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Microbial contamination along the main open wastewater and storm water channel of Hanoi, Vietnam, and potential health risks for urban farmers

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HIGHLIGHTS

- We assessed the wastewater systems in reducing microbial contamination in Hanoi, Vietnam.
- We found that bacterial contamination in water used in agricultural field exceeds safety limits.
- We propose a series of control measures that would allow reducing microbial contamination.
- This paper can guide cities in Asia on how to work towards the Sustainable Development Goal 6.3 linked to safe use of wastewater.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of wastewater in agriculture and aquaculture has a long tradition throughout Asia. For example, in Hanoi, it creates important livelihood opportunities for >500,000 farmers in peri-urban communities. Discharge of domestic effluents pollute the water streams with potential pathogenic organisms posing a public health threat to farmers and consumers of wastewater-fed foodstuff. We determined the effectiveness of Hanoi's wastewater conveyance system, placing particular emphasis on the quality of wastewater used in agriculture and

Abbreviations: CFU, colony forming unit; HSDC, Hanoi Sewerage and Drainage Company; MPN, most probable number; NIHE, National Institute for Hygiene and Epidemiology; QMRA, quantitative microbial risk assessment; SDG, Sustainable Development Goal; SSP, sanitation safety planning; Swiss TPH, Swiss Tropical and Public Health Institute; TC, total coliforms; WHO, World Health Organization.

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aquaculture. Between April and June 2014, a total of 216 water samples were obtained from 24 sampling points and the concentrations of total coliforms (TC), *Escherichia coli*, *Salmonella* spp. and helminth eggs determined. Despite applied wastewater treatment, agricultural field irrigation water was heavily contaminated with TC (1.3×10^7 colony forming unit (CFU)/100 mL), *E. coli* (1.1×10^6 CFU/100 mL) and *Salmonella* spp. (108 most probable number (MPN)/100 mL). These values are 110-fold above Vietnamese discharge limits for restricted agriculture and 260-fold above the World Health Organization (WHO)'s tolerable safety limits for unrestricted agriculture. Mean helminth egg concentrations were below WHO tolerable levels in all study systems (<1 egg/L). Hence, elevated levels of bacterial contamination, but not helminth infections, pose a major health risk for farmers and consumers of wastewater fed-products. We propose a set of control measures that might protect the health of exposed population groups without compromising current urban farming activities. This study presents an important example for sanitation safety planning in a rapidly expanding Asian city and can guide public and private entities working towards Sustainable Development Goal target 6.3, that is to improve water quality by reducing pollution, halving the proportion of untreated wastewater and increasing recycling and safe reuse globally.

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1. Introduction

Asia has a long tradition in the use of wastewater in agriculture and aquaculture (Qadir et al., 2010). Particularly, in peri-urban areas of large urban centres, farmers benefit from the all-year-round availability of wastewater and its high nutrient content (Drechsel et al., 2015). However, as Asian cities have grown rapidly, and continue to do so, appropriate infrastructures to collect and treat wastewater are often lacking, and hence, there are high levels of environmental pollution (Evans et al., 2012). Moreover, sewerage usually receive combined effluents from households, hospitals and industries, which in turn can contaminate the environment with a diffuse mix of pathogenic organisms and toxic chemicals (Phung et al., 2015). Consequently, safe wastewater management is of considerable public health relevance for people living along wastewater channels, farmers using wastewater, as well as consumers of wastewater irrigated crops and wastewater-fed fish (Hanjra et al., 2011; Utzinger et al., 2015). Safe wastewater management and use is also prominently featured in the Sustainable Development Goal (SDG) target 6.3, which was put forth by the United Nations and aims at improving water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and increasing recycling and safe reuse globally (UN, 2015).

A prominent example is Hanoi, the capital city of Vietnam. Over the past 20 years, the urban area has expanded, the population grew at an annual rate of 3.5%, resulting in 6.7 million people living on an area of 3329 km² in 2011 (GSO, 2011). More than 90% of the households in Hanoi rely on flush toilets that are connected to septic tanks, from where effluents are informally discarded into a wide network of drainage channels. In addition, these channels receive industrial effluents. In response to these challenges, the system was expanded in recent years to control the water flow out of the city and treat the wastewater with conventional treatment plants and decentralised water management systems (Kuroda et al., 2015). The latter should prevent flooding events, while regulating the water flow with water gates and a series of artificial ponds. In these artificial ponds, the wastewater is partially treated through sedimentation in combination with oxygenation. As a common practice, this partially treated wastewater is used in aquaculture and agriculture (Lan et al., 2012). Indeed, an estimated 658,000 farmers use wastewater on an area of approximately 43,778 ha in Hanoi (Raschidally and Jayakody, 2008). It must be noted that the use of wastewater creates important livelihood opportunities, as its high nutrient load is valuable for growing fresh vegetables and farm livestock and fish (Lan et al., 2012).

Several studies have reported high levels of microbial and chemical pollution in river sediments, irrigation water, splashing water used on markets and wastewater-fed foodstuff in Hanoi (Ingvertsen et al., 2013; Nguyen and Dalsgaard, 2014; Kuroda et al., 2015). Adverse health outcomes, such as diarrhoeal diseases, helminth infections and

dermatitis, due to exposure to wastewater are well documented (Anh et al., 2007; Do et al., 2007a; Hien et al., 2007; Pham-Duc et al., 2013). Of note, as far as 60 km downstream of Hanoi, in Hanam province, adverse health conditions were associated to the city's wastewater (Pham-Duc et al., 2013, 2014). Additionally, flooding events exacerbated negative health impacts with considerable burden for public health such as drowning of people and cholera epidemics (Bich et al., 2011). While the current evidence suggests multiple environmental and health issues, a systematic assessment of the effectiveness of the different components of Hanoi's wastewater conveyance and treatment system that might reduce microbial contamination is currently lacking. This includes the identification of targeted mitigation strategies for improving the quality of products from urban farming in Hanoi (Fuhrmann et al., 2014; WHO, 2015).

