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Potential of Bayesian networks for adaptive management in water recycling

Denise Beaudequin [a, c, f, *], Fiona Harden [b, c], Anne Roiko [d, e], Kerrie Mengersen [a, f]

[a] Science and Engineering Faculty, Queensland University of Technology, Gardens Point Campus, 2 George Street, Brisbane, Queensland 4000, Australia
[b] Faculty of Health, Queensland University of Technology, Gardens Point Campus, 2 George Street, Brisbane, Queensland 4000, Australia
[c] Institute of Health and Biomedical Innovation (IHBI), Queensland University of Technology, 60 Musk Avenue, Kelvin Grove, Queensland 4059, Australia
[d] School of Medicine, Griffith University, Gold Coast Campus, Parklands Drive, Southport, Queensland 4222, Australia
[e] Smartwater Research Centre, Griffith University, Gold Coast Campus, Edmund Rice Dr, Southport, Queensland 4215, Australia
[f] Institute for Future Environments (IFE), Queensland University of Technology, Gardens Point Campus, 2 George Street, Brisbane, Queensland 4000, Australia

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ABSTRACT

Water recycling is an important solution to increasing water scarcity. However, universal wastewater treatment standards deter uptake of recycling schemes. Lack of data also impedes fit-for-purpose water recycling and water managers are challenged by decision making under uncertain conditions. Bayesian networks (BNs) are increasingly recognised as a valuable tool for decision making under uncertainty. In this study BNs are used to model health risks associated with wastewater irrigation of a public open space. Three BNs based on quantitative microbial risk assessment model risk reduction potential along a treatment chain and at the site of reuse. The BNs simulate multiple exposure profiles and scenarios, providing conditional probability of infection or illness, comparable with health-based targets. Study findings highlight the significant impact of post treatment risk mitigation, despite challenging conditions. BNs provide a transparent, defensible evidence base for mapping and quantifying risk pathways, comparing decision options and predicting outcomes of management policies.

1. Introduction

Water is an increasingly valuable commodity worldwide. Water scarcity is growing, due to an exponentially rising global population with attendant food and water requirements, and climate-related decrease of fresh water supplies in some areas. Irrigation, which currently consumes 70% of the world's fresh water (UN-Water, 2014), is an important focus area for solutions.

Reuse of previously underutilised water resources such as treated wastewater is now being actively pursued to augment fresh water supplies. Despite this, concern regarding residual microbial contamination and difficulties with reliable and accurate determination of risk continue to inhibit its acceptance and implementation. Assessment of reclaimed water as being fit for its intended purpose should not be contingent solely on pathogen reduction benchmarks, as reuse-related health risk depends on a host of factors in the treatment-to-reuse chain (Keraita et al., 2010; World Health Organization, 2008). These include multiple variables in exposure pathways and post-treatment risk abatement measures, such as subsurface and drip irrigation systems, irrigation withholding periods and restriction of public access during and after irrigation events (NRMMC-EPHC-AHMC, 2006).

'Fit-for-purpose' wastewater reuse requires development of tools for rapid scenario assessment (Petterson and Ashbolt, 2003). (United States Environmental Protection Agency, 2014). Ideally, such tools should incorporate all of the key influences on health risk, including effects on treatment performance, fate and transport of pathogens during storage and distribution to the point of release, exposure pathways and impacts on dose-response relationships, including assessment of individual susceptibility (Beaudequin et al., 2015). In the same way as a quantitative characterisation of treatment performance is essential, a quantitative understanding of exposure and dose-response scenarios is imperative. The ability to

Abbreviations: BN, Bayesian network; CFU, colony-forming unit; DALY, disability-adjusted life year; PCR, polymerase chain reaction; pppy, per person per year; QMRA, quantitative microbial risk assessment.

* Corresponding author. Science and Engineering Faculty, Queensland University of Technology, Gardens Point Campus, 2 George Street, Brisbane, Queensland 4000, Australia.

E-mail addresses: d.beaudequin@qut.edu.au (D. Beaudequin), fiona.harden@qut.edu.au (F. Harden), a.roiko@griffith.edu.au (A. Roiko), k.mengersen@qut.edu.au (K. Mengersen).

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integrate the effects of these elements on health risk outcomes plausibly and with transparency is also necessary.

Wicked problems presented by complex environmental systems require holistic solutions. Systems thinking is increasingly used to make reliable inferences to underpin decisionmaking in integrated environmental modelling (Whelan et al., 2014). Sentinel authorities such as the United States Environmental Protection Agency have called for a paradigm shift from viewing health risk challenges 'water contaminant by water contaminant', to systems-based approaches (Anastas et al., 2010; Cohen Hubal et al., 2011). The authors of a paper on a screening-level assessment of microbial risks from wastewater reuse note that the most important limitation in carrying out exposure analysis in quantitative microbial risk assessment (QMRA) is a lack of quantitative data on pathogens in water and their relative reduction at each stage of the treatment train (Petterson et al., 2001). Bayesian networks (BNs) offer not only a systems approach but also a number of other useful features (Jensen and Nielsen, 2007; Pearl, 2000) to the characterisation of complex environmental risk assessments. BNs are also able to be quantified using diverse data types, including expert opinion, when insufficient or no empirical data exist (Barton et al., 2012; Düspohl et al., 2012).

