Quantifying The Impact of Socioeconomic Development and Climate Change on *Escherichia coli* Concentrations in The Pakistani Kabul River

MUHAMMAD SHAHID IQBAL

Thesis Committee

Promotor

Prof. Dr. Rik Leemans

Professor of Environmental Systems Analysis

Wageningen University & Research

Co-promotor

Dr. Ir. Nynke Hofstra

Assistant professor, Environmental Systems Analysis Group

Wageningen University & Research

Other members

Prof. Dr Bart Koelmans, Wageningen University & Research

Prof. Dr Fulco Ludwig, Wageningen University & Research

Prof. Dr Gertjan Medema, Delft University of Technology and KWR Water-cycle Research Institute, Nieuwegein

Prof. Dr Jack Schijven, Utrecht University and RIVM, Bilthoven

This research was conducted under the auspices of the Graduate School for Socioeconomic and Natural Sciences of Environment (SENSE).

Quantify the Impact of Socioeconomic Development and Climate change on *Escherichia coli* Concentrations in The Pakistani Kabul River

MUHAMMAD SHAHID IQBAL

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 30 August 2017
at 4 p.m. in the Aula.

Muhammad Shahid Iqbal
Quantifying the Impact of Socioeconomic Development and Climate Change on *Escherichia coli* Concentrations in The Pakistani Kabul River
(192) pages.

PhD thesis, Wageningen University, Wageningen NL (2017)
With references, with summary in English.

ISBN: 978-94-6343-447-8
DOI 10.18174/416179

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

Clean and safe freshwater is critical for the well-being of humans. However, concerns over water quality have been raised internationally. Water quality requires urgent attention as, for example, human population increases, agricultural activities flourish and climate change causes major changes to the hydrological cycle. Diarrhea is a waterborne disease and the fourth leading cause of death globally (UN, 2015). This may be due to infectious (bacteria, parasites and viruses) or non-infectious (food intolerances, contaminated water) constituents but both are a major public health problem. Diarrhea associated morbidity is primarily found in children and immunocompromised people and has less effect on healthy adults. Approximately 2.3 billion people are suffering from waterborne diseases globally and an estimated 0.7 million deaths are due to diarrhea annually (Walker et al., 2013). Around 7% of all deaths that occurred in the Kabul River Basin, which is located in the Southern Afghanistan and North-Western Pakistan, were due to waterborne diseases (Azizullah et al., 2011).

The waterborne disease risks are related to the concentration of waterborne pathogens in water resources. The main sources of water contamination are human and animal waste and agricultural activities. In Kabul River Basin farmers either apply raw sewage and manure on agricultural land as organic fertilizer, burn it as fuel or dump it directly into the water resources when the manure is not used. Over 80% of raw sewage in developing countries is discharged directly into the water resources (WHO, 2008b). In Kabul river basin, the majority of the people is connected to a sewer, but waste water treatment plants have been destroyed during the extreme 2010 flood (EPA-KP, 2014) and the effluents enter Kabul river directly. The large inputs from humans and agriculture cause high concentrations of micro-organisms in the river water and a high burden of disease in the area.

The microbial concentration in rivers is influenced by climatic factors, such as surface air temperature, extreme precipitation and floods (Hofstra, 2011). During floods, large number of micro-organisms are transported and contaminate water resources. High episodes of waterborne diseases are then reported (Hashizume et al., 2008). In the future, more floods are expected when the climate-changes (Molden et al., 2016). The expected increased surface air and water temperatures likely increase inactivation processes and therefore reduce the micro-organism concentrations (Seidu et al., 2013). More frequent heavy precipitation events may dilute micro-organism concentrations, but can also facilitate micro-organism transportation from land to surface waters due to increased surface runoff. Similarly, decreased precipitation can increase micro-organism concentrations because the fraction of micro-organisms that comes from the constant input from point sources will be larger (Atherholt et al., 1998). Different interacting pathways and processes thus influence the pathogen concentrations in surface water. However, the pathways that change hydro-climatic variables (i.e. precipitation, surface air temperature, water temperature and river discharge) are relatively well understood qualitatively, but their net effect is poorly quantified (Hofstra, 2011).

Future micro-organism concentrations are also related to socioeconomic developments, such as population growth, agricultural management changes, land use changes. Thus far no studies linked changes in socioeconomic development and climate in assessments of their impact on *E. coli* micro-organism concentration in surface water (Vermeulen and Hofstra, 2013). This thesis studies the joint impacts of hydro-climatic and socioeconomic changes on micro-organism *E. coli* concentrations in Kabul River, using statistical and process-based modelling, and scenario analysis.

A number of pathogens, such as viruses and bacteria are present in water resources. The detection of these pathogens are hard due to countless range of these pathogenic microorganism (Ouattara et al., 2013). Thus, to analyse the microbial contamination of water resources, usually indicators, such as faecal coliforms and Escherichia coli (*E. coli*), are used (Coffey et al., 2007; Odonkor and Ampofo, 2013). Although *E. coli* strains are mostly not pathogenic, their presence indicates the possible presence of other pathogenic organisms. Therefore the *E. coli* concentration is commonly used as indicator bacteria (Adingra et al., 2012b), also in the present thesis.

1.2 Study Area

The Kabul River Basin is located in Southern Afghanistan and North-Western Pakistan. The Kabul River originates from the Sanglakh range of the Hindukush mountains in Afghanistan,. The river drains into the Indus River system and sustains the livelihoods of millions of people in Afghanistan and Pakistan (Figure 1.1). The total area of the Kabul basin is approximately 92,600 km^2. The Kabul

River Basin is vulnerable to frequent floods due to the combined effect of heavy monsoon precipitation and snow/glacier melt in summer (Wang et al., 2011). The Kabul River in Pakistan crosses a region with a dry desert climate, with maximum daily temperatures in early summer that often exceed 45°C and mean monthly temperatures in winter that measure as low as 10°C (Khalid et al., 2013; Khan et al., 2014). High temperature in summer causes snow melt on mountain slopes. With increasing temperature, more snow melts quickly and increased runoff increases the discharge of Kabul River. Elevation in the basin ranges between 271m and 7603m above sea level, while its topography comprises high mountains with steep slopes (up to 10%) in the north and western parts, and low slopes (up to 2%) and valleys in the lower basin. Land use in the Kabul Basin consists of agricultural crops, pastures, urban areas, barren areas, water resources and forests. The predominant soil texture is loam to clay-loam along with silty clay and clay (Nachtergaele et al., 2012) .

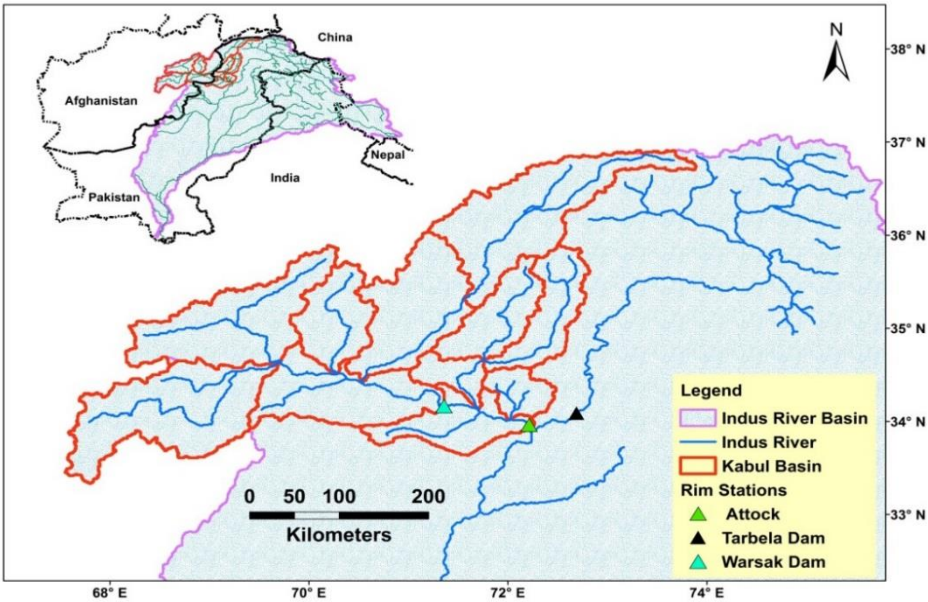

Figure 1.1: Study area Kabul River Basin, including neighboring countries and all major tributaries of the Kabul River.

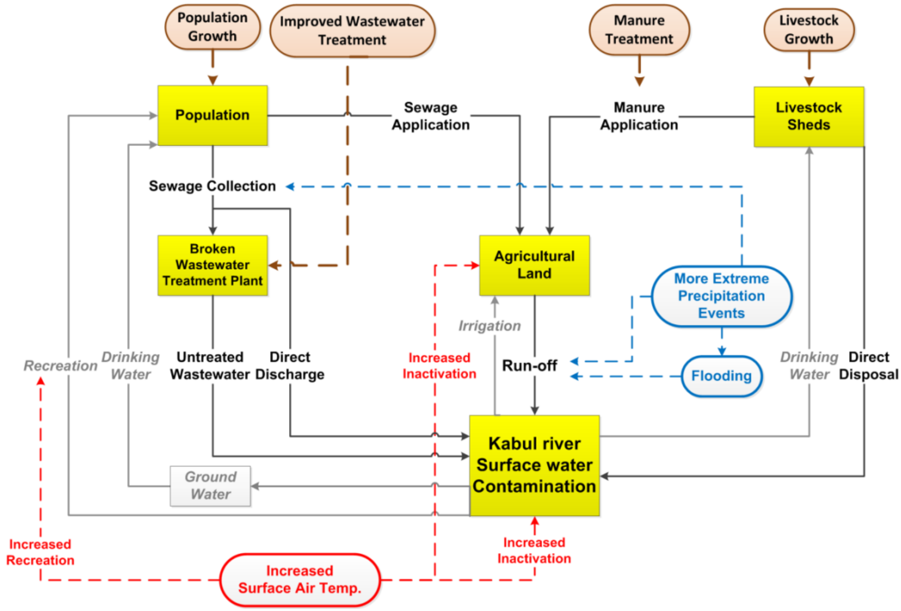

Figure 1.2: Sources, pathways and climatic influences of surface water contamination. Black arrows indicate the transport of indicator bacteria from land to surface water including direct disposal of manure from animal sheds, possible point and non-point of pollution sources of Kabul River (e.g. application of manure and sewage on agricultural land as fertilizer). Red boxes and arrows indicate the impact of temperature, blue boxes and arrows indicate the impact of extreme precipitation (floods) on the transport of bacteria from land to the river, brown box and lines indicate the impact of socioeconomic variables and grey lines show the feedbacks within the system.

1.3 *E. coli* Fate and Transport

Water resources are contaminated through different sources and pathways. Figure 1.2 illustrates possible sources and pathways of *E. coli* contamination.

1.3.1. Human Source

Approximately 22.6 million rural and urban people live in the Kabul River Basin (https://tntcat.iiasa.ac.at/SspDb). Due to a lack of wastewater treatment plants raw sewage is discharged directly into Kabul River through irrigation canals and urban drains. This causes serious microbial pollution of Kabul River. Raw sewage is also used as fertilizer on the agricultural land. Sewage does not contain only high concentrations of beneficial nutrients and other elements that stimulate soil fertility, but also high concentrations of pathogenic microorganisms (Gerba and Smith, 2005).

1.3.2. Livestock Source

Livestock manure is another major source of microbial pollution in water resources. Livestock density is high in the basin. In the lower Kabul river basin in Pakistan 0.89, 1.15 and 1.32 million cattle, sheep and goats are kept. In flood-prone areas, where manure is applied on agricultural land as fertilizer, manure may flush into the surface water through sub-surface runoff (Boyer et al., 2009). Additionally, manure is deposited into the surface water directly from livestock sheds. Grazing of cattle and other animals also leads to contaminated surface waters. Wildlife feces may also play a role as a source of *E. coli* in water resources but this role is difficult to quantify and likely much lower than the role of livestock manure, simply because their density is much lower.

1.3.3. Global Environmental Change and Contamination

The impact of climate change on waterborne diseases has been discussed in many studies and most of them have conducted in developed countries (e.g. Howard et al., 2016; Levy et al., 2016; Philipsborn et al., 2016; Rose et al., 2001b). Such studies are, however, difficult to conduct in developing countries due to under-reporting and non-registration of waterborne diseases in, for example, hospitals (Hashizume et al., 2007). Table 1.1 summarises a brief literature review of the impact of surface air temperature and heavy precipitation events on diarrheal outbreaks. Temperature is usually positively associated with diarrheal diseases. In summer more diarrheal cases occur than in winter. Moreover, also extreme precipitation events are strongly related to diarrheal disease, with an increase in disease outbreaks with high precipitation events. In the future we expect increases in both surface air temperature and precipitation in the Kabul river basin (Chapter 3) and we could therefore also expect more disease outbreaks.