The objectives of the present study were: (i) to assess whether the existing treatment scheme is effective in reducing microbial (bacteria and helminth) contamination along the main wastewater channels and retention drainages prior to the use of water in aquaculture ponds and agricultural fields; and (ii) suggest control measures that might provide a safe management and use of wastewater in agriculture and aquaculture in Hanoi. This environmental assessment was part of a larger study, comprising of a cross-sectional parasitological survey in selected population groups exposed to wastewater and a quantitative microbial risk assessment (QMRA) to determine disease burden related to microbial contamination (Fuhrmann et al., in press). Moreover, the data contributed to the development of the sanitation safety planning (SSP) manual that has recently been published by the World Health Organization (WHO) (WHO, 2015).

2. Materials and methods

2.1. Study area

Hanoi is located in the north of Vietnam, situated in the Red River delta (geographical coordinates: 21° 01' 42.5" N latitude and 105° 51' 15.0" E longitude). Hanoi's climate is sub-tropical. The main rainy season occurs from April to September. There is year-round high humidity ranging from 80% to 90% (Climate-Data.org, 2015). The wastewater flows from north to south, along a topographic gradient from 20 m to 5 m above mean sea level in four main rivers, namely To Lich River, Nhue River, Kim Nguu River and Red River (Nguyen and Parkinson, 2005; Kuroda et al., 2015).

2.2. Sampling sites and procedure

A cross-sectional survey was conducted between April and June 2014. The present study focused on three parts of Hanoi's wastewater system, namely (i) the urban wastewater conveyance and treatment system (operated by the Hanoi Sewerage and Drainage Company

(HSDC)); (ii) the peri-urban wastewater conveyance, treatment and reuse system in the districts of Hoang Mai and Thanh Tri; and (iii) a comparison site in a rural area of Thanh Tri district, where Red River water (not considered as wastewater) is used for aquaculture and agriculture. As shown in Fig. 1, 24 sampling points were selected and a total of 216 samples obtained over the whole study period (a total of nine samples per sampling point were taken, one every week) in the three study systems. At each sampling point, three separate water samples (2×100 mL and 1 L) were collected approximately 10 cm below the surface of the respective water body in sterile wide mouth glass bottles. Samples were collected between 08:00 and 12:00 h each Monday (T_{R1-5} , R_{R1} , $N_{R1/2}$, WW_{D1-3} and WW_{F1-3}) or Tuesday (R_{R2} , C_{D1-3} , WW_{D1-3} and WW_{F1-3}). Upon collection, samples were transferred within 4 h to a nearby laboratory in a cool box (temperature 4 °C).

2.2.1. Sampling sites in the urban wastewater system

To Lich River (T_R) is the main open storm water and drainage channel of the city. It is 14 km long, starts at West Lake and is draining into Nhue River and Red River. The river arm flowing towards Red River drains into a series of artificial lakes, where it is partially treated through primary sedimentation ponds and sequential batch reactors at the Yen So wastewater treatment plant. Subsequently, the wastewater is screened and actively pumped into a drainage channel (3 km) that discharges into Red River. The arm flowing into Nhue River is controlled by a water gate that releases the raw wastewater without treatment into Nhue River (Duc et al., 2007; Kuroda et al., 2015). In To Lich River, five sampling points (T_{R1} to T_{R5}) spread over a distance of 9 km, starting from one at the Bang B pagoda just before the water is partly flowing into the Nhue River (T_{R1}), two in Bang B village and Tam Hiep commune (T_{R2} and T_{R3}), one just before the Yen Son lake system (T_{R4}) and one just before the water drains into Red River (T_{R5}).

Nhue River (N_R) originates from Red River in the north of Hanoi and flows south along the peri-urban area, where it receives domestic, hospital and industrial effluents (Duc et al., 2006). In Nhue River two sampling points were chosen (N_{R1} and N_{R2}), one just before the To

Lich River drains into Nhue River (N_{R1}) and one 500 m downstream after the two rivers join (N_{R2}).

Red River (R_R) has its source in China and is draining in the Gulf of Tonkin. The Red River delta is the second most important rice growing area in Vietnam, and also known as an intensive pig production system (Nguyen et al., 2014). In Red River, two sampling points were chosen (R_{R1} and R_{R2}), one at 150 m before To Lich River drains into Red River (R_{R1}) and the second at 3 km downstream, where water is pumped for agricultural purposes in Duyen Ha commune (R_{R2}).

2.2.2. Sampling sites in the peri-urban wastewater system

Bang B village and Tam Hiep commune, representing typical peri-urban communities pumping wastewater from To Lich River into local drainage channels (W_D) for use in agricultural fields (W_F), were selected as peri-urban sampling sites. The communities are located in Hoang Mai and Thanh Tri district, respectively (geographical coordinates: 20° 57' 17.54" N latitude and 105° 49' 42.48" E longitude) and are prone to rapid demographic transition, industrial development and land use change. A large part (33%) of the community members are involved in agriculture (e.g. rice, morning glory, neptunia and watercress) or aquaculture (Lan et al., 2012). Water was sampled at six sites in the drainage and pond systems (W_{D1} to W_{D6}), which connect and retain the water pumped from To Lich River to aquaculture ponds and agricultural fields. Another six sites (W_{F1} to W_{F3}) were selected in agricultural fields (primarily vegetables and rice) fed with water from the local drains and ponds.