This paper demonstrates use of BNs as an innovative technique to both visualise and quantify microbial exposure pathways, extending the means currently available to assess microbial health risks in water recycling schemes. With the overarching objective of facilitating fit-for-purpose wastewater treatment and reuse, this study had the multiple objectives of bridging the gap between microbial treatment performance measures and health-based targets, while incorporating the multiple barrier risk reduction paradigm in the determination of conditional probabilities for illness and infection. Building on our previous work, described in Beaudequin et al. (2016) and elsewhere, we present BNs for three reference pathogens in a context of recycled water irrigation of public open space.

We begin with background information on QMRA and BNs and describe the pathogens and exposure scenarios considered. In the Methods section we describe the case study in more detail, including the assumptions and data sources and the multiple infection barriers modelled. The QMRA modelling phase is explained, and we describe the construction of the BNs. In the Results section we present firstly, a comparison of the risks for four 'visitor' profiles by pathogen class. We then demonstrate the flexibility and expedience of BNs by modelling three multifaceted, theoretical scenarios, and conclude with results of a sensitivity analysis.

2. Background

BNs are based on probability distributions and are a powerful risk assessment tool for reasoning under uncertainty (Jensen and Nielsen, 2007; Pearl, 1988). They are able to accommodate both quantitative and qualitative types of information where data may be lacking. BNs are particularly useful for modelling and supporting decision making in complex systems such as environmental domains. BNs can incorporate management options, input from multiple disciplines, information from different processes and stakeholder's perceptions with those of modellers (Kelly et al., 2013). Due to their visual platform, BNs are also useful for evaluation of scenarios, management options and relative risks. Although BNs may require discretisation of continuous variables, leading to a reduction in precision of model predictions, their strength lies in their ability to provide relative assessments of options where there are a number of choices, rather than prediction of absolute risks. Moreover, uncertainty is explicit in BN outputs, because the models are based on probabilistic relationships (Kelly et al., 2013).

BNs are comprised of a set of random variables linked by arrows indicating causal relationships. Variables or nodes are categorised by a set of user-defined 'states' that can be qualitative, discrete or continuous. Each state is assigned a conditional probability, reflecting the strength of the causal links between the variables (Jensen and Nielsen, 2007). Conditional probabilities are derived from empirical data, models, simulations or the opinion of experts. In this study, QMRA has been used to quantify BNs.

QMRA is a structured approach to the quantitative assessment of the likelihood and severity of potential adverse health outcomes associated with microbial exposures. In QMRA, the integration of data with mathematical models is conducted in a four step process comprising hazard identification, exposure assessment, dose response assessment and risk characterisation (Center for Advancing Microbial Risk Assessment, 2013, United States Environmental Protection Agency-United States Department of Agriculture/Food Safety and Inspection Service, 2012). In countries such as The Netherlands and Canada, QMRA has replaced the use of indicator-based approaches to regulation of drinking water quality (Smeets, 2013) and this is also the case for recycled water guidelines in Australia (Bichai and Smeets, 2013).

QMRAs are typically limited to quantifying risk arising from exposure to a single pathogen, due to the pathogen-specific nature of the established dose-response relationships. Bacteria, viruses and protozoa are represented in this study by *Campylobacter*, norovirus and *Cryptosporidium*, respectively. We examine these three organisms in a scenario of wastewater irrigation of a municipal park, sports field or golf course (hereinafter referred to as a park), in two potentially exposed populations: municipal employees and recreational users.

3. Methods

3.1. Case study description

In this case study it is assumed that treated wastewater alone is used for irrigation of established grassed areas, delivered daily via spray nozzles. In the interests of a conservative assessment, it is assumed that no natural die-off or decline in infectivity occurs in pathogens as a result of desiccation or exposure to sunlight. Consideration of pathogen inactivation is limited to study of the

Table 1
Summary of simulated visitor profiles.

Visitor profile	Wastewater volume ingested per visit (mL)	Annual frequency of visits	Reference
casual park visitor	1	fortnightly	(NRMMC-EPHC-AHMC, 2006)
golfer	1	weekly	(Asano et al., 1992; NRMMC-EPHC-AHMC, 2006)
football player	5	twice weekly	(Ryu, 2003)
occupational exposure (e.g., municipal worker)	5	daily	(Cherrie et al., 2006; Gorman et al., 2014),