The diarrheal disease risk is related to concentrations of these diseases in surface water. People are exposed to waterborne diseases by consuming contaminated water or eating vegetables irrigated or washed with contaminated water (Lloyd et al., 2007). The risk of waterborne diseases also depends on several other factors, such as water usage for recreational activities (e.g. bathing or swimming) or domestic use (e.g. washing, cleaning and cooking) (Hashizume et al., 2008). A better understanding of the relationship between hydro-climatic variables and concentration of waterborne pathogens or indicators of faecal contamination, such as *E. coli*, in water resources is essential (Cann et al., 2013c). Table 1.1 summarises the results of a brief literature review. Temperature can be positively and negatively correlated with pathogen and faecal indicator organisms, depending on the location. Heavy precipitation events are positively correlated with concentrations of micro-organisms in surface water. Due to increased precipitation in the face of anticipated climate-change there are increased chances flooding. The Kabul River Basin has been strongly affected by destructive floods during recent decades (Wiltshire, 2014) and this induced massive infrastructural, socioeconomic and environmental damages, especially during the flood of 2010. The vulnerability will increase due to climate-change. Flooding is related to water contamination. During the flood surface water overflows and carries untreated or ineffectively treated sewage, manure and other contaminants from the banks into the river. This eventually increases the concentrations of waterborne pathogens (see Figure 1.2).

1.3.4. Socioeconomic Factors

E. coli concentrations in water resources are influenced by socioeconomic changes (e.g. population growth, urbanization, livestock numbers, wastewater treatment and sanitation) For example, an increasing population increases the pressure on sanitation system. Similarly, with the increase in livestock number more manure is produced and its application on agricultural lands increases. This result in a considerable increase of E. coli concentrations in the surface water resources through the runoff from these lands. Intense agricultural practices without pre-treated manure can thus increase contamination load to water resources (Rankinen et al., 2016). The net impact of socioeconomic and climate change processes on *E. coli* contamination of surface water is understudied (Hofstra and Vermeulen, 2016b). Figure 1.2 shows the combined influence of socioeconomic and climate factors on *E. coli* sources and concentrations in Kabul River. Surface water microbial water quality based on socioeconomic scenario analysis studies are lacking.

Table 1.1 Relationship of waterborne diseases and waterborne pathogen concentration with surface air temperature and heavy precipitation events.

The relationship between waterborne diseases and waterborne pathogen concentration with surface air temperature.

Pathogens	Climate Variable	Location	Results / Conclusion	Statistical Technique Used	Reference
All Causes	Minimum Surface Air Temperature (Monthly)	Matlab, Bangladesh	Temperature is positively associated with *E. coli* and diarrhea.	Auto-correlation	Ali et al. (2013)
Bacterial	Surface Air Temperature (Weekly)	Adelaide & Brisbane, Australia	Temperature and *E. coli* are negative associated in Adelaide while positively associated in Brisbane.	Regression Analysis	Bi et al. (2008)
Salmonella	Surface Air Temperature (Monthly)	New Zealand	15% increase in reported Salmonella cases for each 1 degree rise in temperature.	Correlation Analysis	Britton et al .(2010)
Bacterial	Average Temperature (weekly)	Dhaka, Bangladesh	positive association with an average of 1^{0}C increase in temperature caused 5.6% increase in diarrheal cases and *E. coli* concentration in water resources.	Regression Analysis	Hashizume et al .(2007)
Bacterial	Average Temperature (weekly)	Dhaka, Bangladesh	the positive association between average temperature and diarrheal cases along with increased concentration of Waterborne pathogens.	Regression Analysis	Hashizume et al. (2010)
Bacterial	Average Minimum and Maximum Temperature	Shenyang, China	Both minimum and maximum temperature are positively correlated with diarrheal incidences, *E. coli* concentrations also increased initially and then decreased	Correlation Analysis	Huang et al. (2008)
Bacterial	Average Temperature (Monthly)	Matlab, Bangladesh	Mean monthly temperature is positively associated with diarrheal incidences	Classification and Regression	Islam et al. (2009)

				Tree Analysis (CRTA)	
All Causes	Average Temperature (Annual)	Vietnam	Significant positive correlation between temperature, diarrhea and waterborne pathogen concentration in water resources	Multivariate Analysis	Kelly-Hope et al. (2007)
Bacterial	Maximum Temperature (Weekly)	Lusaka, Zambia	1 ^{0}C increase in temperature causes 5% increase in diarrhea cases. *E. coli* concentration decreases	Auto-correlation	Luque Fernandez et al. (2009)
Bacterial	Maximum and Minimum Temperature (Monthly)	Dhaka, Bangladesh	Diarrhea negative with maximum temperature but positive with minimum temperature	Auto-correlation	Matsuda et al. (2008)
Bacterial	Average Temperature (Weekly)	Cuernavaca, Mexico	Higher incidence of diarrhea and *E. coli* in summer than winter	Autoregression and Correlation Analysis	Paredes-Paredes et al. (2011)
All Causes	Average Temperature (Weekly)	Lima, Peru	Positive correlation between weekly temperature and reported diarrheal cases	Correlation Analysis	Speelmon et al. (2000)
All Causes	Maximum Temperature (Monthly)	Tanzania	1^{0}C increase in temperature associated with 29% increase in diarrhea	Correlation Analysis	Traerup et al.(2011)
Bacterial	Maximum Temperature (Monthly)	Jinan, China	1^{0}C increase in temperature associated with 11% increase in diarrhea and *E. coli* concentration increases in summer compared to winter times.	Time Series Analysis	Zheng et al. (2008)
The relationship between waterborne diseases and waterborne pathogen concentration with heavy precipitation Events.					
Bacterial	Heavy Precipitation events	Matlab, Bangladesh	No observed relationship between heavy precipitation (monsoon) and diarrhea cases. Also no substantial increase in *E. coli* concentration	Linear Threshold Model	Glass et al. (1982)
All Causes	10mm increase or decrease of precipitation over 52mm	Dhaka, Bangladesh	Diarrhea increases by 5.1 %, Also concentration of *E. coli* increases in open water resources	Linear Threshold Model	Hashizume et al. (2007)

All Causes	Precipitation exceeding upper limit 95%	England and Wales	Significant relationship between cumulative rainfall sum of 7 days and diarrhea and *E. coli* concentrations	Correlation Analysis	Nichols et al. (2009)
All Causes	Heavy Precipitation events	Northern Ghana	Maximum precipitation events association with outbreak of diarrhea	Auto Correlation	Seidu et al. (2013)
All Causes	Maximum 5-day rainfall in a six week period	Canada	Increased risk of diarrheal outbreaks following precipitation events	Step-wise regression analysis	Thomas et al. (2006)
Diarrheal disease	Air temperature, precipitation and relative humidity	Taiwan	Relative humidity and precipitation events significantly contributed to diarrhea cases	Regression analysis	Chou et al. (2010)
Bacterial	Consumption of Walkerton Municipal water	Walkerton, Canada	People living in homes connected to municipal water supply suffered from diarrhea, as after precipitation event water led to ground water saturation and causes *E. coli* and fecal contamination.	Correlation Analysis	Auld et al. (2004)
Bacterial	Consumption of untreated water	Swaziland, Southern Africa	High cases of diarrhea reported due to high contamination levels of *E. coli* and other waterborne pathogens in water	Auto Correlation	Effler et al. (2001)
Bacterial	Contact with freshwater stream flowing across seaside beach	Cornwall, England	High cases of diarrhea reported due high contamination level of *E. coli* (O157:H7)	Correlation Analysis	Ihekweazu et al. (2006)
Bacterial	Heavy Precipitation events	Ontario, Canada	Heavy snowfall followed by runoff in summer and heavy rainfall events increase outbreaks of illness and waterborne pathogen concentrations in water resources	Regression Model	Milson et al. (1990)
All Causes	Heavy Precipitation events	Delhi, India	Water resources were the probable cause of illness as during heavy precipitation events water was contaminated due to open defecation.	Correlation Analysis	Patil et al. (2011)

1.4 Opportunities In Using Process Based Modelling With Scenario Analysis

Most studies in Table 1.1. are based on statistical analysis. Though statistical analysis can be useful to better understand the net impact of climate variables on micro-organisms, correlation is not the same as causation and this analysis is limited to enable thorough understanding of the fate and transport of micro-organisms in surface water Moreover, it is difficult to include all relevant processes in statistical models. Therefore, in this thesis process-based modelling is used. Process based modeling is an important and indispensable tool for water and environmental studies (Devia et al., 2015). Models are classified as lumped or distributed models, static or dynamic models, conceptual or physical based models. Examples are the MIKE-SHE model (Refshaard et al., 1995), the HBV model (Bergstrom, 1976), the TOP-MODEL (Beven et al., 1984; Beven and Kirkby, 1979), and the VIC-model (Cherkauer et al., 2003; Liang et al., 1994; Park and Markus, 2014).

In this PhD study, the Soil and Water Assessment Tool (SWAT) is used to model the hydrology and *E. coli* concentrations in the Kabul River Basin. The SWAT model is a physically-based semi-distributed hydrologic model (Arnold et al., 1998a; Neitsch et al., 2011), which routes on a continuous time scale. This model has become an established and flexible tool used for studies into a variety of hydrologic and water quality issues at various watershed systems. It is also a tool that is very adaptable for applications demanding improved hydrologic and other increased simulation needs (Gassman et al., 2010). The SWAT model uses an ArcGIS interface to define the watershed hydrological features (Benham et al., 2006; Neitsch et al., 2011). The basic elements of the SWAT model include: hydrology, bacterial and nutrient loads, sediment yields, weather, plant growth, pesticides and land-use management.

Water quality models comprise the sources of the micro-organisms, the hydro-dynamics or hydrology of water resources and decay rates of the microorganisms in the water resources (Sokolova et al., 2013). However, process-based modeling to predict the microbial load in water resources is rare, especially in the developing countries where waterborne diseases are common (Hofstra, 2011). According to Pechlivanidis et al. (2011) water quality models can be divided into three categories; (i) spatially explicit statistically distributed models (e.g. LDS, Arc-Hydro, SELECT and SPARROW) (ii) Mass balance models, which explains the bacteria concentrations considering their input and decay process. In other words, mass balance models specify the potential loads of biological contaminants from the complete upstream watershed to the downstream surface water resources and (iii) Complex deterministic or mechanistic models, which emphasis the land management practice. These models simulate all interactions between all process that are responsible for the fate and transport of microorganisms from watershed to downstream surface water. Mechanistic models are efficient and have been used for long periods in different parts of the world to model the pollutant sources (Table 1.2). The SWAT bacterial model, which falls into category …, was developed by Sadeghi and Arnold (2002) to predict pathogen loads in water resources in watersheds. Sources of bacterial contamination are included in the model. The SWAT bacterial sub-model has the capacity to simulate fate and transport of bacteria.

Table 1.2: Various models applied for bacterial modeling (pathogenic and non-pathogenic) considering the point and non-point sources of pollution.

Indicator Microorganism	Pollution Source	Region	Models Applied	Reference
E. coli	point and non-point sources	France	Soil and Water Assessment Tool (SWAT-model)	Bougeard et al. (2011)
Fecal coliform		United States		Cho et al.(2012)
E. coli		Ireland		Coffey et al. (2010a)
Fecal coliforms and *E. coli*		Various watersheds of the world		Sadeghi and Arnold (2002)
Cryptosporidium		Ireland		Tang et al. (2011)
Fecal coliforms and *E. coli*	point and non-point sources	New Zeeland	Watershed Assessment Model (WAM View)	Tian et al. (2002)
E. coli	point and non-point sources	Texas, the United States	Hydrologic Simulation Program in FORTRAN (HSPF)	Desai et al. (2011)
Fecal coliform		Portugal		Fonseca et al. (2014)
Fecal coliform		New York (USA)		Russo et al.(2011)
E. coli, Campylobacter spp.,	point and non-point sources	Canada	WATFLOOD/SPL	Dorner et al.(2004)

Cryptosporidium spp. and Giardia spp.				
Cryptosporidium	point and non-point sources	Global	based on the nitrogen model of Bouwman et al. (2009)	Hofstra et al. (2013)
E. coli	point and non-point sources	Belgium	SENEQUE-EC model consists of the hydro-ecological SENEQUE/RIVERSTRAHLER model	Ouattara et al. (2013)
Fecal coliform	point and non-point sources	France	hydro-ecological SENEQUE/Riverstrahler model	Servais et al. (2007)
Cryptosporidium and Giardia	Point sources	The Netherlands	Water-model National (WATNAT) and the emission (from wastewater) model PROMISE	Medema and Schijven (2001)
Fecal coliform	non-point sources	United States	Spatially Explicit Delivery Model (SEDMOD)	Fraser et al. (1998)
E. coli	non-point sources	Australia	Simple Hydrology (SIMHYD),	Haydon and Deletic (2006a)
E. coli	point and non-point sources	New Zeeland	Watershed Assessment Model (WAM/GLEAMS)	Collins and Rutherford (2004)
Cryptosporidium, Giardia and *E. coli*	Point sources	Australia	The non-linear loss module of the IHACRES rainfall-runoff model	Ferguson et al. (2007)
Fecal coliform	point and non-point sources	Europe	World Qual, Part of WaterGAP3	Reder et al. (2015)
E. coli	point and non-point sources	Mexico	tRIBS Model	Robles Morua et al. (2012)
Cryptosporidium, Giardia, and *E. coli* OH157: H7	point and non-point sources	United States	WATFLOOD/SLP9 Model	Wu et al. (2009)

The SWAT model has been tested on a watershed in Missouri (USA) for *E. coli* and fecal coliforms (Baffaut and Benson, 2003). Similarly, Parajuli (2007) has also tested the SWAT microbial to watershed in Kansas (USA). Although most mechanistic models require large datasets to run effectively (which lead to high running cost), the SWAT model requires fewer data to simulate bacterial fate and transport from upstream watershed systems to the downstream surface water resources. The SWAT model is also freely available. So we used the SWAT model due to its low running cost and possibility to run it with only the sparsely available datasets in the Kabul Basin. A further detailed description of the SWAT-bacterial modelling is given in Chapters 3 and 4.