2.2.3. Comparison site: rural non-wastewater system

Duyen Ha commune was selected as a comparison site (C_D) to represent a typical farming community relying on irrigation water from Red River. About 38% of the people work in agriculture (Fuhrmann et al., in press). The commune belongs to Thanh Tri district and is about 5 km from the outskirts of Hanoi (geographical coordinates: 20° 55' 42.37" N latitude and 105° 52' 23.32" E longitude). Water samples were collected at three sites (C_{D1} to C_{D3}), which transport the water from Red River to the agricultural fields. It is important to note that

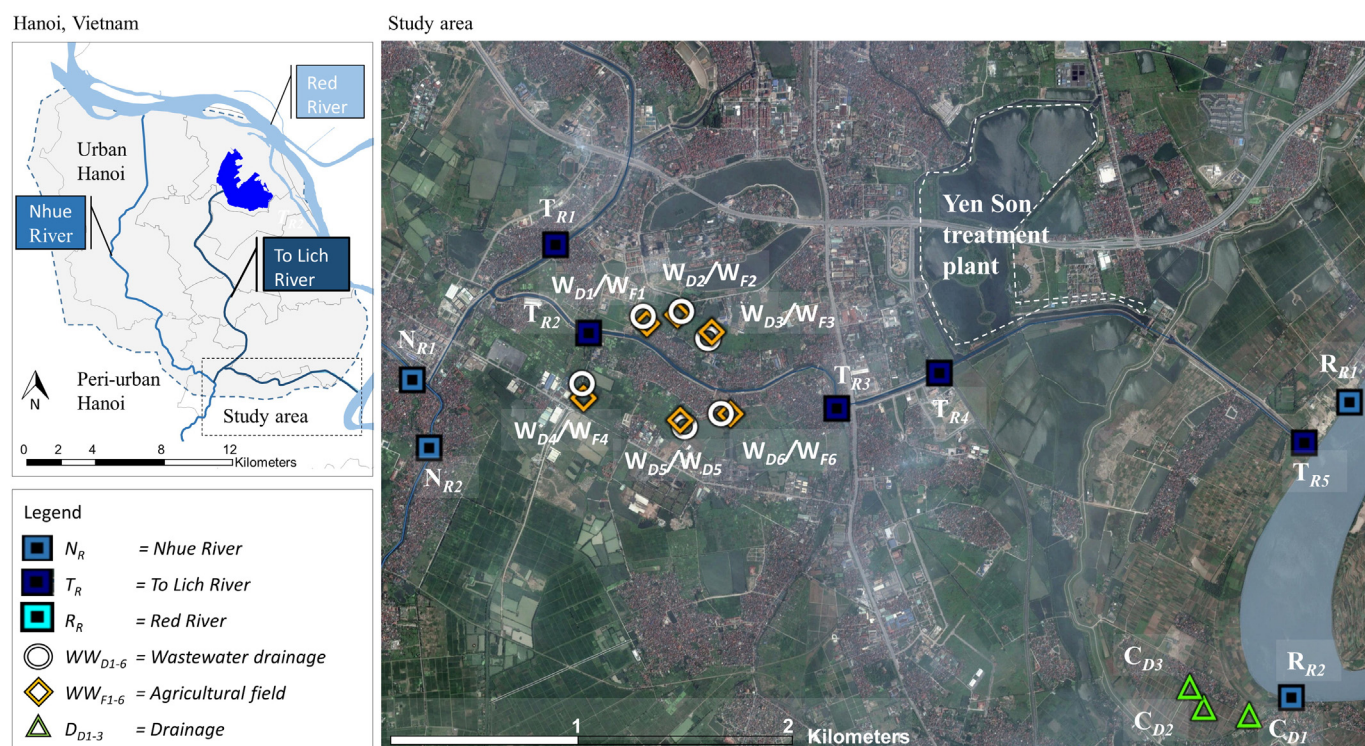


Fig. 1. Map of Hanoi showing the study area and respective sampling points (Google Earth, 2010).

these local drainage channels are potentially contaminated with household effluents but do not contain wastewater from Hanoi city.

2.3. Microbial analysis

2.3.1. Total coliforms and *Escherichia coli* analysis

TC and *E. coli* enumeration was performed by the National Institute for Hygiene and Epidemiology (NIHE), on Brilliance *E. coli*/coliform Selective Agar (CM1046, Oxoid) following incubation at 37 °C for 24 h. One milliliter of the water sample was aseptically transferred to a sterile tube containing 9 mL peptone saline broth (1:10). The sample was mixed well and 10-fold and 100-fold dilutions were prepared. 100 µL of each dilution was surface-spread onto duplicate agar plates. Agar plates showing growth of dark purple to indigo blue colonies were designated as *E. coli*, while pink colonies were considered TC. *E. coli* and TC counts were calculated using the standard formula and are expressed as CFU per 100 mL (Nguyen and Dalsgaard, 2014).

