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The impact of socio-economic development and climate change on *E. coli* loads and concentrations in Kabul River, Pakistan

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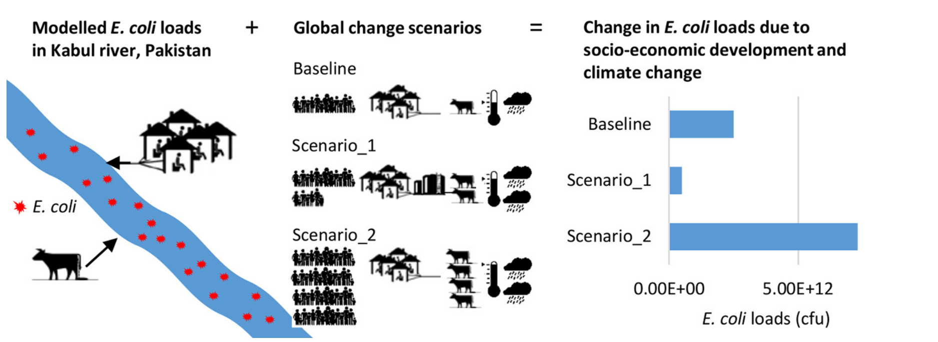
HIGHLIGHTS

- *E. coli* concentrations are influenced by socio-economic development and climate change.
- The SWAT model is run for Kabul river with scenarios based on IPPC's SSPs and RCPs.
- *E. coli* concentrations are large and expected to double in a BAU scenario.
- Concentrations are expected to reduce to 0.6–7% of baseline in a sustainable scenario.
- Reduction of *E. coli* concentrations in Kabul river requires stringent measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Microbial pollution is a major problem worldwide. High concentrations of *Escherichia coli* have been found in Kabul River in Pakistan. *E. coli* concentrations vary under different socio-economic conditions, such as population and livestock densities, urbanisation, sanitation and treatment of wastewater and manure, and climate-change aspects, such as floods and droughts. In this paper, we assess potential future *E. coli* loads and concentrations in the Kabul River using the Soil and Water Assessment Tool with scenarios that are based on the most recent Shared Socio-economic Pathways and Representative Concentration Pathways (SSPs and RCPs) developed for the Intergovernmental Panel on Climate Change (IPCC). Scenario_1 considers moderate population and livestock density growth, planned urbanisation and strongly improved wastewater and manure treatment (based on SSP1, "Sustainability"), and moderate climate change (RCP4.5, moderate greenhouse gas (GHG) emissions). Scenario_2 considers strong population and livestock density growth, moderate urbanisation, slightly improved wastewater treatment, no manure treatment (based on SSP3, "Regional rivalry") and strong climate change (RCP8.5, high GHG emissions). Simulated *E. coli* responses to Scenario_2 suggest a mid-century increase in loads by 111% and a late century increase of 201% compared to baseline loads. Similarly, simulated *E. coli* loads are reduced by 60% for the mid-century and 78% for the late century compared to the baseline loads. When additional treatment is simulated in Scenario_1, the loads are reduced even further by 94%, 92% and 99.3% compared to the baseline concentrations when additional tertiary treatment, manure treatment or both have been applied respectively. This study is one of the first to apply combined socio-economic development and climate change scenario analysis with an *E. coli* concentration model to better understand how these concentrations may change in the future. The scenario analysis shows that reducing *E. coli* concentrations in

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Pakistan's rivers is possible, but requires strongly improved waste water treatment and manure management measures.

1. Introduction

Safe and clean water is essential for human health. However, due to the increasing pressure of population growth, urbanisation and lack of sanitation, safe and clean water is difficult to sustain. Water contamination due to microbiological contaminants (e.g. bacteria, viruses or parasites) impairs the water quality in these systems. Waterborne pathogens may cause diseases, such as diarrhoea, which is the fourth leading cause of death in children under five years of age (UN, 2015). To analyse the microbial contamination in water systems, often faecal indicator bacteria are used, such as faecal coliforms and *Escherichia coli* (*E. coli*) (Coffey et al., 2007; Odonkor and Ampofo, 2013). Although *E. coli* is most often not pathogenic, its presence in high concentrations may indicate faecal contamination, and the possible presence of pathogenic microorganisms, and therefore an increased human health risk (Wu et al., 2011).

Concentrations of *E. coli* in surface water systems fluctuate with changing socio-economic variables, such as population growth, urbanisation and sanitation, and climate change, which includes variations in surface air temperature and precipitation patterns. Examples of the mechanisms that influence *E. coli* concentrations in surface water are ubiquitous. While, for instance, a properly constructed pit latrine leaches minimal microorganisms to the water system, a sewer without treatment emits large amounts (Graham and Polizzotto, 2013). Increases in population put pressure on sanitation systems. Moreover, climate-change induced extreme precipitation may increase microbiological discharges to surface water through an increased number of sewer overflows and manure runoff from the land. Conversely, increased precipitation may also increase dilution and therefore reduce surface water concentrations (Boxall et al., 2009; Rose et al., 2001; Whitehead et al., 2009). The potential overall impact of socio-economic development and climate change on microbial contamination of surface water is understudied (Hofstra and Vermeulen, 2016).