Process-based models can be used with future scenarios. Several studies have focussed on the relationship between climate change and faecal indicators or waterborne pathogens (Jalliffier-Verne et al., 2016; Liu and Chan, 2015; Rankinen et al., 2016; Sterk et al., 2016). In these studies, increased combined sewer overflows in Quebec, Canada were a result of increased precipitation events (Jalliffier-Verne et al., 2016) and future projected decreased discharge causes increased faecal coliform concentrations in Taiwan (Liu and Chan, 2015), while limited climate change impacts were observed in Finland (Rankinen et al., 2016) and the Netherlands (Sterk et al., 2016), These studies did not simultaneously account for future changes in socioeconomic growth and social development. For the first time we combine the climate change scenarios with socioeconomic scenarios and perform a scenario analysis for *E. coli* concentrations in surface water resources. The scenarios that have been newly developed for this thesis are based on joint climate change and socioeconomic development pathways that have been developed for the IPCC community. Details about new scenario matrix framework is given in Chapter 5.

1.5 Objective, Research Question

In the previous literature review the main research gaps were identified. This thesis aims to fill these gaps. The objective is to **Quantifying the Impact of Socioeconomic Development and Climate Change on *Escherichia Coli* Concentrations in the Pakistani Kabul River Basin**. The following research questions (RQs) are addressed to achieve the above mentioned objective:

RQ1 What are *E. coli* concentrations in Kabul river, and how do different climate variables affect these concentrations in the Kabul River?

RQ2 How does the SWAT model perform when compared with observed discharge datasets and which RCP and GCM scenarios represent the local conditions in the basin best to see the flood frequencies changes in the future?

RQ3 How can observed *E. coli* concentrations adequately be modeled with the SWAT model?

RQ4 How would *E. coli* concentrations in Kabul River change in the future, for two comprehensive integrated socioeconomic development and climate change scenarios?

1.6 Thesis Outline

The research questions from Section 1.6 have been answered in four thesis chapters and a consequent synthesis chapter. Figure 1.3 describes how the different research questions are answered in each chapter and shows the different input data for each step. Chapter 2 addresses RQ 1. This chapter provides insight into the *E. Coli* concentrations in the basin and the relation between these concentrations and hydro-climatic variables. Water samples have been collected and the microbial concentration is analysed to indicate fecal contamination. Correlation and regression analysis relate hydro-climatic variables with the *E. coli* concentration.

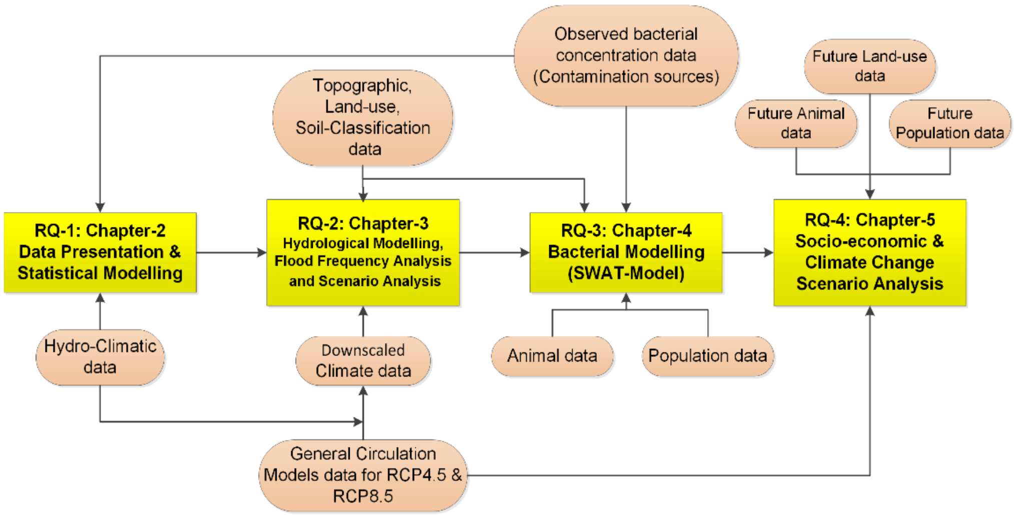

Figure 1.3: Schematic representation of methodological framework with input data applied in this thesis. Round boxes are data/variables/knowledge inputs and boxes (yellow color) are major analysis and results in this thesis (Chapters 2 to 5). Arrows show the data flow.

Chapter 3 addresses RQ 2 and presents the SWAT model to simulate the hydrology of the Kabul River Basin. This model is an effective tool that in Chapter 4 serves as the basis for the evaluation of point and nonpoint source of pollution into the river. The Kabul Basin is vulnerable to frequent annual floods. A flood frequency analysis is performed using the HEC-SSP software package to identify the return periods of the floods. Scenario analysis was performed using model outputs of four General Climate Models (GCMs) for two RCPs. These future climate data have been downscaled to the meteorological stations that serve as input for the SWAT model.

Chapter 4 addresses RQ 3 and applies the SWAT bacterial model to simulate the *E. coli* concentrations in the Kabul River Basin. Such a bacterial model helps to distinguish the sources of pollution present in the watershed and the contribution of different factors involved in the concentrations of waterborne pathogens in Kabul River.

Chapter 5 addresses RQ 4 by providing detailed insights in the future projections of *E. coli* concentrations. This chapter explores the changes in *E. coli* concentrations for two scenarios, that have been based on combined SSPs and RCPs and own assumptions. These new scenarios allow for the determination of future *E. coli* concentrations. The what-if scenario approach helps to understand the future concentrations of *E. coli,* for instance when floods are prolonged for longer than the current two to three months. The simulated outcomes quantify the waterborne pathogens (*E. coli*) concentrations.

Finally, Chapter 6 delivers a concise synthesis and draws insights with broad practical implications from key findings presented in the empirical chapters of this thesis. My thesis improves the understanding of socioeconomic development and climate-change impacts on *E. coli* concentrations in water resources. This systemic study will provide vital information and understanding of current and future pathogen concentrations and could stimulate a new era of managing, planning and developing water quality in the Kabul River. Outcomes of my study on the current and future E. coli concentrations could be helpful for health professionals in assessing current and future microbial water quality. The developed model could also be used to estimate other harmful pathogen concentrations in water resources. It also helps to develop an early warning system for the river's downstream areas to prevent flood hazards and improve water quality to cope with waterborne diseases. The developed approach is generic and can serve other regions in the world having similar climatological conditions and problems.

CHAPTER 2

THE RELATIONSHIP BETWEEN HYDRO-CLIMATIC VARIABLES AND *E. COLI* CONCENTRATIONS IN SURFACE AND DRINKING WATER OF THE KABUL RIVER BASIN IN PAKISTAN

This chapter is based on:

Iqbal M. Shahid, Ahmad M. Nauman and Nynke Hofstra. The Relationship between hydro-climatic variables and *E.coli* concentrations in surface and drinking water of the Kabul River Basin, Pakistan (Submitted)

Abstract

Water contamination due to microorganisms poses a risk for human health, as it can cause waterborne diseases, such as diarrhoea. Hydro-climatic variables, such as temperature, precipitation and discharge influence *E. coli* concentrations in surface and drinking water resources. The net impact of these variables is unclear. Although some recent studies have focused on this topic, these were mostly based in developed countries. Similar studies in developing countries are lacking. In this study we assess the impact of hydro-climatic variables on *E. coli* concentrations of the Kabul river in Pakistan. This river floods every year. In total 700 biweekly samples were collected and tested for *E. coli.* Nine sampling sites were located along the river and five drinking water sites from Nowshera were sampled for the period April 2013 – September 2015. Surface water samples exceed bathing water standards, while drinking water samples exceed drinking water guidelines; the water is grossly polluted. Water temperature, surface air temperature, discharge and precipitation correlate positively with *E. coli* concentrations. Increased runoff transports microbes from agricultural lands to Kabul river and high temperatures coincide with high precipitation and discharge. A linear regression model was developed to assess the net effect of the climate variables on *E. coli* concentrations. This model had coefficients of determination (R^2) of 0.61 for surface and 0.55 for drinking water samples. This suggests that climate variables account for more than half of the observed variation in *E. coli* concentrations in surface and drinking water. This study indicates that increased precipitation together with higher surface air and water temperature, as is expected in this region with climate change, likely increases *E. coli* concentrations. Waterborne pathogens are expected to respond similarly to these climate changes, indicating that disease outbreaks could well become more frequent in the future.

Key Words: Kabul river, water quality, climate change, *E. coli*, regression analysis.

2.1 Introduction

Diarrhea, including infectious (bacteria, parasites, and viruses) and non-infectious (food intolerances or intestinal diseases) diarrhea, remains a major public health problem around the world (Cloete, 2004; Lloyd et al., 2007). People affected mostly by diarrheal disease are those with limited access to hygienic facilities. Children below the age of five, primarily in Asian and African countries are the most affected by waterborne diseases (Seas et al., 2000). About 2.3 billion people are suffering from waterborne diseases worldwide (Cloete and Cloete, 2004) and annually an estimated 0.7 million deaths are due to diarrhea (Walker et al., 2013). In the Kabul River Basin in the North-West of Pakistan, where this study is conducted, approximately 7% of deaths, including children and adults, is attributable to waterborne diseases, such as diarrhea (Azizullah et al., 2011). In this basin people suffer from various waterborne diseases. The most common diseases include cholera, typhoid, bacterial diarrhoea and dysentery (Nabeela et al., 2014).

The prevalence of diarrheal disease may be affected by climate change and its associated factors. For instance, more diarrheal cases were recorded after floods due to the contamination of food and drinking water (Hashizume et al., 2008) and more floods are expected with climate change in the future (Lutz et al., 2014; Molden et al., 2016). Several studies have focused on the impact of climate-change on diarrhea (Moors et al., 2014). Such studies are, however, difficult due to under-reporting and non-registration in hospitals of these cases and the many confounding variables (Bagchi, 2007; Hashizume et al., 2007). The disease risk due to waterborne pathogens is related to the concentration of waterborne pathogens in surface and drinking water (Azizullah et al., 2011; Saeed and Attaullah, 2014). People are exposed to pathogens by drinking contaminated water, using it for recreation or eating vegetables irrigated or washed with contaminated water (Lloyd et al., 2007; Zhang et al., 2012).

Pathogen concentration in surface waters and, more indirectly, drinking water are influenced by changes in hydro-climatic variables, such as water temperature, surface air temperature, precipitation and discharge. Increased surface air and water temperature, as expected in the future, may increase the inactivation and therefore reduce the concentration of pathogens in the surface water (An et al., 2002a; Vermeulen and Hofstra, 2013). Increased precipitation may decrease the surface water concentration due to dilution (Delpla et al., 2011), while decreased precipitation may increase the surface water concentration, because a larger percentage of the discharge originates from the more constant input from point sources (Senhorst and Zwolsman, 2005). Extreme precipitation events are expected to increase the concentration of pathogens in the surface water, as manure and sewage applied to the agricultural land are taken into the river with the overland flow (Atherholt et al., 1998), and because of sewer overflows (Gibson et al., 1998) and resuspension from sediments (Wu et al., 2009). The pathways through which changes in hydro-climatic variables influence waterborne pathogen concentrations in surface water are relatively well understood, but the net effect is poorly quantified. (Hofstra, 2011).

The main objective of this study is to evaluate *E. coli* concentrations and analyse the influence of the hydro-climatic variables water temperature, surface air temperature, precipitation and discharge on surface and drinking water *Escherichia coli* concentrations in the Kabul River Basin in Khyber Pakhtunkhwa Province, Pakistan. We focus on *E. coli* rather than pathogens, because sampling of pathogens and their analysis are expensive. Although, pathogens and *E. coli* are not necessarily correlated, presence of *E. coli* indicates faecal pollution. *E. coli* has been extensively used as an indicator bacterium for faecal pollution of water sources (Odonkor and Ampofo, 2013). We hypothesise that pathogens and *E. coli* have a similar response to changes in hydro-climatic variables.

This study seizes the opportunity to assess the impacts of flooding and other hydro-climatic variables on *E. coli* concentrations in a region that floods every year. The resulting empirical correlation and general linear model will help to assess potential future threats due to climate change in this region and other developing regions that are prone to flooding. We have described the study area, sampling procedure and the statistical analysis (Section 2) and then statistically relate the measured *E. coli* concentrations to the hydro-climatic variables (Section 3).

2.2 Material and Methods

2.2.1 Study Area Description and Sampling Locations

The study area is the Kabul River Basin in the Khyber Pakhtunkhwa Province (KPK in Pakistan) situated east of Warsak dam. Nine sampling sites in the river and five sampling sites of drinking water sources from Nowshera city were selected (Figure

2.1). These sites were generally selected near, in between, and after the river passes through big cities to allow for different point and non-point pollution inputs. After one year of sampling, four river sampling points were excluded, because the *E. coli* concentrations among the points were highly correlated and time and money were better spent otherwise (Table 2.1).

