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Application of disease burden to quantitative assessment of health hazards for a decentralized water reuse system

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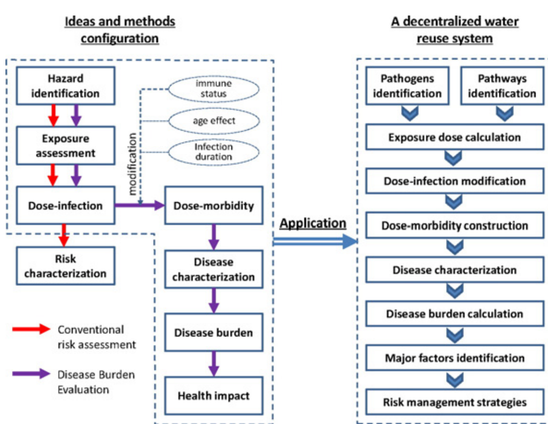
HIGHLIGHTS

- Disease burden was adopted as a new indicator for health impact assessment.
- Health hazards of a water reuse system were analysed by calculating disease burden.
- Dose-morbidity was built by modifying dose-infection to quantify disease burden.
- Individual immune, age and infection duration were introduced in dose-morbidity.
- Major risk pathogen and pathway of the system were identified by this new method.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this article is to introduce the methodology of disease burden (DB) to quantify the health impact of microbial regrowth during wastewater reuse, using the case study of a decentralized water reuse system in Xi'an Si-yuan University, located in Xi'an, China. Based on field investigation findings, *Escherichia coli* (*E. coli*), *Salmonella* and *rotavirus* were selected as typical regrowth pathogens causing potential health hazards during the reuse of reclaimed water. Subsequently, major exposure routes including sprinkler irrigation, landscape fountains and toilet flushing were identified. Mathematical models were established to build the relationship between exposure dose and disease burden by calculating the disability adjusted life year (DALY). Results of disease burden for this case study show that DALYs attributed to *E. coli* were significantly greater than those caused by other pathogens, and DALYs associated with sprinkler irrigation were higher than those originating from other routes. A correlation between exposure dose and disease was obtained by introducing a modified

Abbreviations: DB, disease burden; DALY, disability adjusted life year; WWTP, wastewater treatment plant; IID, intestinal infectious disease; DCPC, disease control and prevention centre; ID, infectious diarrhoea; PEG, polyethylene glycol; YLD, years of life lost due to disability; YLL, years of life lost due to premature death; CFR, case fatality rate; SDWT, Shanghai disability weight table; pppy, per person per year.

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Morbidity
Pathogen
Water reuse

calculation of morbidity, which can extend the assessment endpoint of health risk to disease burden from the conventional infection rate.

1. Introduction

The increase in pollution in existing water sources combined with a rising human population continues to increase the demand for alternative water sources. In this case, urban wastewater reclamation and reuse can not only effectively alleviate the current situation of water shortage, but can also directly reduce the amount of wastewater discharge (Hamilton et al., 2007). As a new non-potable water source, reclaimed water has been widely used for many purposes, including landscape replenishment, sprinkler irrigation and toilet flushing. However, although pathogenic microorganisms can be effectively removed by water treatment process, especially after chemical disinfection, such as chlorination adopted in this study, microbial regrowth of bacteria or viral pathogens such as *Escherichia coli*, *Salmonella* and *rotavirus*, due to the decreasing doses of disinfectant residuals during water reuse processes, or the enrichment of nutritional supplement such as biodegradable dissolved organic carbon (BDOC), nitrogen and phosphorus which supporting the regrowth of pathogens in reclaimed water, may bring about potential health risks, and thus may restrict the utilization of reclaimed water to a large extent (Hamilton et al., 2007; Dan et al., 2013).

