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Modelling microbial health risk of wastewater reuse: A systems perspective

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ABSTRACT

There is a widespread need for the use of quantitative microbial risk assessment (QMRA) to determine reclaimed water quality for specific uses, however neither faecal indicator levels nor pathogen concentrations alone are adequate for assessing exposure health risk. The aim of this study was to build a conceptual model representing factors contributing to the microbiological health risks of reusing water treated in maturation ponds. This paper describes the development of an unparameterised model that provides a visual representation of theoretical constructs and variables of interest. Information was collected from the peer-reviewed literature and through consultation with experts from regulatory authorities and academic disciplines. In this paper we explore how, considering microbial risk as a modular system, following the QMRA framework enables incorporation of the many factors influencing human exposure and dose response, to better characterise likely human health impacts. By using and expanding upon the QMRA framework we deliver new insights into this important field of environmental exposures. We present a conceptual model of health risk of microbial exposure which can be used for maturation ponds and, more importantly, as a generic tool to assess health risk in diverse wastewater reuse scenarios.

1. Introduction

Current predictions of the effects of climate change include worldwide water shortages (IPCC, 2014). As an estimated 80% of the world's wastewater is not collected or treated (UN-water, 2014), recycling water that has previously been regarded as unusable serves a dual purpose, providing water for uses that are supplied unnecessarily by potable water, and reducing the impacts of wastewater discharged into pristine or sensitive receiving environments (NRMMC-EPHC-AHMC, 2006). However, concerns about health risk due to difficulties with detection and identification of pathogens contribute to underutilisation of this resource. The systematic, comprehensive and transparent determination of the microbial safety of reclaimed water for specific purposes such as irrigation is a public health imperative when considering, for example, the estimated 3.5–4 million hectares in 50 countries that are irrigated with wastewater from varying sources (Haas et al., 2014).

Maturation ponds, a subgroup of waste stabilisation ponds, are used worldwide as secondary or tertiary wastewater treatment systems with the primary purpose of reducing the number of disease-causing microorganisms (Gloyna, 1971; Von Sperling, 2007). Maturation pond technology uses environmental influences such as sunlight (Maïga et al., 2009a) and pH (Curtis et al., 1992b) to inactivate pathogens, and is used as a disinfection process for wastewaters in developing countries and in rural and remote locations in the developed world (Mara, 2004; Shilton, 2005; Von Sperling, 2007). The treated wastewater progresses through the ponds

Abbreviations: CAMRA, Center for Advancing Microbial Risk Assessment; DALYs, Disability-Adjusted Life Years; EPA-QLD, Environmental Protection Agency Queensland; FAO-WHO, FAO-WHO, Food and Agriculture Organization of the United Nations and World Health Organization; HIV/AIDS, Human Immunodeficiency Virus/Acquired Immune Deficiency Syndrome; IPCC, Intergovernmental Panel on Climate Change; NRC, National Research Council; NRMMC-EPHC-AHMC, Natural Resource Management Ministerial Council Environment Protection and Heritage Council and Australian Health and Medical Council; QMRA, Quantitative Microbial Risk Assessment; US EPA-USDA/FSIS, United States Environmental Protection Authority, United States Department of Agriculture/Food Safety and Inspection Service; WHO, World Health Organisation.

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over a period of several days to weeks in order to achieve pathogen reduction (Shilton, 2005). The effluent from these ponds may then be used for non-potable recycling purposes.

The aim of this study was to create a conceptual model of factors impacting health risk due to waterborne microbial exposures, integrating elements of the quantitative microbial risk assessment (QMRA) framework with environmental effects on pathogen concentrations. The study focused on sewage maturation ponds as a case in point. The objectives of the research were to inventory known and unknown factors influencing health risk in this scenario and to make assumptions explicit, thereby forming the basis of a future predictive health risk model for reuse of treated wastewater. To achieve the aim, the significant factors influencing health risk of maturation pond water reuse, and their interactions, were identified and mapped using a participatory process. The result, an unparameterised causal network, describes the significant influences on the health risk of an individual in a single exposure event, arising from exposure to the treated effluent at the point of discharge from a sewage maturation pond. This research is a component of a project with the objective of characterising and validating sewage maturation ponds with respect to pathogen removal, with a view to reusing the treated wastewater, under the broader aim of increasing regional and remote water security in Australia.

'Systems thinking' (Capra et al., 2014; Meadows, 2008), based on the premise that the components of a complex environmental system are best studied from the perspective of their relationships with each other and other systems, was an underlying tenet of the research. Thus, human health risk was considered as an endpoint of a system, rather than the result of single factors such as pathogen concentration or dose viewed in isolation. While this paper focuses on wastewater treated in maturation ponds, the QMRA submodels are generic and can be extrapolated to any water use or reuse options.