Kabul river is a 700 kilometre long river that starts in the Sanglakh Range of the Hindu-Kush mountains of Afghanistan and ends in the Indus river near Attock, Pakistan (Khan; et al., 2014; Sayama et al., 2012). The main tributaries of Kabul River are the Logar, Panjshir, Kunar, Gharband, Bara and Swat rivers. After the Afghanistan-Pakistan border, Warsak dam is situated (site 1 in Figure 2.1). From the Warsak reservoir irrigation canals run through the heavily cultivated areas towards Peshawar and return to the river at Shah Alam (site 4 in Figure 2.1). After Warsak dam, Kabul river is divided into three tributaries: Sardaryab (site 2 in Figure 2.1), Shabqadar (site 3 in Figure 2.1) and Shah Alam (site 4 in Figure 2.1). The Swat river (called Khyali (site 5 in Figure 2.1) near Charsadda)) runs from the mountains in the north of the study area into Kabul river at MT Pull (site 6 in Figure 2.1). All these river branches join again near Amangarh (site 7 in Figure 2.1), the river crosses farming areas and small towns before it reaches Nowshera (site 8 in Figure 2.1). Nowshera is divided in two parts by the river and suffers the most from floods. After Nowshera, Kabul river passes Hakeem Abad (site 9 in Figure 2.1) before entering into the Indus river at Attock. Kabul river water is used for drinking, irrigation, power generation and recreational purposes at different points (see Table 2.1).

Kabul river crosses two major climatic belts. Its upper stream has a continental warm-summer climate with a mean summer temperature of approximately 25°C and a mean winter temperature below 0°C (Lashkaripour and Hussaini, 2008). In the down-stream area in Pakistan, Kabul river crosses a region with a dry desert climate, with maximum daily temperatures in early summer that often exceed 42°C and mean monthly temperatures in winter that measure 10°C (Khalid; et al., 2013; Khan; et al., 2014; Shaikh; et al., 2010). High temperature in summer causes snow melt on the mountain slopes. With increasing temperatures, more and more snow melts quickly and the increased runoff increases the discharge of Kabul river and thus causes floods in May and June. Annual precipitation in the full basin is less than 500mm, although precipitation is higher on the mountain slopes around its headwaters. Extreme precipitation in the monsoon season causes flooding in late July or early August every year.

Peshawar, Charsadda, and Nowshera are the main cities in this basin. The population in the two latter cities (in total 3.14 million) is at high risk of frequent flooding and waterborne diseases associated with the floods (Arshad Ali, 2012). *E. coli* enters the surface water with the sewer effluent, with manure from the animal sheds and with precipitation that has run off the agricultural lands. Upstream from Warsak dam, sewage from the main cities Jalalabad, Qandahar and smaller settlements like Torkham, Landi Kotal, Jamroad, and Sparesung entered into Kabul river. Manure and sometimes raw sewage are applied to the agricultural lands along the river as source of fertilizer (Thurston-Enriquez et al., 2005a). In the current study area, downstream of Warsak dam, sewage from Charsadda, Nowshera and from the big city of Peshawar (3.13 million inhabitants) and from smaller settlements is collected in sewers and directly enters Kabul river without treatment. Peshawar used to have a waste water treatment plant, but this has been broken since the 2010 floods. Agriculture (crops like wheat, corn, sugarcane, barley and vegetables like tomato, spinach, okra) is practiced on the banks of the river outside the cities and more inland, and manure and sometimes untreated sewage are applied to these lands as fertilizers. Additionally, near Amangarh raw manure from animal sheds is entered into the river directly.

Kabul river recharges the groundwater. Due to extensive pumping of groundwater and low river flow, the water table in the basin declines very rapidly. Therefore, groundwater may be recharged with contaminated river water and this is a problem for drinking water supplies (Khan et al., 2012). The drinking water sampling locations are all located in the city of Nowshera, as Nowshera is expected to be mostly influenced by the flood. The selected sampling points are a tube well (NCT), hand pump (NSB), the Hakeem Abad tube well (HKTW), a dug well (AGO) and a dug well at the Boys College. Both HKTW and Boys College are quite close (100 meters) to the river banks, while the others are located further away from the river. During flooding the HKTW and Boys College are submerged in the Kabul river water. Water from these sources is mainly used for drinking, bathing and other domestic use. People usually consume water from the wells and pump directly without any treatment, such as water boiling, chlorination or filtration. AGO is an exception, as during the sampling period, in June 2015, water filters have been installed.

Table 2.1. Overview of the surface and drinking water sampling sites selected for this study, their location, data availability, water use and main contamination source.

No	**Location**	**Data availability (years)**	**Predominant water use**	**Main contamination source**
Surface water samples				
1	Warsak (Reservoir)	2	Water storage, drinking, power generation, and irrigation.	Non-point
2	Shabqadar (North branch)	1	Irrigation and recreation	Non-point
3	Sardaryab (Middle branch)	1	Irrigation and recreation	Non-point
4	Shah Alam (South branch)	2	Irrigation	Point (Untreated sewage from Peshawar)
5	River Khyali (Swat river near Charsadda)	2	Irrigation	Point (Untreated sewage from Charsadda)
6	M T Pull (Junction Swat and Kabul rivers)	2	Irrigation	Non-point
7	Amangarh (Junction three branches)	1	Irrigation	Point (Animal sheds)
8	Nowshera (Inside city)	2	Recreation	Point (Untreated sewage from Nowshera)
9	Hakeem Abad (East of Nowshera)	1	Irrigation and recreation	Non-point
Drinking water samples				
10	NCT (Tube Well)	2	Drinking and other domestic use	n.a.
11	NSB (Hand Pump)	2	Drinking	n.a.
12	HKTW (Tube Well)	2	Drinking and other domestic use	n.a.
13	AGO (Dug Well)	2	Drinking and other domestic use	n.a.
14	Boys College (Dug Well)	2	Drinking and other domestic use	n.a.

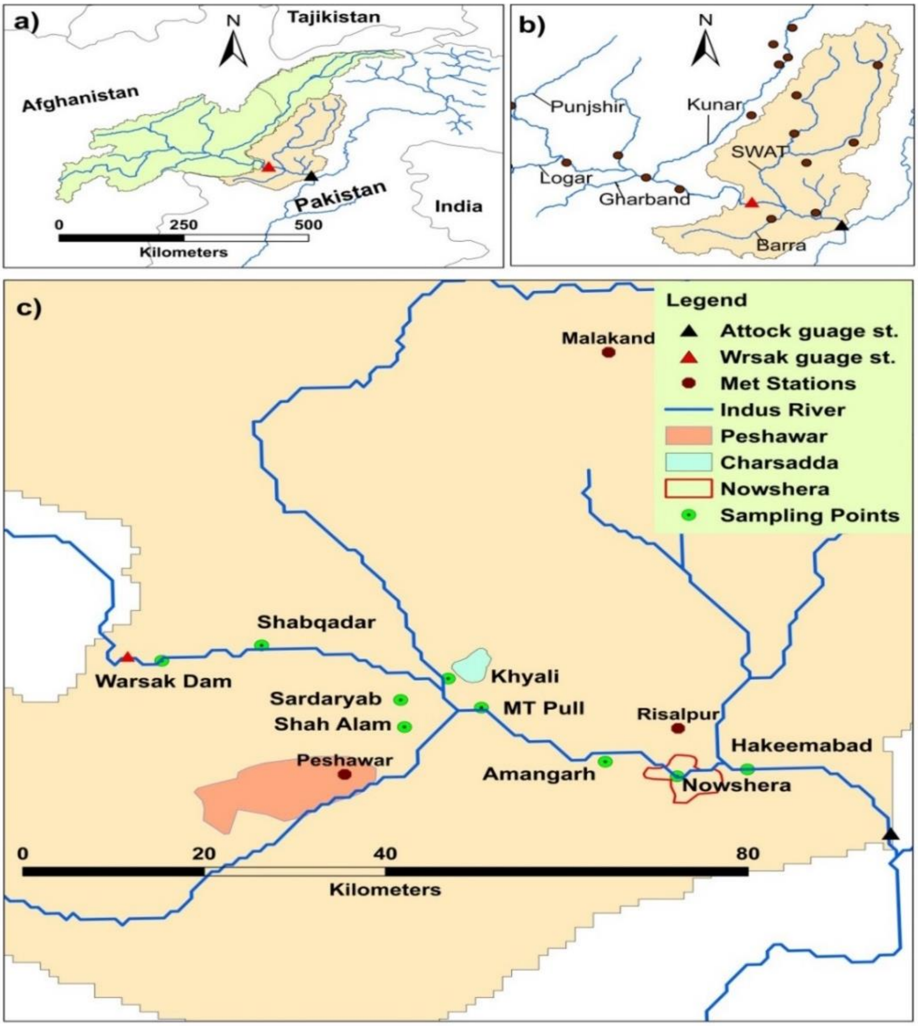

Figure 2.1. Study area map of the lower Kabul River Basin: a) shows the full basin along with neighbouring countries. b) Kabul basin indicating the main branches (indicating names) and meteorological stations, c) shows the downstream area of Kabul basin with urban areas of Peshawar, Charsadda, and Nowshera (highlighted). Green points correspond to the sampling points in Table 2.1 while the red and black triangles are the gauge station where discharge is measured. At black triangle Kabul river discharges into the Indus river.

2.2.2 Water Sampling

Water samples were collected biweekly for 30 months (April 2013 – September 2015) from the nine sampling locations along Kabul river and the five drinking water sources from the city of Nowshera**.** Surface water samples were collected in sterilized plastic containers from three points in the river; both banks and the middle of the river. All three samples were then mixed to take one composite sample, which is seen as a good representation of the full width of the river at each location. Water temperature was measured on the spot. For microbial analysis the samples were transferred to clean plastic bottles that were pre-sterilized and had no air bubbles. Drinking water samples were collected in separate clean sterilized plastic bottles. Water collection from tube wells and hand pumps was allowed to run for a 5 minutes before filling the bottles and then the water flow was reduced to enable filling of the bottle without splashing. Gases from the bottles were expelled by filling up, then emptying over the source, and refilling in the same manner. Water collection from the open well is different form the water collection of tap sources. From the open well we fill the bucket and dip the pre-sterilized bottle at 7 to 9 cm depth for 5 minutes to fill and expel out all the air bubbles. Upon completion of samples collection, surface and drinking water samples were kept in a cold box and transferred to the laboratory for microbial analysis within 8 hours of sampling.

2.2.3 Microbial Analysis *(E. coli)*

All samples were analysed for *E. coli* at the Nuclear Institute of Food and Agriculture, Peshawar. The Most Probable Number (MPN) technique was used to determine the *E. coli* concentration of the water samples in cfu[1]/100ml (van Lieverloo et al., 2007). To prepare, all the glass wares were sterilized in a hot air sterilizer at 160^{0}C for 2 hours. After cooling at room temperature these were used for the analysis. For total coliform counts a series of five fermentation tubes of Mackonky broth (Merck) were inoculated with appropriate volumes of ten-fold dilutions of water samples, and incubated at 37 °C for 24 h. Gas-positive tubes were considered positive for the presence of total coliform (Franson, 1995). Gas-positive Mackonky broth tubes were subjected to further analysis for the confirmation of *E. coli*. The tubes were incubated at 44.5 °C for 24 hours . Each positive test-tube was

[1] colony forming unit (cfu)

also exposed to a hand-held long-wavelength (366 nm) ultraviolet light lamp (Merck). Fluorescence in the tube denoted the presence of *E. coli* (Brenner et al., 1993). Concentrations of *E. coli* in water samples were recorded using an MPN table (WHO, 1985).

2.2.4 Hydrological and Metrological Data

Figure 2.1 shows the sampling locations, discharge gauge and meteorological stations. Water temperature was measured at the sampling site when the water samples were collected. Daily maximum, and minimum surface air temperature, and precipitation were obtained from the metrological stations situated in the studied area. Daily discharge (Kabul river) at Warsak dam and Attock stations were obtained from Water and Power Development Authority Pakistan. Discharge and precipitation were both used as variables in this study. Although precipitation influences discharge, in this case precipitation is seen as an indicator of runoff nearby, while the discharge also takes account of upstream areas. Such approach is commonly described in the literature (Cann et al., 2013b; Vermeulen and Hofstra, 2014). We also include both water temperature and mean surface air temperature (minimum + maximum / 2) to get an understanding of their relation with *E. coli* concentration.

2.2.5 Statistical Analysis

All the data were statistically analysed using the SPSS 22.0 computer package**.** *E. coli* and discharge data were log-normally distributed, so we always use the ^{10}log transformed data for both variables. Average surface air temperature was used for all the measurement sites normally distributed, while water temperature followed a bimodal distribution and this is also seen in other studies (Shrestha and Kazama, 2007; Wunderlin et al., 2001). Precipitation was gamma distributed. Descriptive statistics of the data were studied. Then standard Pearson correlations between *E. coli* concentration, water temperature, surface air temperature, and Kabul river discharge were calculated. Spearman's rank correlation analysis between *E. coli* concentration and precipitation was performed. We studied whether precipitation summed over between two and seven days obtained better correlation than daily precipitation. A longer time span could be expected to have a better correlation as precipitation may take a while before it runs off into the river, but after some time the water is out of the system and correlation may decrease. Summation of precipitation with comparative means was done in other studies as well (Bush et al., 2014; Carlton et al., 2014; Hata et al., 2014; Martinez et al., 2014; Vermeulen and Hofstra, 2014). We found different optimum summation times (including the sampling day) for the different sampling sites to have the highest correlation with the concentration of *E. coli* (see Table 4). We use the optimum for each sampling site.