2.3.2. *Salmonella* spp. analysis

Salmonella spp. enumeration was conducted by the National Institute of Veterinary Research (NIVR) using the most probable number (MPN) technique (ISO 6579, 2002). Briefly, a series of 10-fold dilution sample with Buffer Peptone Water (BPW-Merk, Germany) was prepared; 2.5 mL of each dilution was transferred into a 12-well microtiter plate and incubated at 37 °C for 18 h. After incubation, 20 µL of incubated suspension was transferred into another 12-well microtiter plate, where each well contained 2 mL Modified Solid Rappaport Vassiliadis (MSRV-Merck; Darmstadt, Germany) and incubated at 41.5 °C for 24 h. Results were read after 24 h of incubation. Subsequently, 1 µL loop of the suspected MSRV (grey-white, turbid zone extending out from the inoculated drop) was sub-cultured on Xylose Lactose Tergitol TM4 (XLT4-Merck; Darmstadt, Germany) agar plate and invert incubated on XLT4 plate at 37 °C for 24 h. After 24 h of incubation, the typical colonies of *Salmonella* spp. grown on XLT4 (with black centre) were isolated to perform the confirmation test by biochemical (lysine, urease, citrate utilize and indole) and serological (poly OH) tests. The number of wells giving a positive confirmed reaction was counted for each dilution and the MPN were calculated from the number of positive confirmed wells (EPA, 2012).

2.3.3. Helminth egg analysis

Helminth egg detection was done by National Institute of Malaria, Parasitology, and Entomology by means of the Romanenko technique (WHO, 2004; NIMPE, 2013). In brief, the water samples (1 L each) were allowed to settle for a period of 10 to 15 h before approximately 90% of the supernatant was removed using a siphon. The sediment was moved into a tube, and the bottles were rinsed with detergent Tween 80 (0.1%). Next, the tube was centrifuged at 1000g for 15 min, the supernatant discarded. Flotation solution was added to the tube (saturated NaNO₃) and centrifuged at 1000g for 15 min. The flotation solution above was discharged and new flotation solution added (up to 40 mL), stirred with a glass chopstick and centrifuged at 1000g for 5 min. Subsequently, flotation solution was added until it reached the top of the tube. A slide was placed on top of the tube for 20 min and replaced by a second slide for another 10 min. Finally, glycerine was added to cover the slides and helminth eggs were counted under a microscope (10×, and 40× magnification) and reported as numbers of eggs/L.

2.4. Statistical analysis

Statistical analysis were done using STATA version 12.0 (Stata Corporation; College Station, USA). Geometric means with 95% confidence intervals (CIs) and minima and maxima of bacteria and helminth egg concentrations and prevalence rates were calculated as the proportion of positive sample in each sampling system. Distribution and change in bacteria concentration were calculated at the log₁₀-scale,

where 1 unit reduction is equivalent with 90% and 2 units with 99% reduction on the original scale. Gradients between neighbouring sampling points were assessed by means of non-parametric Wilcoxon rank-sum tests. Level of water contamination was compared with WHO Guidelines for the Safe Use of Wastewater in Agriculture (WHO, 2006) and the National Technical Regulation on Domestic Wastewater (QCVN 14: 2008/BTNMT) and Industrial Water (QCVN 24: 2009/BTNMT) of Vietnam (MONRE, 2008, 2009). Maps, including geographical coordinates of the sampling points, were established in ArcMap version 10 (Environmental System Research Institute; Redlands, USA).

2.5. Ethics statement

The study protocol was approved by the institutional research commission of the Swiss Tropical and Public Health Institute (Swiss TPH; Basel, Switzerland; reference no. FK 106). Ethical approval was obtained from the ethics committee in Basel (EKBB; reference no. 137/13) and the Hanoi School of Public Health (Hanoi, Vietnam; reference no. 010/2014/YTCC-HD3). This study is registered with the clinical trial registry ISRCTN (identifier: ISRCTN13601686).

3. Results

3.1. Bacteria and helminth egg contamination

Fig. 2 and Table 1 summarise concentrations and prevalence rates of TC, *E. coli* and *Salmonella* spp. in the study systems. Highest mean concentrations of TC, *E. coli* and *Salmonella* spp. were obtained in the water from To Lich River (5.6×10^7 and 4.2×10^6 CFU/100 mL and 1044 MPN/100 mL, respectively). The lowest concentrations of TC and *E. coli* were measured (1.1×10^6 and 1.7×10^4 CFU/100 mL, respectively) in Red River, where no *Salmonella* spp. was detected. In agricultural fields of Bang B and Tam Hiep, where wastewater is reused, mean concentrations of *E. coli* were approximately four times higher than the mean concentrations measured in Duyen Ha commune where Red River water is used (1.1×10^6 CFU/100 mL vs. 2.5×10^5 CFU/100 mL, respectively). *Salmonella* spp. counts were approximately four times higher in Duyen Ha than in Bang B and Tam Hiep (108 MPN/100 mL vs. 455 MPN/100 mL, respectively), while prevalence of *Salmonella* spp. was 1.7 times higher (21.7% vs. 12.5%, respectively).

Table 2 summarises egg counts and prevalence rates of helminths. Helminth eggs were obtained in 12% of all the samples, 8% were positive for *A. lumbricoides* eggs and 6% for *T. trichiura* eggs. No hookworm eggs or any other helminth eggs were detected. Overall, the mean concentration of helminth eggs in water samples was 0.22 eggs/L. Highest mean concentration of 0.59 eggs/L (0.17 and 0.43 eggs/L for *A. lumbricoides* and *T. trichiura*) could be detected in agricultural fields in Bang B village and Tam Hiep commune, with maximum egg counts of 22 eggs/L.

