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How can we improve understanding of faecal indicator dynamics in karst systems under changing climatic, population, and land use stressors? – Research opportunities in SW China

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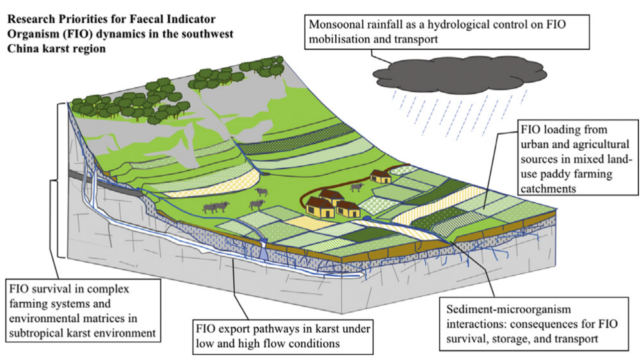
HIGHLIGHTS

- Gaps exist in our understanding of FIO dynamics in karst catchments.
- SW China represents a karst region exemplar for identifying research opportunities.
- Research needs identified by critical review and catchment surveys.
- Five priority themes for FIO research in karst terrain emerge.

GRAPHICAL ABSTRACT



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ABSTRACT

Human exposure to water contaminated with faeces is a leading cause of worldwide ill-health. Contaminated water can be transmitted rapidly in karst terrain as a result of the connectivity of surface and groundwater systems, high transmissivity of aquifers over large areas, and well-developed underground conduit systems. Faecal indicator organisms (FIOs) are the most widely-used indicator of faecal contamination and microbial water quality; however, the conceptualisation of FIO risk and associated sources, pathways, and survival dynamics of FIOs in karst landscapes requires a degree of modification from traditional conceptual models of FIO fate and transfer in non-karst systems. While a number of reviews have provided detailed accounts of the state-of-the-science concerning FIO dynamics in catchments, specific reference to the uniqueness of karst and its influence on FIO fate and transfer is a common omission. In response, we use a mixed methods approach of critical review combined with a quantitative survey of 372 residents of a typical karst catchment in the southwest China karst region (SWCKR) to identify emerging research needs in an area where much of the population lives in poverty and is groundwater dependent. We found that the key research needs are to understand: 1) overland and subsurface FIO export pathways in karst hydrology under varying flow conditions; 2) urban and agricultural sources and loading in mixed land-use paddy farming catchments; 3) FIO survival in paddy farming systems and environmental matrices in karst terrain; 4) sediment-FIO interactions and legacy risk in karst terrain; and 5) key needs for improved hydrological modelling and risk assessment in karst landscapes. Improved knowledge of

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these research themes will enable the development of evidence-based faecal contamination mitigation strategies for managing land and water resources in the SWCKR, which is highly vulnerable to climate change impacts on water supply and quality of water resources.

1. Introduction

Exposure to water resources contaminated with either human, livestock or wildlife faeces can pose a potential risk to human health (Kay et al., 2007). Disease (primarily gastroenteritis) caused by microbial pathogens from faecal matter disproportionally affects developing and rural regions, and is the second leading cause of child mortality under age five worldwide (Gall et al., 2015; WHO and UNICEF, 2014). Microbial pathogens can persist in a variety of catchment matrices including ground and surface waters, sediments, animal and human faecal matter, and soils (Alegbeleye et al., 2018; Sidhu et al., 2015). Faecal indicator organisms (FIOs), for example *E. coli*, are the most routinely used microbial compliance parameter for confirming faecal (though not necessarily pathogen) contamination of the environment, and their use in water quality legislation around the world demonstrates their widespread utility (Oliver et al., 2016). Quantification of FIOs is subsequently a key environmental management tool, serving as a direct indicator of faecal contamination levels of soil, water and other target media, and as a fundamentally important parameter in models that predict microbial pollution at larger spatial and temporal scales that cannot be easily monitored (de Brauwere et al., 2014). Understanding the sources of FIOs, and their associated fate and transfer processes, across multiple scales thus provides the underpinning evidence-base for informing effective management of microbial water quality in catchments (Bradford et al., 2013).