We studied the observed difference in *E. coli* concentration in surface and drinking water by fitting the data to a general linear model to evaluate the comparative contributions of hydro-climatic variables (independent variables) to the observed variations in *E. coli* concentrations (dependent variable). The model is explained in detail in the results section. All hydro-climatic variables are added to the model one by one and the significance of their contribution to the results is evaluated. The variables that were added to the best fitted models, were selected based on the significance of the variable's contribution or strong improvement in the model's coefficient of determination (R^2). We also test whether or not interaction effects should be included in the model and we test the independent variables for collinearity. The R^2, determines how well the model explains the observed variation in *E. coli* concentrations. All statistical tests were analysed for significance at the 95 % confidence level ($p< 0.05$).

2.3 Results

2.3.1 Correlations

All samples were positive for *E. coli*, with very high concentrations compared to guidelines (<1 cfu/100 ml for low risk drinking water (WHO 2011) and (235 cfu/100ml) for bathing water (USEPA, 2001)(see Figure 2.2). The surface water samples showed higher *E. coli* concentration than the drinking water samples (Table 2.3 and Figure 2); this water is grossly polluted (Medema et al., 2009a). *E. coli* concentrations in surface water range from 820 to 160,000 cfu/100ml and in drinking water from 11 to 540 cfu/100ml. The mean *E. coli* concentrations per sampling site ranged from 119 – 8.4 x 10^4 cfu/100 ml subjected to different sampling sites, and the median values were 40 – 92,000 cfu/100 ml, including both surface and drinking water samples. Differences in *E. coli* concentrations between sampling sites are minor. Warsak and Khyali seem to have the comparatively lowest concentrations. Afterwards sewage from Peshawar and Charsadda is added to the river. However, concentrations at Warsak are already very high. Concentrations are highest at Shah Alam, which is located just after the sewage of Peshawar has entered the river, and Nowshera, where the sampling site was located just after the sewage from Nowshera enters Kabul river. AGO has the lowest values among the drinking water sources. The concentrations at this location did not change after the filter was installed and are still very high. The biweekly water temperature ranged from 9.9 to 29.1 ^{o}C. Surface air temperature ranged from 5.5 to 47 ^{o}C and total precipitation over the full 30 months from 2109 to 3333mm. Peshawar is the hottest and the driest, while Malakand is the coldest and the wettest of the meteorological stations. Discharge ranges from 2.2 to 3.8 ^{10}log m^3/s and discharge at Warsak is lower than discharge at Attock (Table 2.2), which is understandable as river SWAT and the irrigation canal enter Kabul river within the study area. The seasonal pattern is comparable for all variables, with high concentrations, temperature, precipitation and discharge in the months June to August.

Correlation analysis showed that *E. coli* concentrations in surface water correlate significantly positively with the hydro-climatic variables water temperature, surface air temperature, precipitation and discharge for most of the sampling sites (Table 2.4). The mean of the correlations over the 9 sampling sites are equal for water temperature, surface air temperature and discharge (0.64), although differences between the sites exist. Shah Alam often has the lowest correlation. This sampling site is strongly influenced by direct inputs from Peshawar and this may influence the relation with hydro-climate variables. For precipitation only significant correlations were found for sites that have 2.5 years of data (n=60). The average correlation over the significant sites (0.33) is much lower than for the other hydro-climatic variables. The correlations between the average *E. coli* concentrations over the sampling sites and average water temperature, surface air temperature, discharge and total precipitation are similar to the average correlations over the sampling sites, except for the correlation with discharge that is higher (0.728). For average *E. coli* concentrations discharge is the most important variable.

The *E. coli* concentration of drinking water samples were also significantly positively correlated with hydro-climatic variables. The mean of the correlation coefficients over the drinking water sites were lower than the mean of the correlation coefficients over the surface water sites. However, correlations between average *E. coli* concentrations in drinking water and hydro-climatic variables were only marginally different from the correlations between average *E. coli* concentrations in surface water and hydro-climatic variables. The correlation between average *E. coli* concentrations in drinking water and average discharge is the highest at 0.723. Although correlation does, of course, not imply causation, such a high correlation would indicate that discharge strongly influences the *E. coli* concentrations in drinking water. In particular during floods that makes sense, as some of the drinking water sources can be submerged in the flood water. Together with high temperatures that could cause growth in standing water in the tropics, these high correlations could be explained.

Figure 2.3 graphically presents the correlation between *E. coli* concentration of surface water samples with water temperature (both averaged over all sampling sites), surface air temperature averaged over the meteorological stations, total precipitation on the sampling day summed over the meteorological stations, and Kabul river discharge, averaged over the two discharge measurement locations. Correlations are high, in particular for discharge (R^2 is 0.53 for surface and 0.52 for drinking water samples). The correlation with precipitation is lower than expected (R^2 equals 0.046 for surface and 0.083 for drinking water samples). The low R^2 is due to high concentrations at days without precipitation.

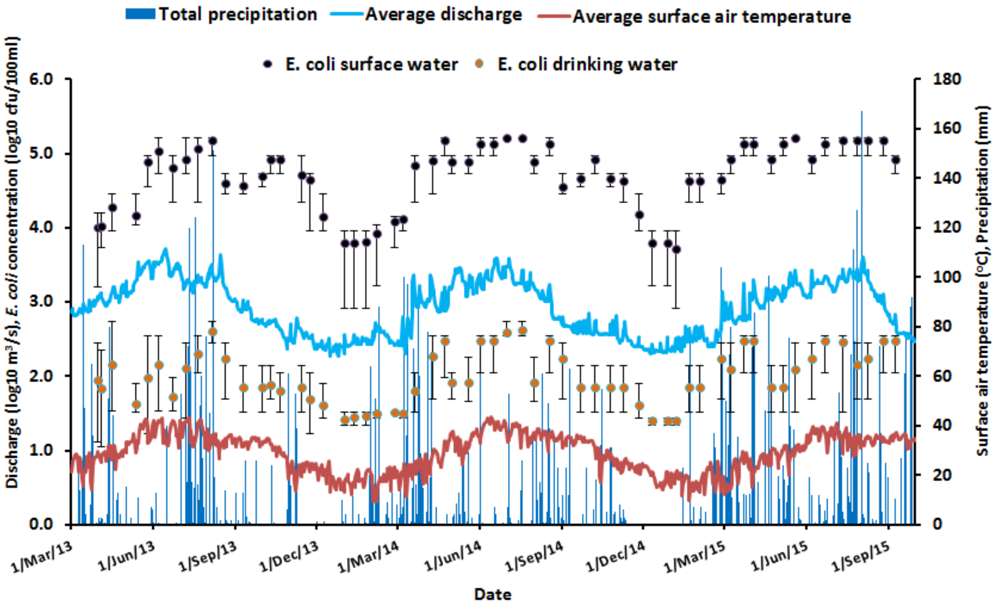

Figure 2.2. *E. coli* concentration of both drinking water and surface water sampling sites (bullet is mean, whiskers represent the spread in concentrations over the sampling sites), mean surface air temperature and total precipitation over the three meteorological stations, and mean discharge over the two discharge measurement points.

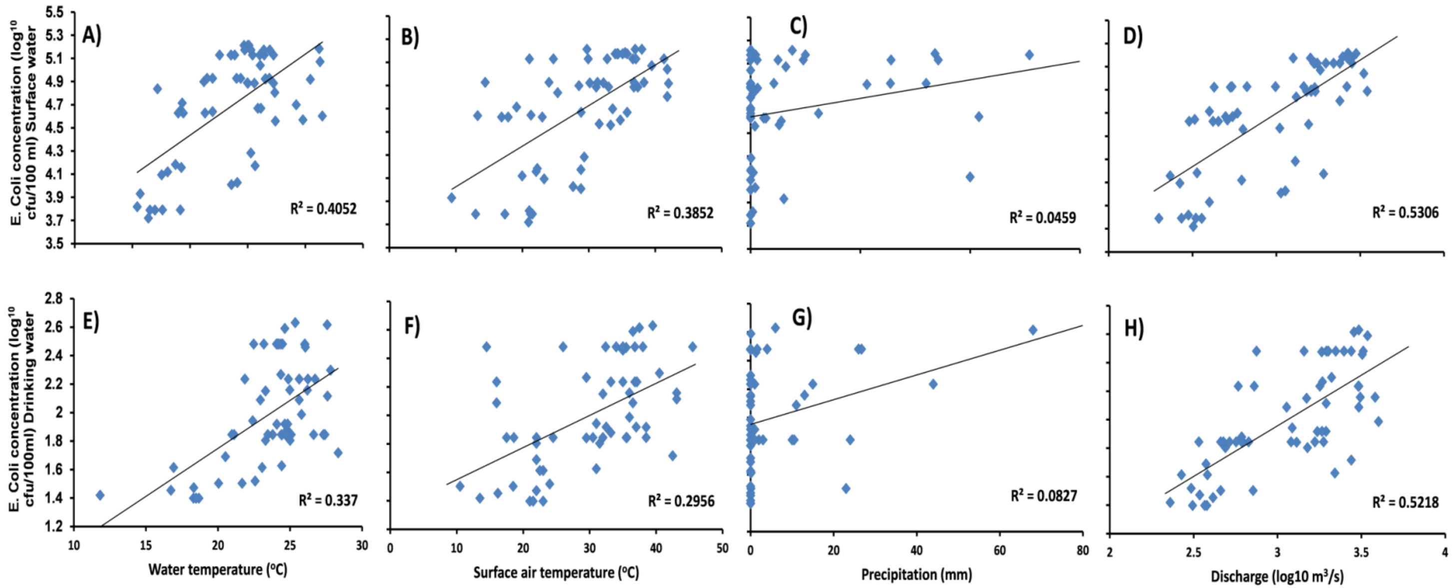

Figure 2.3. Correlations between the *E. coli* concentration (log cfu/100ml) averaged over all (Nine in the first year and five in the second year) Surface water (A-D) and five drinking water (E-H) sampling locations and the hydro-climatic variables water temperature (^{0}C) (averaged over all corresponding sampling locations) (A & E) surface air temperature (^{0}C) averaged over the meteorological station (B) and measured at Risalpur (F) total precipitation (mm) summed over the meteorological stations (C) and measured at Risalpur (G) Kabul river discharge (^{10}log m^3/s) averaged over Warsak and Attock (D) and at Attock (H).

Table 2.2. Summary of biweekly *E. coli* concentrations and water temperature data. The Sampling period is March 2013 – September 2015.

Measurement site			Water temperature			*E. coli* concentration				N
	Latitude	Longitude	Mean	Min	Max	Mean	Median	Min	Max	
Warsak	34.16	71.35	18.1	9.9	26.0	4.7	4.7	2.9	5.2	60
Shabqadar	34.10	71.33	18.4	10.2	26.8	4.7	4.5	3.7	5.2	25
Sardaryab	34.13	71.69	18.7	10.4	27.1	4.7	4.5	3.7	5.2	25
ShahAlam	34.08	71.64	18.8	10.5	26.6	4.9	5.0	3.7	5.2	60
Khyali	34.14	71.70	17.3	9.9	25.8	4.7	4.5	3.7	5.2	60
MT Pull	34.09	71.74	18.6	10.3	26.0	4.9	4.9	3.7	5.2	60
Amangarh	34.08	71.92	18.8	10.7	26.9	4.7	4.7	3.7	5.2	25
Nowshera	34.00	71.97	19.9	10.5	27.1	4.9	5.0	3.7	5.2	60
Hakeem Abad	34.01	72.04	19.4	11.2	27.8	4.8	4.7	4.0	5.2	25
NCT	34.00	71.59	23.9	10.9	28.4	2.2	2.0	1.0	2.7	60
NSB	33.59	71.59	24.1	11.3	29.1	2.2	2.1	1.4	2.7	60
AGO	34.00	71.56	23.6	12.3	28.6	2.1	1.6	1.2	2.5	60
HKTW	34.00	71.55	22.7	12.1	28.1	2.1	1.8	1.3	2.7	60
Boys College	34.00	71.59	24.0	12.5	28.5	2.1	1.7	1.1	2.7	60

Table 2.3. Summary of daily surface air temperature, total and maximum daily precipitation, Days with precipitation, and discharge of Kabul river over the period April 2013 – September 2015.

Meteorological stations	Mean surface air temperature (°C)			Precipitation (April 2013 – September 2015)		
	Mean	Min	Max	Total (mm)	Daily max (mm)	Days with precipitation
Peshawar	30.5	11.3	47.0	2422	110	252
Malakand	26.6	5.5	41.5	3333	137	296
Risalpur	29.6	8.5	45.9	2109	80	226
	Discharge (^{10}log m^3/sec)					
Discharge stations	Mean	Min	Max			
Warsak	3.0	2.2	3.7			
Attock	3.1	2.3	3.8			

Table 2.4. Correlations for each Sampling site and for Average *E. coli* and corresponding hydro-climatic variables as in Figure 3. For precipitation the sum of days that had the highest correlation was chosen (see footnote). Correlations are statistically significant (p<0.01) unless otherwise indicated. For the average surface water correlation averages over the meteorological and discharge measurement stations were used. Precipitation was summed over 2 days, unless indicated otherwise.