3.2. Microbial reduction along the different study systems

3.2.1. Urban wastewater system

Fig. 3 shows that there were only marginal differences of all three measured bacteria groups along the To Lich River with increasing distance from Hanoi city (between point T_{R1} and T_{R4}). Further, the wastewater treatment through the Yen So stabilisation pond and treatment systems significantly reduced the TC, *E. coli* and *Salmonella* spp. counts concentration by 0.5, 0.7 and 0.8, respectively, on the log₁₀-scale ($p \leq 0.03$) (T_{R4} to T_{R5}). Significant log reductions were also determined for TC, *E. coli* and *Salmonella* spp. (1.0, 1.9 and 2.1, respectively) in Red River (R_{R2}) 5 km downstream of the discharge point of To Lich River. Moreover, the water from Red River showed no significant difference in pollution after discharge of To Lich River between R_{R1} and R_{R2} . Nhue River showed a similar high level of contamination as To Lich River

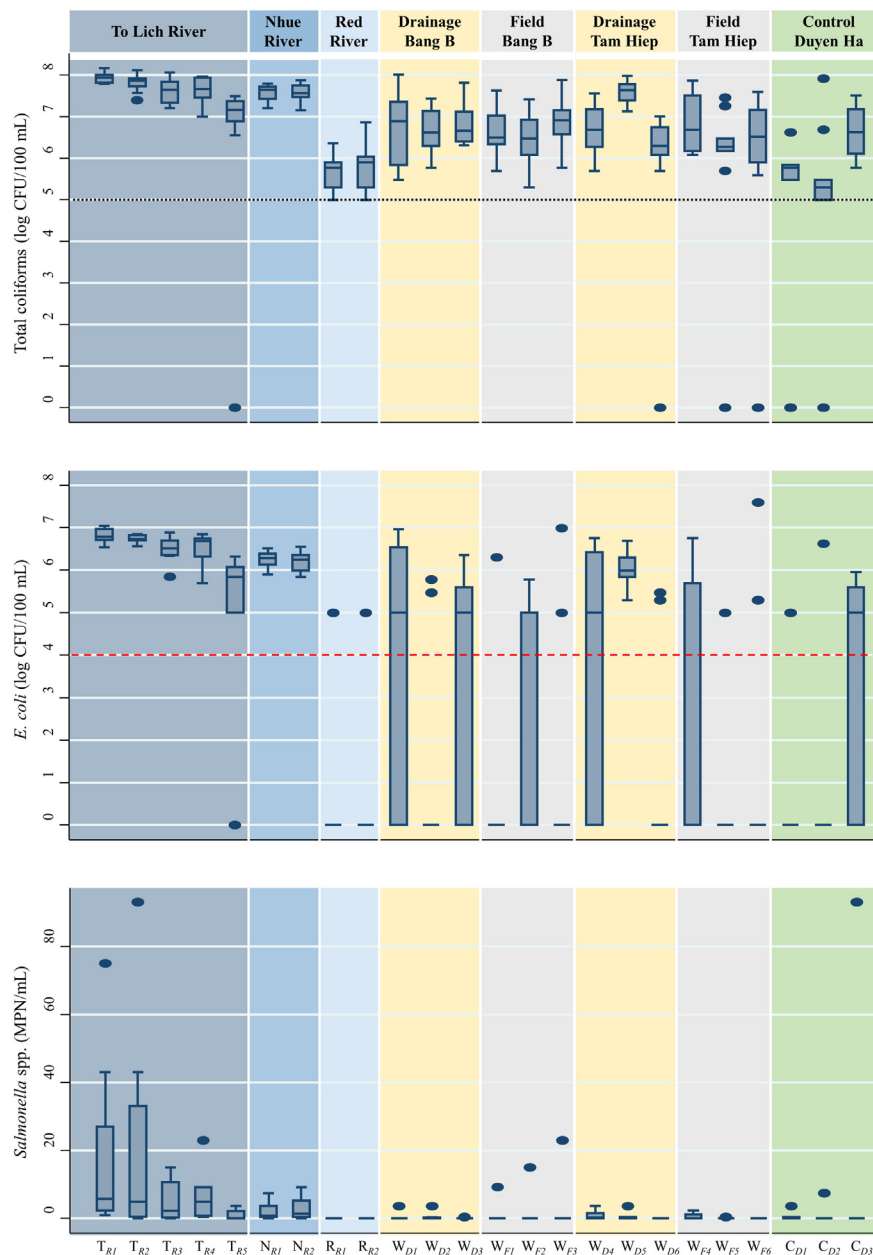


Fig. 2. Box-and-whisker plots of the log concentration of colony forming unit (CFU) total coliforms (TC) and *E. coli* per 100 mL, and MPN *Salmonella* spp. per mL. For each sampling point, a total of nine samples were collected along the wastewater systems in Hanoi, Vietnam (sampling period: 4 April to 6 June 2014). Black-dotted line maximum acceptable concentrations of TCs (MONRE, 2008) and red-dashed line: maximum acceptable concentrations of *E. coli* (WHO, 2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and no significant difference after To Lich discharges between N_{R1} and N_{R2} .

3.2.2. Peri-urban wastewater system

We observed significant higher concentration of TC, *E. coli* and *Salmonella* spp. between To Lich River (T_{R2} and T_{R3}) and the pond and drainage systems in Bang B village and Tam Hiep commune (WW $_{D1}$ to WW $_{D6}$) of 0.5, 0.7 and 1.5, respectively ($p < 0.01$) on the log₁₀-scale (Fig. 3). Between the drainage and ponds and the agricultural fields (WW $_{F1}$ to WW $_{F6}$), no significant difference in bacteria concentration could be observed. For *E. coli*, there was even a significant higher contamination measured (by 0.1 on the log₁₀-scale, $p < 0.01$).

