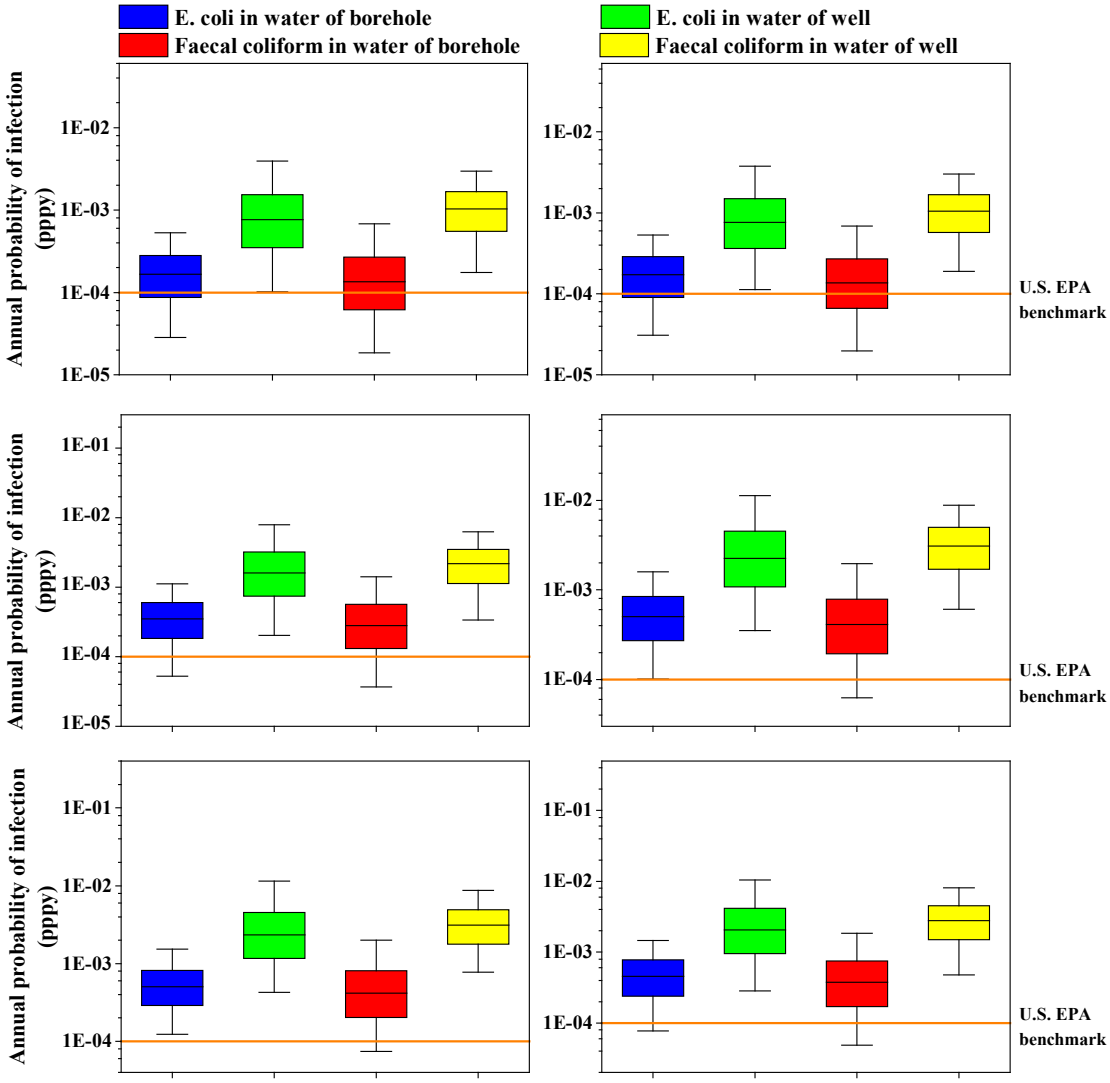
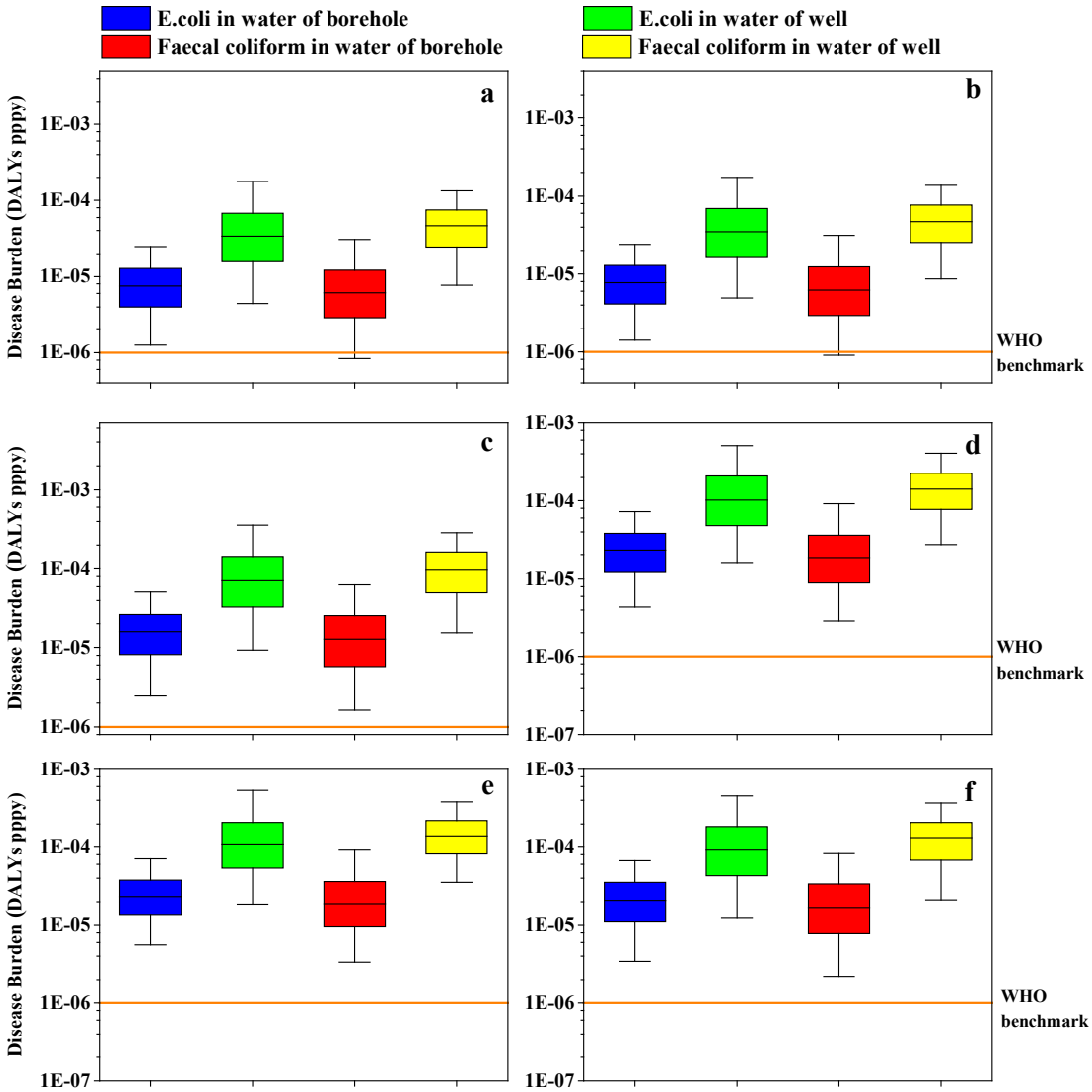