To assess the impact of socio-economic development and climate change on *E. coli* concentrations in surface water systems, researchers may apply scenario analysis using mathematical models (Hofstra, 2011). Scenario analysis explores future developments in complex systems. Scenario analysis is standard practice in other climate impact fields. Relevant examples of such scenario analyses include Ridley et al. (2013) and Wiltshire (2014), who explained the projected increases in precipitation in the Hindukush Karakorum Himalayan (HKH) region, including the Kabul River Basin, in the mid to end of the 21st century. Vörösmarty et al. (2010), highlighted the importance of freshwater stress in the face of climate change and found that approximately 80% of the world's population is at risk of water security. Climate change impacts on microbial water quality have been discussed by Jalliffier-Verne et al. (2017), who applied a hydrodynamic model to simulate the transport of faecal contaminants from combined sewer overflows affecting drinking water quality in Quebec, Canada. They found an increase in *E. coli* concentrations of up to 87%, depending on future climate and population changes in the worst case scenario. Rankinen et al. (2016) used the INCA-Pathogen model in the agricultural Lominijoki River Basin in Finland and concluded that pathogen concentrations in surface water are expected to be diluted due to increased precipitation in the future and that the water quality will not be deteriorated due to future agricultural expansion when the animal density remains relatively low and manure used as fertilizer is pretreated. They also concluded that the water quality in the basin can be improved substantially if wastewater treatment would be improved. Similarly, Sterk et al. (2016) found that overall climate change has limited impact on runoff of waterborne pathogens from land to surface water. In most of these analyses, climate change scenarios were utilized. Islam et al. (2018) is, to the authors' knowledge, the only study that assessed the impacts of combined socio-economic development and climate change on microbial water quality. They found that for a case study in Bangladesh socio-economic development influenced the microbial water quality more than climate change and that for a sustainable scenario loads could be strongly reduced.

The objective of our study is to assess the effects of potential future socio-economic development and climate change on *E. coli* loads and concentrations. As an example, we apply this generic assessment to Kabul River in Pakistan. High concentrations of *E. coli* are found in the main stream and tributaries of Kabul River. Bathing water criteria are violated year round and floods strongly increase concentrations due to increased runoff of manure from the land (Iqbal et al., 2017). This suggests that people who use the contaminated water for bathing, cleaning and other domestic activities are at risk of waterborne diseases. We developed scenarios (Section 2.3) based on the state-of-the-art scenarios used for the most recent Intergovernmental Panel on Climate Change (IPCC) assessment and created specific assumptions for the Kabul River Basin that are in line with the storylines. We apply these scenarios within a Soil and Water Assessment Tool (SWAT, Moriasi et al., 2015) based-model (Section 2.2) that has been calibrated and validated for hydrology and monthly *E. coli* concentrations in earlier publications (Iqbal et al., 2018; Iqbal and Hofstra, 2018). This scenario-based approach helps researchers and water managers to understand what possible futures could emerge and to identify alternative pathways to improve the Kabul River's impaired water quality contaminated with microbial pollutants. The approach could also be applied to other river basins in the world.

2. Data and methods

2.1. Study area

Our study was conducted in the Kabul River Basin (Fig. 1). The characteristics of this watershed have been described in detail by Iqbal et al. (2018). The River basin covers 92.6×10^3 km^2 and frequently floods due to monsoon precipitation (from July to September) and snow and glacier melt in summers (from April to September). With increasing temperature, snowmelt accelerates and precipitation patterns change. Resulting increases in runoff and discharge can cause floods in the Kabul River (Iqbal et al., 2018). Mean monthly river flows observed at the Attock rim station indicate that 4/5 of the annual flow occur during the April–September months with a peak in August (Iqbal et al., 2018). Flooding can transport large amounts of faecal waste (which often contains pathogenic organisms) from the land and contaminate the river. Most people in the river basin are connected to a sewer, but wastewater treatment has been dysfunctional ever since the waste water treatment plant in the basin was damaged by a large flood in 2010. Many livestock sheds are present in this area. Manure from these sheds is applied as fertilizer on agricultural fields, used for fuel or dumped directly into the river. Manure application on land is not regulated in the river basin. The Kabul River therefore carries untreated sewage effluents and manure from urban and rural settlements.

2.2. Water quantity and quality modelling

The SWAT hydrological model, together with its bacterial sub-model (Sadeghi and Arnold, 2002), was used to analyse the fate and transport