3.2.3. Comparison site: rural non-wastewater system

The lowest concentration with bacteria could be measured in water pumped at R_{R2} from Red River (Fig. 3). The three sampling points along

the drainage of Duyen Ha commune (D $_{D1-3}$) showed a significantly higher concentration with TC, *E. coli* and *Salmonella* spp. of 0.6, 1.6 and 2.8 log ($p < 0.01$), respectively, when compared water samples obtained from Red River (R_{R2}).

4. Discussion

4.1. Microbial contamination along the wastewater system

Wastewater used in aquaculture ponds and agriculture fields of Hanoi is heavily contaminated with TC, *E. coli* and *Salmonella* spp. (on average 1.3×10^7 CFU/100 mL, 1.1×10^6 CFU/100 mL and 108 MPN/100 mL, respectively). These values are 110-fold above the Vietnam discharge limits of 5000 CFU TC/100 mL in wastewater for agriculture reuse (MONRE, 2008) and 260-fold above WHO tolerable safety limits for unrestricted irrigation (10^3 – 10^4 CFU *E. coli*/100 mL) (WHO, 2006).

Table 1

Total coliforms, *E. coli* and *Salmonella* spp. concentrations and prevalence along the wastewater systems in Hanoi, Vietnam (sampling period: 4 April to 6 June 2014). Geometric mean, standard deviation (SD), minimum and maximum concentration, and 95% confidence intervals (CIs) are indicated.

Sampling system	Counts for total coliforms and <i>E. coli</i> in CFU/100 mL or <i>Salmonella</i> spp. in MPN/100 mL						Prevalence rates
	Mean	SD	Min.	Max.	Lower 95% CI	Upper 95% CI	%
Bacteria in water							
To Lich River (n = 45)							
Total coliforms	5.6×10^7	3.70×10^7	0	1.5×10^8	4.4×10^7	6.6×10^7	98.3
<i>E. coli</i>	4.2×10^6	2.8×10^6	0	1.1×10^7	1	5.1×10^6	96.2
<i>Salmonella</i> spp.	1044	2007	0	9300	402	1685	77.5
Nhue River (n = 18)							
Total coliforms	4.2×10^7	1.7×10^7	1.4×10^7	7.4×10^7	3.3×10^7	5.1×10^7	100
<i>E. coli</i>	1.9×10^6	8.8×10^5	6.9×10^5	3.6×10^6	1.4×10^6	2.3×10^6	100
<i>Salmonella</i> spp.	251	308	0	920	80	422	87.7
Red River (n = 18)							
Total coliforms	1.1×10^6	1.7×10^6	9.9×10^4	7.3×10^6	2.5×10^5	1.9×10^6	100
<i>E. coli</i>	1.7×10^4	3.8×10^4	0	9.9×10^4	0	3.5×10^4	17.1
<i>Salmonella</i> spp.	0	0	0	0	0	0	0
Urban drainage: Bang B and Tam Hiep (n = 54)							
Total coliforms	1.8×10^7	2.6×10^7	0	1.0×10^8	1.1×10^7	2.5×10^7	98.2
<i>E. coli</i>	8.9×10^5	1.8×10^6	0	9.1×10^6	4.1×10^5	1.4×10^6	52.4
<i>Salmonella</i> spp.	41	104	0	360	10	72	23.4
Urban agriculture fields: Bang B and Tam Hiep (n = 54)							
Total coliforms	1.3×10^7	1.9×10^7	0	7.7×10^7	7.7×10^6	1.8×10^7	96.5
<i>E. coli</i>	1.1×10^6	5.5×10^6	0	3.9×10^7	0	2.6×10^6	24.4
<i>Salmonella</i> spp.	108	410	0	2300	11	228	12.5
Peri-urban drainage: Duyen Ha (n = 27)							
Total coliforms	6.4×10^6	1.7×10^7	0	8.3×10^7	0	1.3×10^7	85.6
<i>E. coli</i>	2.5×10^5	8.1×10^5	0	4.2×10^6	0	5.7×10^5	30.6
<i>Salmonella</i> spp.	455	1935	0	9300	0	1292	21.7

Our findings confirm results from a previous study reporting that water bodies in urban and peri-urban areas of Hanoi are contaminated with faecal matter (Kuroda et al., 2015). The average treatment of 0.5 and 0.7 log CFU for TC and *E. coli* due to drainage and retention ponds is not sufficient to comply with safety thresholds. In addition, bacteria contamination was higher in the agriculture field compared to drainage and retention ponds, most probably due to local defecation or even illegal discharge of faecal sludge (Fuhrmann et al., in press). Clearly, high charges with human, and potentially animal waste, in combination with the insufficient treatment of bacterial contamination along Hanoi's wastewater conveyance system, represent a public health concern for people living along wastewater channels, farmers using wastewater, and consumers of wastewater irrigated crops and wastewater-fed fish (WHO, 2006; MONRE, 2008).

4.2. Potential implication for public health

The association between health risks and the high level of bacterial contamination is further underpinned by studies that have shown significant associations between diarrhoeal diseases and use of wastewater in children in peri-urban and rural communities around Hanoi (Hien et al., 2007; Pham-Duc et al., 2014). With regard to helminth egg concentrations along the wastewater system, our findings are in line with studies by Do et al. (2007b), who showed no significant association between peri-urban wastewater use and helminth infections in Hanoi. However, other studies reported that the use of wastewater from Nhue River was significantly associated with helminth and intestinal protozoa infections as well as self-reported diarrhoea (Pham-Duc et al., 2013, 2014). In order to better understand the risk of the specific causative agents, a context-specific QMRA is required (Mok and Hamilton, 2014). For example, as shown by Pham-Duc (2012), the estimated risk of diarrhoeal diseases due to the exposure to wastewater reused for rural agriculture across communities in Hanam was 100-fold greater than the acceptable risks (Pham-Duc, 2012). Other hazards and pollutants such as antibiotic-resistant bacteria, heavy metals and toxic chemicals were observed by other studies in the wastewater and sediment of Hanoi city (Ingvertsen et al., 2013; Pham et al., 2015). These findings point to a challenge when aiming at the safe use of wastewater and sediments for any kind of land application. In combination with the reported

microbial pollution, this also poses a serious risk of groundwater and drinking water pollution (Holm et al., 2010; Sanders et al., 2014; Kuroda et al., 2015).