Sampling site	**Water temperature**	**Surface air temperature**	**Precipitation**	**Discharge**
Warsak ♦*Δ*	.675	.607	.332	.727
Shabqadar ♦*Δ*	.672	.730	-.085**	.553
Sardaryab ♦*Δ*	.625	.677	-.133**	.533
ShahAlam ♦*Δ*	.538	.548	.283*	.683
Khyali●*Δ*	.580	.595	.371	.691
MT Pull●*Δ*	.678	.578	.344	.695
Amangarh▲∞	.644	.713	-.043**&	.596
Nowshera▲∞	.634	.582	.306*	.719
Hakeem Abad▲∞	.666	.695	.003**&	.569

Average surface water	.637	.620	.348	.728
NCT▲∞	.462	.438	.228**&	.468
NSB▲∞	.541	.380	.432&	.508
AGO▲∞	.325*	.508	.202**&&	.615
HKTW▲∞	.427	.391	.291*&	.612
Boys College▲∞	.366	.406	.299*&&&	.607
Average drinking water ▲∞	.580	.544	.309*	.723

***. Correlation is not significant.*
**. Correlation is significant at the 0.05 level.*
♦. Precipitation and surface air temperature measured at meteorological station Peshawar.
●. Precipitation and surface air temperature measured at meteorological station Malakand
▲. Precipitation and surface air temperature measured at meteorological station Risalpur
Δ. Discharge measured at Warsak dam station
∞.Discharge measured at Attock station
&. Precipitation on the sampling day is used, &&. Precipitation sum of 5 days is used, &&&. Precipitation sum of 6 days is used

2.3.2 Model

A general linear model was applied to assess the impact of the hydro-climatic variables on *E. coli* concentrations. The multi-variable general linear model has the following form:

$$\log(Y) = \beta_0 + \beta_1 T + \beta_2 p + \beta_3 \log(D) + \beta_4 T * \log(D) + \varepsilon \qquad \text{Equation 1}$$

Where Y represents the dependent variable (*E. coli* concentration), β_i are constants, T is the temperature in ^oC; this could be either water or surface air temperature, p is the total precipitation summed over a variable number of days (see Table 2.4) before and including the sampling day in mm, D is the Kabul river discharge in m^3/s, T*log (D) represents the interaction effect of water or surface air temperature and Kabul river discharge, while ε is the residual error. Not all variables have been included (see Table 2.5) for all sampling sites. Water temperature and surface-air temperature have not been added to the model together, because they are highly correlated (R^2 = 0.65 for average surface air temperature and water temperature averaged over the surface water sampling sites). Discharge and water temperature are also correlated (R^2 = 0.42 for average discharge and water temperature averaged over the surface water sampling sites), but no collinearity existed for these variables and they add conceptually different processes to the regression model. For averaged surface and drinking water samples the model fitted explained a large proportion of the variation in *E. coli* concentration in Kabul river. The resulting model had a coefficient of determination (R^2), adjusted for degrees of freedom, of 0.61 for average surface water and 0.55 for average drinking water sources.

β-estimates of all independent variables and their coefficient of determination (R^2) for all the sampling sites and have been listed in Table 2.5. For the surface water sites that had 60 biweekly samples, the best-fit models included the variables water temperature, precipitation (except Shah Alam), discharge and the interaction effect of water temperature and discharge. Not all variables had a significant contribution, but inclusion did improve the model fit. For the sites that had only 25 biweekly samples, surface air temperature significantly contributed to the model and in some cases also precipitation was included. The sign of all beta values is positive, except for the interaction effect. The sign for that is negative in all cases. The intercept is sometimes positive and in other cases negative. In all cases, the beta value for precipitation is very low. One mm increase in precipitation, while the other variables stay the same, increases the *E. coli* concentration by 0.001 – 0.008 ^{10}log cfu/100ml. Surface air temperature has a more or less equal influence for the four sites with 25 biweekly samples. There, one degree increase in temperature increases the *E. coli* concentration by 0.035 – 0.038 ^{10}log cfu/100ml. For the other sites, the influence of water temperature is a factor 10 higher, from 0.215 – 0.465 ^{10}log cfu/100ml for each degree increase in water temperature. Also the impact of discharge is large. An increase of one ^{10}log m^3/s increases the *E. coli* concentration by 1.56 – 3.37 ^{10}log cfu/100ml. We can put this into perspective for MT Pull, for example, a site with average beta values for water temperature and discharge. Here a difference of 15.7 degrees in water temperature between minimum and maximum (see Table 2.1) would result in a change of 4.1 ^{10}log cfu/100ml, while a difference of 1.5 ^{10}log m^3/s in discharge between minimum and maximum would also result in an change of 4.1 ^{10}log cfu/100ml. The adjusted R^2 ranges from 0.43 to 0.66.

The models are much more variable for drinking water. The adjusted R^2 is lower than for surface water sites. It ranges from 0.26 to 0.42. For all sites, except boys college, precipitation significantly influences the *E. coli* concentrations. For some sites temperature (water or surface air) contributes significantly, while for others temperature is not included in the model. For some sites discharge contributes significantly, while for others discharge is not included in the model. The interaction effect is never included in the model, except for the average model. The beta value for precipitation is similar, if not slightly higher, than for surface water samples, while the beta value for temperature and discharge are a factor 10 lower than for the surface water samples. The two sites that are submerged in water when the river floods, HKTW and Boy's college, have a very similar model. The model includes precipitation and discharge, and discharge has an understandable much higher impact on these two drinking water sites than on the other drinking water sites.

Table 2.5: β estimates and R^2 for the models based on Equation 1 for all sampling locations in Kabul River Basin. Shaded boxes indicate statistically significant ($p<0.05$) contribution of the variables. Each sampling site is linked to the same meteorological and discharge station as explained in Table 2.4. Water temperature is used in the model unless indicated otherwise. Precipitation is summed over 2 days (sampling day and day preceding the sampling day), unless indicated otherwise.

Sampling site	**β0**	**β1**	**β2**	**β3**	**β4**	**R2**
Warsak	-6.093	0.465	0.005	3.373	-0.145	0.66
Shabqadar	3.351	0.038*				0.51
Sardaryab	3.376	0.038*				0.43
ShahAlam	-1.995	0.256		2.288	-0.085	0.50
Khyali	-0.560	0.205	0.004	1.562	-0.059	0.55
MT Pull	-1.800	0.274	0.002	2.023	-0.082	0.58
Amangarh	3.379	0.038*	0.008♦			0.52
Nowshera	-1.333	0.215	0.004	1.909	-0.065	0.59
Hakeem Abad	3.496	0.035*	0.007♦			0.49
Average surface water	-1.888	0.259	0.001	2.076	-0.079	0.61
NCT	1.181	0.025*	0.008♦			0.26
NSB	-0.006	0.050	0.010	0.254		0.41
AGO	0.207	0.016*	0.005^Δ	0.371		0.42
HKTW	-0.351		0.007	0.708		0.40
Boys College	-0.352		0.006	0.713		0.38
Average drinking water	-2.174	0.100	0.005	1.288	-0.030	0.55

* Surface air temperature is used instead of water temperature
♦ Precipitation is summed over 3 days
Δ Precipitation is summed over 5 days

2.4 Discussion

We measured *E. coli* concentrations in surface water of Kabul river and drinking water in the city of Nowshera through which Kabul river runs. Concentrations in surface water are very high (2.9 – 5.2 ^{10}log cfu/100ml); the river is grossly polluted. Concentrations in Kabul river are higher than found in earlier studies in Bangladesh (2.9 – 3.4, Islam et al. 2017a), China (1.8 – 3.4, Liu et al. (2009), Southeast Asia (2.8–4.3,Widmer et al. (2013), the Mekong river basin (2.0 – 3.1 Boithias et al. (2016), and Côte d'Ivoire (2.55–3.47, Adingra et al. (2012a). The reason for that is that the river basin is densely populated by people, who nearly all are connected to a sewer, but where the waste water treatment systems have been broken by a large flood in 2010. In addition to people, the basin is also densely populated by livestock, including cattle, buffaloes, sheep and goats. The concentrations in Kabul river do compare to other studies, such as for Ghana (0 – 9.0 Amisah and Nuamah (2014), for the Santa Cruz watershed in Arizona (5.15-5.73 (Sanders et al., 2013)) and for Indiana lakes and streams (5.20-5.90 Frankenberger (1995). Concentrations in drinking waters are also very high (1 – 2.7 ^{10}log cfu/100ml). The water found at all of the drinking water sites is unsuitable for drinking and should at least be boiled before consumption. The concentrations found compare to concentrations found in other studies (e.g. 2.30 – 2.91^{10}log cfu/100ml Warner et al. (2008).

E. coli concentrations in surface water were highly correlated with discharge, and in most cases also with precipitation. The reasons for higher *E. coli* concentrations in wet weather are increased runoff of agricultural lands and urban areas, leakage from manure storage (diffuse sources) and resuspension of sediments in the river (Hofstra, 2011). Precipitation is linked to runoff in the study area, while discharge is linked to runoff upstream. Precipitation is in most cases summed over several days, which mimics the time it takes for runoff to reach the river. Positive correlations between *E. coli* concentrations and precipitation and discharge were also observed in other studies (Abia et al., 2015; Aragonés et al., 2016; Dastager et al., 2015; Ibekwe et al., 2011; Schilling et al., 2009b; Walters et al., 2011). The positive correlations indicate that during wet weather diffuse sources are relatively more important than in dry weather situations.

Also for drinking water sites *E. coli* concentrations were positively correlated with discharge and precipitation. In Kabul River Basin the groundwater is quickly replenished by river water (Tunnermeier and Houben, 2005). This means that the same mechanism could be in place for drinking water as for surface water. During flooding the drinking water sites could also be directly influenced by flood water. That is in particular the case for the sites that are submerged in the river during floods (HKTW and Boy's College). High correlation between *E. coli* concentrations and drinking water from bore holes and tube wells and precipitation and discharge were also found in other studies (Herrador et al., 2015; Warner et al., 2008). The reason they gave improper wall construction and well coverage, and close-by toilets that cause higher leaching with higher precipitation.

E. coli concentrations in surface and drinking water were also positively correlated with average water and surface air temperature. These positive correlations can be explained by coinciding high temperature with high precipitation and discharge (see Figure 2). The observed positive correlation with water temperature does, therefore, not mean that increased temperature leads to the increased *E. coli* concentrations through bacterial growth. Positive correlation of the *E. coli* concentration with average water and surface air temperature was in line with other studies (Chu et al., 2013; Medema et al., 1997; Wang and Doyle, 1998). Several authors also provide the coinciding high temperature, precipitation and discharge as main reason for the positive correlation (Koirala et al., 2008; Schilling et al., 2009b) while others link it to bacterial growth (Byappanahalli et al., 2003; Hong et al., 2010; Tiefenthaler et al., 2009). We have not found evidence in the literature of bacterial growth in flowing water. Kabul river is a reasonably large river (mean discharge 1000 m^3/s) with a short residence time (less than half a day in the study area) (FFC, 2016). Growth in such a river is unlikely. A positive correlation between *E. coli* concentration and drinking water could be related to bacterial growth in wells. However, discharge and precipitation also influence the drinking water sites in a similar way as the surface water sites, which could indicate that the coinciding high temperature, precipitation and discharge are also the main reason for a high correlation with temperature for the drinking water sites.

Our general linear model explains a large part of the variation in *E. coli* concentration. The R^2s for the models for average surface and drinking water *E. coli* concentrations were 0.61 and 0.55 respectively. This means that hydro-climatic variables are very important determiners of the microbial water quality of Kabul river and the drinking water sites near this river. Of course, also other variables will be important, such as sewage inputs, livestock numbers, manure management, land use, and the mechanisms that determine the transfer of water from Kabul river to the drinking water sites. The R^2 found in our study for surface water sources is high compared to other studies. In other studies R^2 often ranges between 0.1 and 0.5 (Islam et al., 2017a (Submitted); Vermeulen and Hofstra, 2013; Walters et al., 2011; Whitman and Nevers, 2008). Kay et al. (2005) do find similar values (R^2 = 0.49-0.68) for the river Ribble drainage basin in the UK by including similar climatic and environmental variables. For drinking water sources Long et al. (2016) conducted a study in South China and found R^2 equal to 0.29 for *E. coli*, which is lower than the value we find. .

E. coli is an indicator faecal contamination of surface or drinking water. Although the presence of high concentrations of *E. coli* indicate the likely presence of more harmful pathogens, *E. coli* is mostly not directly correlated to pathogens (Teklehaimanot et al., 2014). Moreover, water use is also an important factor to include in health risk assessments. Bathing and irrigations are important uses of the Kabul river water that could pose health risk to the population. The sampled drinking water is used for drinking, but its treatment afterwards (possibly boiling) will influence the risk. This makes it difficult to directly conclude on the importance of the observed concentrations and relation with hydro-climatic variables for the health risk in Kabul River Basin. For that, pathogen data for the basin would be required, although this is expensive (Bruhn and Wolfson, 2007). However, as the *E. coli* concentrations, also in the drinking water sources, are very high, it is safe to say that the population in the basin will be at risk of waterborne pathogens and resulting faecal-oral diseases. The hydro-climatic variables, to which the *E. coli* concentrations in the Kabul River Basin are strongly related, are expected to change in the future for the basin, with increased temperature, precipitation and discharge (Iqbal et al 2017). Such changes will further increase the *E. coli* and pathogen concentrations in the surface and drinking water sites and also likely increases the health risk for the population in the basin.