Karst catchments offer "distinctive hydrological pathways and landforms that arise from high rock solubility and well developed secondary (fracture) porosity" (Ford and Williams, 2007). These are further shaped by a range of climatological, biogeomorphological and biochemical controls (Phillips, 2016). For example, planes of weakness such as faults, fractures, and fissures are a necessary precursor, providing preferential flow pathways, and development of karstic landforms is highly rainfall dependent (Harmand et al., 2017). The preferential dissolution along existing planes of weakness, whose orientation is typically structurally controlled, is a positive feedback loop and results in extreme vertical and horizontal anisotropy of aquifer properties, such as hydraulic conductivity and transmissivity. Karst hydrology is characterised by infiltration of surface water into the groundwater system through sink holes and depressions, and rapid underground transport through conduit systems to springs (Gutiérrez and Gutiérrez, 2016). This results in high connectivity of surface and groundwater systems, and high transmissivity and connectivity of aquifers over large areas, which can lead to uncertainty in our underpinning understanding of hydrological functioning of karst systems (Hartmann et al., 2014). As a result, contaminated water can be rapidly transferred to points of human exposure, e.g. emerging at drinking water bores and springs or used for irrigation and domestic purposes. Managing microbial water pollution in karst landscapes therefore, presents a unique set of challenges, not least because of the extreme heterogeneity observed in aquifer properties.

The conceptualisation of FIO risk and associated sources, pathways, and survival dynamics of FIOs in karst landscapes requires a degree of modification from traditional conceptual models of FIO fate and transfer in non-karst systems. While a number of reviews have provided detailed accounts of the state-of-the-science concerning FIO dynamics in catchments (Cho et al., 2016; Kay et al., 2007; Oliver et al., 2016), specific reference to the uniqueness of karst and its influence on FIO fate and transfer is a common omission. Given that 25% of the world's population are dependent on karst water resources for drinking (Hartmann et al., 2014) it is critical that karst catchments are not overlooked when considering landscape-scale drivers of microbial water pollution. The general framework of source-pathway-receptor used to conceptualise FIO risk is valid for karst, but the processes that control FIO dynamics through this continuum are likely to be very different. Thus, findings of FIO dynamics in non-karst systems provide valuable comparative data but may offer limited transferability due to the fundamental differences in hydrology upon which varying land management approaches may be implemented (Bonacci et al., 2009).

The southwest China karst region (SWCKR) is one of the largest continuous karst zones in the world and represents 20% of the land area in China (Cao et al., 2015). The SWCKR is characterised by well-developed karst geology, high intensity precipitation events, population pressure, intensive agriculture and animal husbandry, and the highest national poverty rates, which have all been identified as causes of increased microbial contamination risk (Balbus and Embrey, 2002; Curriero et al., 2001; Dangendorf et al., 2002; Guo et al., 2009; Howard et al., 2003; Luffman and Liem, 2014). This combination of factors makes this geographical area a high priority for considering the challenges and opportunities of FIO research needs in karst terrain. Thus, the aims of this critical review are to identify research needs for advancing our understanding of FIO fate and transfer in the SWCKR, and to extrapolate from this region to identify a broader, more generic set of research priorities needed to better define our understanding of karst-related FIO behaviour.

2. The southwest China karst region: an exemplar

In rapidly-developing countries such as China, there is high vulnerability to climate change impacts on water supply and quality. Understanding the fate and transfer of FIOs and their pathways of exposure to human populations (e.g. via drinking water, crop irrigation, household food preparation) is therefore important in areas of China where water sources are vulnerable and prone to contamination, e.g. karst landscapes. However, this urgent need to explore microbial pollution issues in the SWCKR is driven by more than climate-change concerns. The Chinese Ministry of Agriculture (2018) stipulated that there must be zero growth of chemical fertiliser consumption by 2020, thus the world's top producer of rice and wheat will need to secure nutrient inputs from alternative sources other than mineral fertilisers. The anticipated response will be a significant increase in the use of organic fertiliser, which is currently under-utilised, to help boost agricultural output (Chadwick et al., 2015). Organic fertilisers such as livestock manures will contribute higher microbial loading to land and when coupled with changing climatic drivers that promote microbial transfer (e.g. increased frequency of storm events) the risk of faecal contamination of water sources is likely to increase. The Environmental Quality Standards for Surface Water (EQSSW) (GB3838-2002) are used in China as a regulatory framework. However, there are suggestions that these standards have struggled to keep pace with rapid economic growth and limited awareness of environmental protection, and that strategic amendments are needed to establish national water quality criteria to support the revision of water quality standards (Zhao et al., 2018).

Rice is a staple crop and major export of provinces in southwest China, and China is the leading global producer of rice (Peng et al., 2009; Wang, 2016). The land-levelling, irrigation, and drainage practices that underpin paddy rice farming differ fundamentally from typical Western agriculture (Sprague, 1975), yet studies of FIO pollution in paddy rice regions are scarce relative to other forms of agriculture.