4.3. Proposed control measures along the wastewater systems

Our observation suggest that the current configuration of the conveyance and treatment system in Hanoi fails in reducing bacterial contamination for safe use of wastewater in agriculture and aquaculture (WHO, 2006). In view of the scale of wastewater use in Hanoi, improvement of the current conveyance and treatment is warranted, as urban farming practices represent an important livelihood strategy (Drechsel et al., 2015). Improvements of the current system will probably require both technical and non-technical measures. In the following paragraph we describe such control measures, however, it is important to note, that they should be further assessed for their cost-effectiveness and their impact in reducing disease burden in the local context (Hanjra et al., 2011; Drechsel et al., 2015).

With regard to technical control measures, a series of options are available at different stages of the wastewater system. First, the total amount of human waste ending up in Hanoi's wastewater should be reduced. This can be achieved by improving the treatment efficiency of septic tanks through regular emptying and the establishment of decentralised treatment systems such as anaerobic baffled reactors (Tilley et al., 2014). Moreover, the practice of informal disposal of faecal sludge into the wastewater conveyance system could be transformed into a more sustainable form of human waste treatment. Indeed, faecal sludge is rich in nutrients and calorific value, clearly presenting a business opportunity for waste recovery and reuse businesses (Strande et al., 2014; Bassan et al., 2015). A prominent example of faecal sludge reuse is the 'honesuckers' in Bangalore, which earn a livelihood by collecting the sludge and selling it to farmers for field application after prior treatment of the material in drying beds (Kvarnström, 2012). However, to induce transformation in faecal sludge disposal and reuse practices, there is a need for a dialogue at community and policy levels (Strande et al., 2014). Second, the existing ponds could be upgraded to waste stabilisation ponds with controlled retention times (Tilley et al., 2014). Functional anaerobic, facultative and aerobic maturation ponds were able to reduce bacteria contamination by up to 6 log, which

Table 2

Helminth egg counts (*Ascaris lumbricoides* and *Trichuris trichiura*) and prevalence along the wastewater conveyance and treatment systems in Hanoi, Vietnam (sampling period: 4 April to 6 June 2014). For egg counts, geometric mean, standard deviation (SD), minimum and maximum concentration are indicated.

Sampling system	Egg counts/L				Prevalence rates
	Mean	SD	Min.	Max.	%
Helminth egg in water					
To Lich River (n = 45)					
<i>Ascaris lumbricoides</i>	0.07	0.33	0	2	4.4
<i>Trichuris trichiura</i>	0.04	0.21	0	1	4.4
Nhue River (n = 18)					
<i>Ascaris lumbricoides</i>	0.12	0.49	0	2	5.9
<i>Trichuris trichiura</i>	0	–	–	–	0
Red River (n = 18)					
<i>Ascaris lumbricoides</i>	0	–	–	–	0
<i>Trichuris trichiura</i>	0	–	–	–	0
Urban drainage: Bang B and Tam Hiep (n = 54)					
<i>Ascaris lumbricoides</i>	0.13	0.73	0	5	3.7
<i>Trichuris trichiura</i>	0.02	0.14	0	1	1.9
Urban agriculture fields: Bang B and Tam Hiep (n = 54)					
<i>Ascaris lumbricoides</i>	0.17	0.97	0	7	5.6
<i>Trichuris trichiura</i>	0.43	2.99	0	22	3.7
Peri-urban drainage: Duyen Ha (n = 27)					
<i>Ascaris lumbricoides</i>	0	–	–	–	0
<i>Trichuris trichiura</i>	0.04	0.19	0	1	1.2
Total (n = 216)					
<i>Ascaris lumbricoides</i>	0.10	0.64	0	7	8.3
<i>Trichuris trichiura</i>	0.13	1.51	0	22	6.4
Total helminth eggs (n = 216)	0.22	1.64	0	22	12.4

would allow for safe use in aquaculture and agriculture (Stenström et al., 2011). Hence, aquaculture practice could be maintained by having a final pond that is specifically assigned for this purpose. Third, regular desludging and basic screening of Nhue River should be implemented to protect downstream communities by reducing the risk of flooding events and thus avoiding dispersion of highly contaminated water and sediments (Tilley et al., 2014). This is already practiced in To Lich River and has proven feasible (World Bank, 2013). Of note, the sludge from river and drainage systems is not recommended for use because of likely contamination with heavy metals and potentially other contaminants (Ingvertsen et al., 2013).

With regard to non-technical control measures, a multi-barrier approach is recommended (Ilic et al., 2010). In practice this means that integrated disease control, including the provision of vaccination (e.g. for rotavirus) and preventive chemotherapy (for soil-transmitted helminthiasis), should be pursued at the level of farmers, as well as the use of personal protective equipment and health education programmes (Uttinger et al., 2009). At the level of markets, awareness on safe processing of produce is necessary to avoid cross-contamination (Nguyen et al., 2008). At consumer level, information campaigns can promote safe storage and processing of wastewater-fed products (WHO, 2006; Drechsel et al., 2015). Finally, the existing sentinel wastewater monitoring system operated by the Vietnam Environment Administration should be upgraded to a surveillance and response system (Vietnam Environment Administration, 2015). Such a system ideally includes both microbial and chemical indicators and is coupled to a pre-defined response for the event that parameter values are above set limits. Such an early warning system would not only allow to recognise trends and seasonal variability of specific health hazards but also enhance a more proactive protection of urban farming communities and consumers of their produce (WHO, 2006; Fuhrmann et al., 2015).