2.5 Conclusions

We performed an analysis of biweekly *E. coli* samples for nine surface and five drinking water sources over a period of 30 months (April 2013 – September 2015) and statistically quantified the relation between *E. coli* concentrations and the hydro-climatic variables water and surface air temperature, precipitation and discharge of Kabul river in the North West of Pakistan, we conclude the following:

- All of the *E. coli* surface water samples exceeded USEPA bathing water quality standards (235 cfu/100ml) (USEPA, 2001). Therefore, the Kabul river is not suitable for swimming or bathing. Similarly, all of the *E. coli* drinking water samples exceeded the WHO standards for drinking water quality (<1/100ml). Therefore , drinking water of Nowshera is not suitable for drinking without additional treatment.
- Temperature, precipitation and river discharge were found to correlate positively with *E. coli* concentrations at most of the sampling sites.
- Our linear regression models for average surface and drinking water explain 61% and 55% of the variability in the observations respectively. The variables water temperature, precipitation, discharge and an interaction factor for temperature and discharge were included in the model.

Although *E. coli* concentrations are not necessarily correlated to waterborne pathogen concentrations, the high concentrations do indicate likely presence of waterborne pathogens and a resulting health risk for the population. Based on our analysis, we can conclude that expected increases in temperature, precipitation and discharge likely increase the *E. coli* concentrations further. This is also expected to increases the health risk for the population in the Kabul River Basin.

Acknowledgements

We thank Nuffic (NFP), Government of the Netherlands for providing the fellowship for M. Shahid Iqbal. We thank the Nuclear Institute for Food and Agriculture (NIFA) for providing laboratory support, Mr. Mian Mushtaq and Mr. Muhammad Irfan, Pakistan Meteorological Department (Regional Office Peshawar) and Water & Power Development Authority Pakistan (WAPDA) for providing data of river discharge. Furthermore, Prof. Dr. Rik Leemans (ESA, Wageningen), Prof. Dr. G. J. Medema (KWR), Dr. E.J. Bakker (Wageningen) and Dr. Afia Zia (AUP) are thanked for their help with the fieldwork plan design, statistical analysis and proofreading of the paper.

CHAPTER 3

THE IMPACT OF CLIMATE CHANGE ON FLOOD FREQUENCY AND INTENSITY IN THE KABUL RIVER BASIN

This chapter is based on:

Iqbal M. Shahid, Dahri Z. Hussain, Querner P. Erik, Khan A. and Nynke Hofstra. Impact of Climate change on flood frequency and intensity in the Kabul River Basin (Submitted)

Abstract

Devastating floods adversely affect human life and infrastructure in the Kabul river basin in Pakistan. We analyse flood frequency and intensity for a contemporary period (1981-2000) and two future periods (i.e. 2031-2050 and 2081-2100) using the RCP4.5 and RCP8.5 scenarios based on four bias-corrected downscaled climate models (INM-CM4, IPSL-CM5A, EC-EARTH and MIROC5). Future floods are modelled with the SWAT hydrological model coupled to HEC-SSP. The model results suggest an increasing trend due to increasing precipitation and higher temperatures (based on all climate models except INM-CM4), which accelerates snow and glacier-melt. All scenario results show that the current flow with a 1 in 50 year return period is likely to occur more frequently (1 in every 3 – 24 years) during the near and far future periods. Such increases in intensity and frequency are likely to adversely affect downstream population and infrastructures and urges for appropriate early precautionary mitigation measures.

Keywords: Kabul basin, Climate-change, GCMs, SWAT model, HEC-SSP, Floods

3.1 Introduction

Recurring floods often pose devastating effects in terms of human sufferings and material losses. The Indus basin, originating from the Hindukush-Karakorum-Himalayan (HKH) region, is prone to such extreme flood hazards. The basin has been strongly hit by destructive floods during recent decades and this induced massive infrastructural, socioeconomic and environmental damages (see Figure S1). The cumulative estimated economic losses of more than US$ 45.607 billion are reported. Around 12655 people lost their lives and nearly 200,000 villages were damaged or destroyed due to these floods in the past 80 years. The most devastating flood in 2010 spread over an area of about 160,000 km^{-2} across 82 districts affected over 20 million people, while including about 2000 deaths and 3000 injuries.

Kabul river, the largest tributary of the Indus river on its right side, originates in Afghanistan and brings frequent intensive flash floods in its low-land downstream areas, particularly when heavy monsoon rains are joined by snowmelt runoff during the summer months (Wang et al., 2011). The most severely affected areas by the 2010 flood include the Peshawar, Charsadda, Mardan, Nowshera, Swabi and Swat districts located in lower reaches of the Kabul river. All these districts suffered from massive damages (see Table S1).

A warming climate and changes in precipitation patterns are expected to substantially influence river flows in the HKH region including the Kabul basin (Lutz et al., 2014). The mean surface temperature increase in the HKH region towards 2100 is expected to be higher than the global mean surface temperature increase (IPCC, 2007a). This temperature increase will probably cause considerable changes in the region's weather patterns hydrological cycle. Relative to the 1961-1990 baseline period, the mean temperature during the near future (i.e. 2021-2050) period is projected to rise 2^{o}C, and an average change of 8 to 12% in annual precipitation is projected under the RCP4.5 (Mukhopadhyay and Khan, 2014). The change in mean temperature and precipitation will probably become larger in the far future (i.e. 2081-2100) due to the increasing greenhouse gas concentrations (Immerzeel et al., 2013; Lutz et al., 2014). Western low pressure weather systems, which generate most of the winter precipitation in the Hindukush and Karakorum regions, are expected to be accelerated by the changing climate (Ridley et al., 2013; Wiltshire, 2014). This can maintain a positive snow/glacier mass balance. This positive mass balance coupled with the increasing summer temperatures and monsoon precipitation will not only intensify the snow/glacier melt but also bring in extreme floods.

To better prepare for the recurring natural flood hazards and prevent financial losses and casualties, the possible future changes in flood frequency and intensity in the Kabul river basin should be analysed. However, such analysis for this important river basin is still lacking. This study therefore determines the projected future climate change and assesses its impacts on river flows in the Kabul river basin. The study provides quantitative estimates of the projected changes in flood frequency and intensity for both the near future (i.e. 2031-2050) and far future (i.e. 2081-2100) periods relative to the contemporary period (i.e.1981-2000). The results of this study will be useful in flood management in the region to design safeguarded hydraulic infrastructures along the Kabul river.

This paper is structured as follows. In section 2, we describe the study area in more detail. Section 3 describes the data used and prepared for the analysis. Section 4 explains the approach used in the hydrological model, flood frequency analysis and selection of climate models. Section 5 described the results followed by the discussion. Finally, the major findings are presented in conclusion.

3.2 The Study Area

The Kabul river originates from the Sanglakh range of the Hindukush mountains in Afghanistan and sustains the livelihoods of millions of people in Afghanistan and Pakistan (Figure 3.1(a)). It contributes around 10 to 12% of the annual flows to the main Indus river system (Inam et al., 2007). The total area of the Kabul basin is approximately 92,600 km^2. Its main tributaries are the Salang, Panjshir, Nerkh, Maidan, Duranie, Kunar, Swat, Jindi, Barra, and Kalpani Rivers. The Kabul basin can be divided into three major sub-basins on the basis of flow generation: the upper Kabul, Panjshir and lower Kabul. The upper Kabul basin generates 2.6% of the average annual flow of the basin, because this part of the basin receives less rainfall and there is no snowmelt contribution in its annual flow, Panjshir generates almost 15% of the annual flow while the rest of the flow is generated by the lower parts of the Kabul river including Chitral, Swat, Jindi and Barra tributaries (Frischmann, 2011).

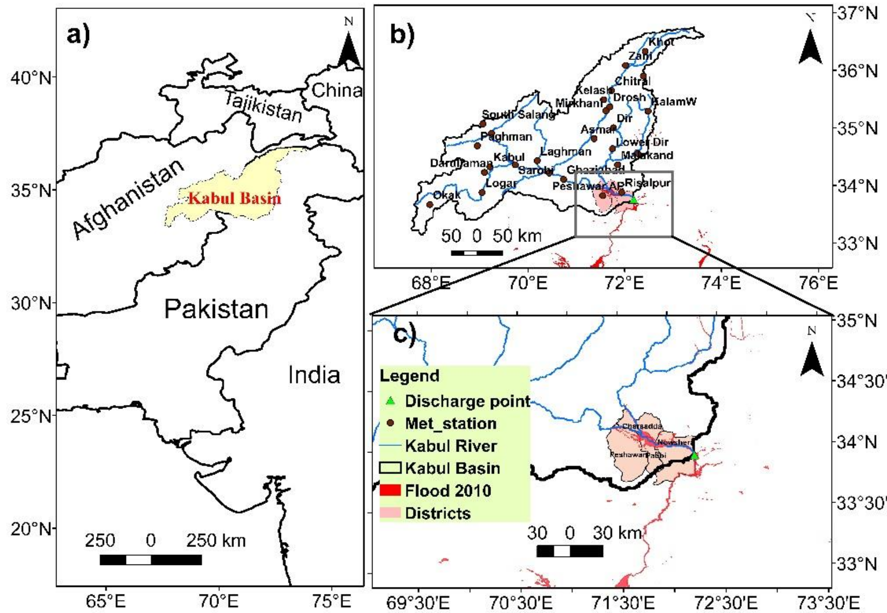

Figure 3.1: Study map of Kabul basin Afghanistan and Pakistan (a) geography of the basin (b) Kabul basin including all major tributaries of the main river as this river is the part of upper Indus basin (c) flood prone urban areas in the lower part of Kabul basin in Pakistan. The green triangle is the gauge station from where the discharge data is collected and model is calibrated and validated.

The basin's average monthly temperature reaches its maximum in July, when snow and glacier-melt considerably contribute to river flows. Mean monthly precipitation encounters two peaks throughout a year: in April and August. The August peak precipitation predominantly stems from the Indian summer monsoon and is mainly experienced in the Chitral, Swat and extreme lower reaches of the Kabul river. The upper Kabul and Panjshir basins are mainly influenced by western disturbances (WDs) that originate from the Mediterranean Sea and receive peak precipitation during April. Chitral and Swat basins are also complemented with snow- and glacier-melt. These factors together cause the major floods along the Kabul river particularly in low-land areas in the lower Kabul basin (Figure 1 (c)). Mean monthly river flows observed at the Attock rim station indicates that about 80% of the annual flows occur during the April-September months with a peak in August (Figure 3.2).

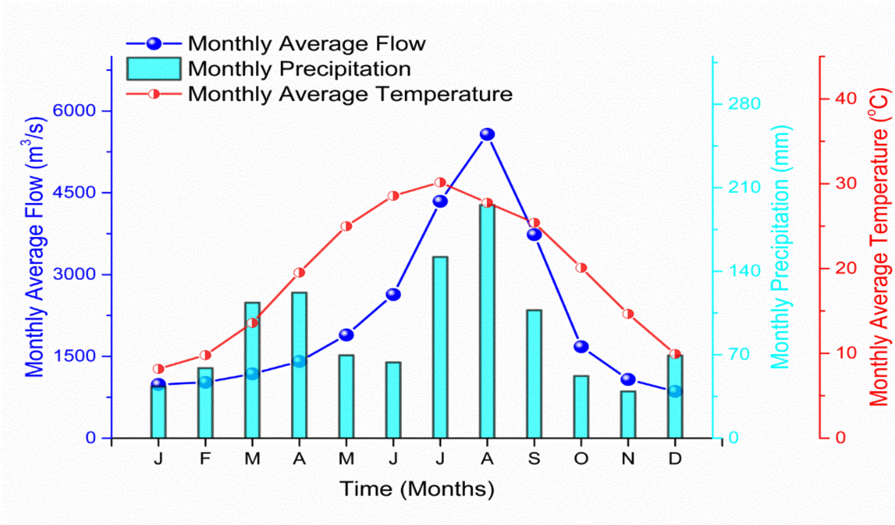

Figure 3.2: Mean monthly flow of the Kabul basin at Attock, monthly average temperature and precipitation variation based on climate stations (see details in Section 3) in the Kabul basin, for the period 1981-2000.

Elevation of the basin ranges between 271m and 7603m, while its topography comprises high mountains with steep slopes (up to 10%) in the north and western part, and low slopes (up to 2%) and valleys in the lower basin (Figure S2(a)). Land use of the Kabul basin consists of agriculture (29.4%), pasture land (26.1%), urban area (19.7%), barren area (9.4%), water bodies (14.6%), and forest (0.6%) (Figure S2 (b)). The predominant soil texture is loam to clay-loam textured (85%) and additionally 12% of the area's soil is silty-clay while only 3% is clay (IIASA. et al., 2012)(Figure S2 (c)).

3.3 Data

3.3.1 Topographic, Soil and Land-cover Data

Delineation of the Kabul basin was carried out using a 90m resolution Digital Elevation Model from the Shuttle Radar Topography Mission, acquired in January 2016 from the website (http://srtm.csi.cgiar.org). The Harmonized World Soil Database (available from http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database) and European Space Agency's land cover data for 2009 (Arino et al., 2010) (available from http://due.esrin.esa.int/page_globcover.php) were employed.

3.3.2 Historic Hydro-climatic Data

The Pakistan climatic data includes, daily precipitation, daily min, max temperature, wind speed, relative humidity and solar radiation for twenty-five years (1981-2015) was acquired from the Pakistan Meteorological Department, while the Afghanistan data was synthesized from the country's meteorological reports by the Afghanistan Meteorological Department (available at http://afghanag.ucdavis.edu/natural-resource-management/weather).

Meteorological stations (either at the periphery or within the Kabul basin) in both countries were selected and used (see Figure 3.1(b)). Data from the selected meteorological stations were used to prepare the necessary weather input files for the SWAT model. Daily measured discharge data at the Attock rim station from January 1981 to December 2015 were acquired from the Water and Power Development Authority of Pakistan. These observed flow data are used to analyse flood frequency and calibration and validation of SWAT model.