In Xi'an Si-yuan University, a decentralized water treatment, reclamation and reuse system was implemented to alleviate the pressure on water supply in this campus, and also to reduce the amount of wastewater discharge. For the safety reuse of wastewater, the sewage collected from the whole campus was carefully treated in the Si-yuan wastewater treatment plant (WWTP) through an A2O (Anaerobic/Anoxic/Oxic) unit and a membrane bioreactor. As a result, a 2-log reduction of pathogen removal could be achieved at least. Additionally, chlorination was implemented as the final step so as to achieve completely inactivation of all bacterial and viral pathogens. After being treated in the WWTP, reclaimed water was stored in the Si-yuan Lake and then be reused for a variety of purposes, such as landscape replenishing, sprinkling irrigation, toilet flushing etc. Since all pathogens have been inactivated by chlorination before being discharged to the Si-yuan Lake, potential microbial risks regarding to water reuse could be avoided to the maximum extent. However, microbial regrowth was detected by an investigation of 2–4-log increase of pathogen concentrations in the Si-yuan Lake, therefore, microbial risks and corresponding health hazards caused by specific pathogens regarding to water reuse by this decentralized water recycling system should be evaluated, and measures for the controlling of microbial regrowth should be made, such as the upgrading of treatment processes so as to decrease the concentrations of biodegradable organic matters (BOM), nitrogen, phosphorus and some other nutrients which are benefit for the regrowth of microbial (Brissaud, 2001). On this basis, the aim of this study is to: firstly, provide a quantitative assessment of potential health impacts caused by pathogenic microorganisms during water reuse in Xi'an Si-yuan University; and secondly, offer recommendations for risk and/or disease control.

Traditionally, infection rate has been commonly employed as an indicator of microbial risk caused by water reuse. This indicator's calculations are based on dose–response relationships, such as the exponential or beta-Poisson models (Haas et al., 1999). However, the application of these two models cannot distinguish between exposure populations with different characteristics, such as immunity status, age or gender. Besides, the infection rate obtained from dose–response analysis is defined as a probability of health risk, which can only represent the magnitude of probability that a certain health impact occurs. However, it cannot be used to describe the severity or duration of this specific health damage, and nor can it serve to provide a quantitative description of health loss after infection occurs (Geelen et al., 2009). In the development of certain health hazards, infection should be recognized as a middle step, occurring between exposure and clinically defined health damage, but not the endpoint of health outcomes resulting from microbial pollution. Although the probability of infection may be high for an individual exposed to pathogenic microorganisms, the ultimate health damage may not be severe, because such a scenario's development generally depends on a series of complicated mechanisms. Therefore, the ultimate health impact caused by microbiological contaminants should not only be judged by infection rates, but evaluated with extended indices.

Disability adjusted life year is an indicator originally designed for the evaluation of overall disease burden due to global or regional disease outbreaks. It is expressed as a sum of healthy years lost due to disability and premature death (Murray and Lopez, 1996). DALY is recognized and adopted as a valid indicator for the evaluation of disease burden caused by environmental pollution (Beyer, 2016), and extends the evaluation of health impact from infection risk assessment. This is because it can comprehensively assess the magnitude of health damage after pollution outbreaks (Gao et al., 2015). In this study, the health hazards caused by the selected waterborne pathogens associated with water reuse in Xi'an Si-yuan University were evaluated by disease burden. In accordance with the methodology of disease burden expressed as DALY, assessing the health impact was conducted using the following steps: the characterization of exposure routes and exposure doses; the estimation of morbidity based on a modified dose–response relationship; and the evaluation of disease burden using DALY. As a consequence, major risk factors leading to the greatest disease burden were confirmed, and instructive measures for future risk or disease control were developed.

2. Methods

2.1. Case description

Xi'an Si-yuan University is located in the south-eastern suburbs of Xi'an in China, an area which is undergoing development and construction. Urban water supply and sewage collection systems are not available in this campus, and in fact the only available sources of water are five groundwater wells with a combined maximum capacity of 3000 m^3/d. However, the actual water demand for this campus is roughly estimated as 6000 m^3/d, more than half of which is for non-potable water. This consumption demand was far beyond the water supply capability and finally led to water supply intension. Therefore, a decentralized sewage collection system has been implemented based on the construction and operation of Si-yuan wastewater treatment plant so as to alleviate the pressure on water supply and to reduce the amount of sewage discharge as well. As illustrated in Fig. 1, groundwater is pumped for both potable and non-potable uses through drinking water pipelines, wastewaters generated from the whole campus, including black water, grey water, and kitchen wastewater collected from university canteens are gathered by an independent sewage collection system and sent to the WWTP for onsite treatment, reclamation and reuse. With a treatment capacity of 2500 m^3/d, the gathered wastewater is treated through a series of facilities, including a regulation basin to receive the collected wastewater, fine screens to remove coarse solid particles, and a biological treatment unit in anaerobic/anoxic/oxic (A^2O) array followed by a membrane bioreactor (MBR) where submerged hollow fibre membrane modules are employed for organic degradation.