4.4. Limitations

Our sampling took place over an 8-week period between April and June 2014, corresponding to the main rainy season. Therefore, our findings represent a snapshot of microbial contamination along the wastewater system in the rainy season and do not allow for generalization to other seasons (Nguyen et al., 2008). As the dilution of wastewater with storm water is high during the rainy season, larger sampled

quantities of wastewater could have improved the detection rate (Ayres and Mara, 1996). Moreover, it is anticipated that helminth eggs may be retained in sludge of septic tanks, soil or river sediments, which may result in underestimating the true prevalence of helminth eggs in wastewater (Strande et al., 2014). It should also be noted that other hazards, such as specific pathogens, antibiotic-resistant bacteria, heavy metals and toxic chemicals should be investigated in future studies to deepen our understanding of the overall risk for people exposed to wastewater in Hanoi.

5. Conclusions

Our results suggest that the wastewater conveyance system linked to To Lich and Nhue River fails to reduce bacterial contamination to safe levels for wastewater use in aquaculture and agriculture. This represents a public health threat for large numbers of farmers and consumers of wastewater fed-products in Hanoi. Yet, control measures at multiple stages of the wastewater system are available. Priorities should be set to improve current faecal sludge management and treatment of wastewater in existing pond systems in the peri-urban areas of Hanoi. Moreover, to protect urban farming communities downstream of Hanoi, the water quality of Nhue River needs to be improved considerably. Thus, such control measures would allow to maximise the gains from wastewater use. Our study has direct implications for sanitation safety planning approaches in rapidly expanding Asian cities and is relevant for SDG target 6.3 that seeks to ensure safe wastewater management and use in agriculture and aquaculture by 2030.

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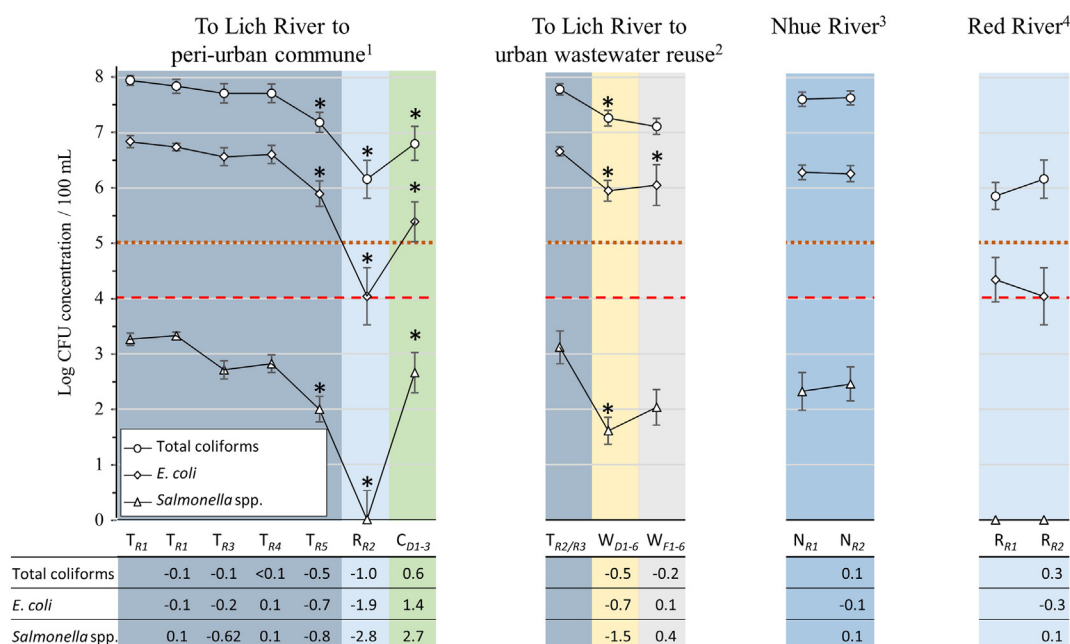


Fig. 3. Mean log concentration of colony forming unit (CFU) total coliforms (TC) and *E. coli* and most probable number (MPN) *Salmonella* spp. and 95% confidence intervals (CIs) along the wastewater system in Hanoi, Vietnam. ¹Along To Lich River (T_{R1-5}) to Red River (R_{R1}) to drainage channels in Duyen Ha; ²along To Lich River (T_{R2/3}) to the peri-urban wastewater conveyance, treatment and reuse system in the districts of Hoang Mai and Thanh Tri (W_{D1-6} and W_{F1-6}); ³along Nhue River (N_{R1-2}); and ⁴along Red River (R_{R1-2}). Sampling period: 4 April to 6 June 2014. *p*-values are given for the changes in mean log concentration from the preceding to the given measuring site were assessed using the Wilcoxon rank sum test. Orange-dotted line indicating discharge limits of TC of domestic wastewater provided by the Vietnam Ministry of Natural Resources and Environment. Red-dashed line indicating verification limit for *E. coli* of the World Health Organization for safe use in unrestricted agriculture. *Significant change (<0.05) between two sampling points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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