Figure 6 $P_{(y)}$ (pppy) corresponding to the self-supply mode of drinking water for six age ranges: (a) infancy period; (b) childhood period; (c) period of youth; (d) maturity stage; (e) senile period; (f) all age. The bottom and top of the box respectively represent the first and third quartiles (25th and 75th percentile values), and the band inside the box denotes the second quartile (general condition). The bottom and top of the whiskers respectively represent the 5th (best-case condition for the optimistic estimate) and 95th (worst-case condition for conservative estimate) percentile values.

E. coli= *Escherichia coli*; U.S. EPA= United States Environmental Protection Agency



828

829 **Figure 7** DB (DALYs pppy) corresponding to the self-supply mode of drinking water
830 for six age ranges: (a) infancy period; (b) childhood period; (c) period of youth; (d)
831 maturity stage; (e) senile period; (f) all age. The bottom and top of the box
832 respectively represent the first and third quartiles (25th and 75th percentile values),
833 and the band inside the box denotes the second quartile (general condition). The
834 bottom and top of the whiskers respectively represent the 5th (best-case condition for
835 the optimistic estimate) and 95th (worst-case condition for conservative estimate)
836 percentile values. *E. coli* = *Escherichia coli*; WHO = World Health Organization

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838 **Table 1 Two types of division of age groups for various exposure scenarios**

The type of age level	Age range (year)	Age level	References
Type I	0-18	Minor	-
	≥18	Adult	
Type II	0-1	Infancy period	U.S. EPA (2011); Dyussenbayev (2017)
	1-11	Childhood period	
	11-21	Period of youth	
	21-65	Maturity stage	
	≥65	Senile period	

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841 **Table 2 Volume of two drinking water types (L/day)**

Items	Age level		Min	Max
Community-supply mode Per Capita intake rates *	Age level Type I	Adult	0.198	2.685
		Minor	0.035	1.144
	Age level Type II	Infancy period	0.004	0.962
		Childhood period	0.052	0.997
		Period of youth	0.069	1.991
		Maturity stage	0.227	2.958
		Senile period	0.279	2.730
		All age	0.134	2.170
Self-supply mode Consumer-only intake **	Age level Type I	Adult	0.202	2.957
		Minor	0.059	1.230
	Age level Type II	Infancy period	0.047	1.057
		Childhood period	0.056	1.052
		Period of youth	0.087	2.226
		Maturity stage	0.192	3.092
		Senile period	0.325	2.960
		All age	0.124	2.881

842 * Per capita intake rates are generated by averaging consumer-only intakes over the
843 entire population (including those individuals who reported no intake) (U.S. EPA, 2011).
844 ** Consumer-only intake represents the quantity of water consumed only by
845 individuals that reported consuming water (U.S. EPA, 2011).
846

Table 3 Parameters for quantitative microbial risk assessment calculation

Parameters	Unit	Values	References
C: Exposure concentration of pathogens concentrations in the water	CFU/L	Supplemental Materials Table 1	-
Exposure dose $d=V\times C$	CFU	V: Table 2	Machdar et al. (2013)
Daily probability of infection beta-Poisson model: $P_i(d)=1-\left[\left(1+\frac{d}{N_{50}}(2^{1/\alpha}-1)\right)\right]^{-\alpha}$	-	α=0.1778; N_{50}=8.6E+7	Sari (2018)
Annual probability of infection $P_{(y)}=1-(1-P_i(d))^n$	pppy	n means exposure frequency n=365 d	Haas (2014); Kundu et al. (2018)
Disease burden $DB=P_{(y)}\times HB$	DALYs pppy	HB (Health burden) = 0.0455	Havelaar et al. (2015)

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