2. Background

Microbial risk assessment of wastewater treated by a technology that is influenced predominantly by environmental conditions is made difficult by two main issues: the plethora of ecological influences on pond microbial populations, and the complexity of human exposure pathways for diverse wastewater reuse scenarios. The common thread in these two issues is the myriad of interacting factors to be considered simultaneously to fully understand the health effects on the exposed individual or population. Robust inference in the public health interest in this context is difficult, as researchers attempt to quantify relationships in a virtually unbounded set of possibly correlated ecological variables, often with limited field data (Marcot et al., 2006). Development of a conceptual model, in which an archetypal set of key variables and their interactions is assembled and documented, provides a basis for communicating assumptions and completing a quantitative risk assessment (Suter, 1999), and is an important precursor to a sound predictive model.

2.1. Microbial health risk assessment

Risk assessment is the quantitative or qualitative determination of adverse consequences resulting from exposure to a hazard (EnHealth, 2012). Quantitative risk assessment entails consideration of the magnitude of the adverse outcome and the probability of its occurrence. The science of quantitative risk assessment is becoming increasingly complex. Improved research methods generate an abundance of data, resulting in multifaceted assessment of multiple risks and risks in vulnerable subpopulations (NRC, 2009). Risk assessment in its simplest form consists of four fundamental steps, illustrated in Fig. 1. These are 1) hazard identification, 2) exposure assessment, 3) dose–response assessment and 4) risk characterisation (NRC, 1983). The framework has been adopted by many agencies worldwide, and has since been further expanded to include risk management and risk communication steps (NRC, 2009).

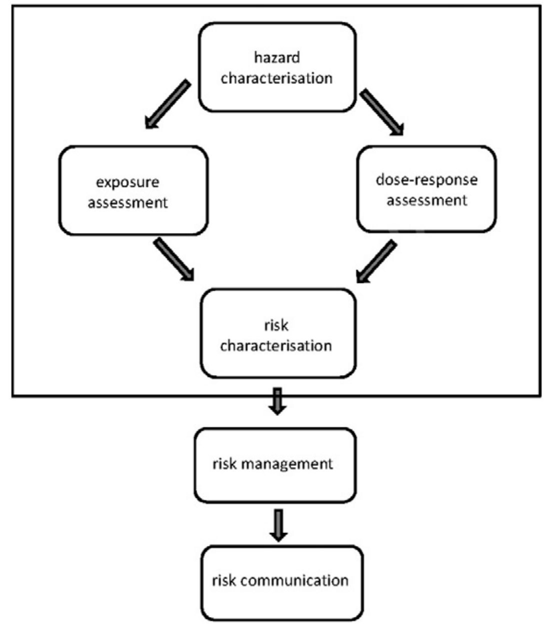

Fig. 1. Generic risk assessment framework.

QMRA is a modelling process based on the National Research Council framework (NRC, 1983; NRC, 2009), that is used for assessing public health risks that arise from exposure to pathogenic microbes, typically via food and/or water. This structured approach integrates information and data with mathematical models to examine the exposure and spread of microbial agents and thereby characterise the nature of adverse outcomes (CAMRA, 2013b; Havelaar, 2012; US EPA-USDA/FSIS, 2012). QMRA models can be used to generate knowledge about propagation of microbiological hazards along the risk pathway from source to exposure and effects in complex real-world scenarios. This allows insight into the dependent relationships between input and output variables and the ability to quantify the effect of mitigation alternatives (Greiner et al., 2013). Haas (2002) envisaged that QMRA would eventually replace the use of indicator-based approaches to regulation of water quality (Haas, 2002). This has occurred for drinking water regulation in countries such as The Netherlands and Canada (Smeets, 2013) and for recycled water guidelines in Australia (Bichai and Smeets, 2013).

Current approaches to health risk analysis of water quality are constrained by a lack of empirical data and are challenging due to the high level of complexity inherent in natural systems. The process of empirical evaluation of health risk from exposure to pathogenic microorganisms, based upon the original four step risk assessment framework (NRC, 1983), has been broadened to account for the dynamic and epidemiologic features of diseases resulting from microbial infection (Fewtrell et al., 2001). The unique features of a dynamic infectious disease process not accounted for in the original risk framework include: microbial growth and death; host immunity and susceptibility; the potential for secondary transmission; a range of possible health endpoints including delayed and/or chronic health effects; genetic diversity of microbial strains and their responses to interventions; detection method sensitivity; and multiple and sequential routes of exposure. Population, community and ecosystem dynamics, as well as heterogeneous spatial and temporal distribution in the environment, are other features of risk analysis involving microbial processes and systems requiring consideration in an idealistic conceptualisation of the pathogen–host–environment interaction (US EPA-USDA/FSIS, 2012).