3.3.3 Future climatic Data

3.3.3.1 GCM and Scenario Selection

General Circulation Models (GCMs) are used to simulate the global climate at different spatial resolutions (100-250km) and provide future climate change projections till 2100. The present-day cutting edge GCMs were prepared by the Fifth Coupled Model Intercomparison Project CMIP5 (Taylor et al., 2012). The CMIP5's data were the basis of the Fifth Assessment Report by the Intergovernmental Panel On Climate Change (IPCC). Over 61 publically available GCMs provide future climate data. However, most of these GCMs underestimate the monsoon precipitation in the HKH region and are not truly representative of this region (Sperber et al., 2013). Therefore, they cannot be directly used for the projection of extreme events (floods) (Lee and Wang, 2014). A recent study by Lutz et al. (2016b) evaluated 94 GCMs runs for RCP4.5 and 69 GCM runs for RCP 8.5 for the HKH region using an advanced envelop-based selection approach integrated with the past performance of the GCMs. They shortlisted a climate model based on the projected average annual changes in the mean temperature and precipitation sum for the 2071-2100 period over the 1971-2000 period. The shortlisted GCM runs are further refined based on the changes in extremes of precipitation and temperature. Finally, the remaining GCM runs are validated by comparing their performance to reproduce the historical climate from a reference product. Based on this approach, Lutz et al. (2016a) applied the advance-envelop based approach and used it to select the four most suitable GCMs for the Upper Indus basin, which includes the area under this study. We relied on Lutz et al. (2016a) and used the GCM runs that they selected for the Upper Indus River Basin. We selected three GCMs that best represent the extremes of floods and droughts. The extreme of drought is represented by two possible dry-cold and dry-warm scenarios, while extreme floods are best represented by a wet-warm scenario. The fourth GCM is selected on the basis of average conditions. The selected four GCMs are INM_CM4_r1i1p1 (Institute for Numerical Mathematics) for the dry-cold scenario, IPSL-CM5A-LR_r3i1p1 (Institute Pierre-Simon Laplace) for the dry-warm scenario, MIROC5_r3i1p1 (Japanese Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for marine-earth Science and Technology) for the wet-warm scenario and EC-EARTH_r12ip1 (EC-EARTH consortium) for the average scenario.

Climate change is expected to substantially alter the hydrological cycle, although projections of flow variations probably contain large uncertainties (Hagemann et al., 2013). Due to such future climate uncertainties, researchers generally use different scenarios that indicate how future climate may change under specific assumptions. IPCC's Fifth Assessment Report provides four Representative Concentration Pathways (RCPs) for climate-change projections and modelling. However, in our current study climatic data for two representative concentration pathways (RCPs) were selected and used: RCP4.5 represents a medium concentration stabilization scenario in which greenhouse gas emissions peak around 2040 and then decline and RCP8.5 depicts a very high baseline scenario where emissions continue to rise throughout this century (Van Vuuren et al., 2011a). The CMIP5 daily climatic data for the four GCMs both RCP scenarios were downloaded from the Earth System Grid Federation Portal (http://cmip-pcmdi.llnl.gov/cmip5/; https://esgf-data.dkrz.de/search/cmip5/) to be used in our analysis.

3.3.3.2 Bias Correction, Downscaling and Grid Cell Selection

The evident inconsistencies in the spatial resolutions of GCMs can be corrected by different downscaling methods. This is necessary when climate models are used to drive hydrological and other models. Many downscaling methods are available to produce climatic data for climate impact models (Hawkins et al., 2013). Downscaling can be divided in two main categories: dynamic (Wood et al., 2004) and statistical downscaling (Wilby and Wigley, 1997). There are many downscaling methods available to produce climate data for impact models (Hawkins et al., 2013). We used the statistical downscaling method explained by Liu et al.(2015). They used the “delta or change factor” method in their study by overlaying the GCM’s data with the observed climate data (Arnell et al., 2003; Diaz-Nieto and Wilby, 2005). This method confirms that the current climate is in reality the observed climate and not the simulated GCM-based climate. Temperature change can be added to the observed temperature. Additions for precipitation, however, result in negative precipitation values. To overcome this problem the multiplicative (relative change) approach is usually used (Hawkins et al., 2013). Liu et al. (2015) also used quantile-quantile correction to ensure that the future data are distributed similarly to the observational data. It’s advantage is that it produces the data for a point rather than a grid and this point can then be used directly in a hydrological model such as SWAT, that relies on point data. This downscaling method requires selection of a grid cell for downscaling. The grid cell on top of the local meteorological station can be used or the grid cells surrounding different stations can be interpolated so that the meteorological station is centred in the grid (Leemans and Cramer, 1991). The difference between these two selection methods is small at the local scale (Leemans et al., 1992). So, we apply the single grid cell on top of the local meteorological station in the current study.

3.4 Methods

Flood frequencies are studied with historic annual flood data and with coupled hydrology (SWAT model) and flood frequency (HEC-SSP statistical software) for a reference period (1981-2000) and two future time periods (2031-2050 and 2081-2100). The methodology is summarised in Figure 3.3.

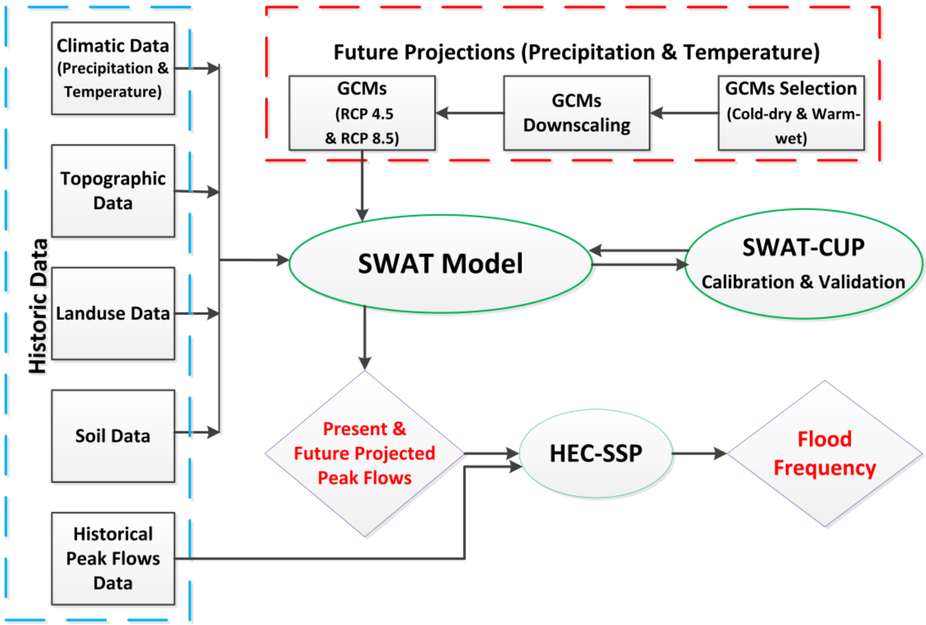

Figure 3.3: Schematic diagram of the hydrological modelling and flood frequency analysis (reference and future projected peak flows).

3.4.1 SWAT Model

The Soil and Water Assessment Tool (SWAT) is a river basin or watershed-scale model. It has been widely used for modelling watershed hydrology at continuous timescale. SWAT was developed to project the effects of water use, sediments and agricultural yields (Neitsch et al., 2011). It is a physically-based semi-distributed hydrologic model (Arnold et al., 1998a; Neitsch et al., 2011), which routes continuously on an hourly or daily time step. The SWAT model uses an ArcGIS interface for the definition of watershed hydrological features (Benham et al., 2006; Neitsch et al., 2011). There are nine basic elements in the SWAT model: hydrology, weather, soil types, sediment yields, plant growth, nutrients loss, pesticides, bacterial load and land-use management. The model subdivides the watershed into sub-basins based on a 90-m resolution digital elevation model . These sub-basins are further split up into hydrological response units (HRUs) that constitute land-use, soil and slope features.

SWAT calculates potential evapotranspiration by applying the Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972) or Hargreaves (Hargreaves and Samani, 1985) parameterization depending on data availability. The Penman-Monteith method has been adopted in this study. The surface runoff from daily precipitation is computed with an altered curve- number method (Service, 1972), which calculates the quantity of runoff based on data for the local land use and soil types. The land component ensures that the quantity of water, nutrients, sediments, bacteria etc. are delivered to a primary channel in every individual sub-basin. All sub-basins are then directed through the main outlet of the basin.

The SWAT model requires hourly surface air temperature, while usually only daily maximum and minimum temperature are provided. Hourly surface air temperature is calculated as follows, assuming that daily maximum temperature occurs at 15.00 o'clock and daily minimum temperature occurs at 03.00 o'clock (Campbell, 1985):

$$\boldsymbol{T_{hr}} \; = \; \boldsymbol{T'_{av}} \; \frac{(\boldsymbol{T_{mx}}-\boldsymbol{T_{mn}})}{\boldsymbol{2}}.\mathbf{cos}(\mathbf{0.216}.(\boldsymbol{hr}\ \mathbf{15})) \quad \text{Equation 1}$$

where T_{hr} is the hourly surface air temperature (^{0}C), hr is the hour, T'_{av} is the average temperature on that day $(T'_{av} = (\frac{T_{mx}+T_{mn}}{2}))$ T_{mx} is the maximum temperature (^{0}C) and T_{mn} is the daily minimum temperature (^{0}C).

High altitudes of the upper part of the Kabul basin receive and store significant amounts of snowfall during winter and releases snow-melt during summer months. Therefore, the snowmelt factor has been included in the model calibration and validation. Equation-2 explains the snowmelt process in the model:

$$\boldsymbol{SNO_{mlt}} = \boldsymbol{b_{mlt}}\cdot\ \boldsymbol{sno_{cov}}\,.\frac{(\boldsymbol{T_{snow}}+\boldsymbol{T_{ms}})}{\boldsymbol{2}} - \boldsymbol{T_{mlt}} \quad \text{Equation 2}$$

where SNO_{mlt} is the amount of snow melt per day (mm water equivalent (w.e)), b_{mlt} is the melt factor (mm day^{-1} ^{0}C^{-1} w.e), sno_{cov} is the fraction of the hydrological response unit's area covered by snow, T_{snow} is the temperature below which precipitation is considered as snow fall (^{0}C), T_{mx} is the maximum temperature on a given day (^{0}C) and T_{mlt} is the base temperature above which snow melt is allowed. The factor b_{mlt} can be estimated with the following equation:

$$\boldsymbol{b_{mlt}} = \frac{(\boldsymbol{b_{mlt6}} + \boldsymbol{b_{mlt12}})}{\mathbf{2}} + \frac{(\boldsymbol{b_{mlt6}} - \boldsymbol{b_{blt12}})}{\mathbf{2!}} . \mathbf{sin}[\frac{\mathbf{2\pi}}{\mathbf{356}} . (\boldsymbol{d_n} - \mathbf{81})] \quad \text{Equation 3}$$

where b_{mlt} is the melt factor (mm day^{-1} ^{0}C^{-1} w.e), b_{mlt16} is the melt factor for June 21(mm day^{-1} ^{0}C^{-1} w.e), b_{mlt12} is the melt factor for December 21 (mm day^{-1} ^{0}C^{-1} w.e), and d_n is the day number of the year, where 1 is for 1st January and 365 is for 31st December (Bengston, 1981).

3.4.2 Sensitivity analysis, Calibration and Validation

Calibration is a crucial step in any hydrological modelling study to reduce the uncertainty in the modelled discharge (Engel et al., 2007) and validation is essential to trust the model's performance (Refsgaard, 1997). For validation four years (2012 – 2015) of observed and simulated discharge data have been used. The calibration process is generally informed by a sensitivity analysis, followed by a manual or automatic calibration (Hamby, 1994). Our sensitivity analysis was conducted to identify the most sensitive hydrological variable before calibration. The aim of sensitivity analysis was to evaluate the rate of change in model output with respect to change in model inputs by using the one-factor-at-a-time (OAT) sampling method proposed by Morris (1991). This method was applied in the Sequential Uncertainty Fitting SUFI-2 algorithm SWAT-CUP automatic sensitivity analysis tool (Abbaspour, 2012) to see that changes in the model output represent the variables value changed. This method is robust and has been extensively used in modelling, but it demands long calculation times (Van Griensven et al., 2002). This sensitivity analysis also helped to evaluate how certain input variables influenced the model's output. The analysis was done by changing individual variables by 10% of the initial value (keeping all other input variables constant) and examining the resulting effect on the predicted flow by the model.

Calibration and validation were carried out by comparing simulated and observed daily discharge records using common hydrological modeling statistical parameters: the coefficient of determination (R^2), Nash-Sutcliffe Efficiency Index (NSE) and the percent bias (PBIAS). Generally, model simulations are called satisfactory if NSE> 0.50, R^2> 0.60 and PBIAS is approximately 25%. Negative values of PBIAS indicate that the model overestimates flow while positive values of PBIAS indicate underestimated flow (Gupta et al., 1999). Similarly, Moriasi et al. (2007) and Parajuli (2007) categorized the model performance as excellent if (NSE >0.90), very good (NSE >0.75-0.89), good (NSE >0.50-0.74), fair (NSE >0.25-0.49), Poor (NSE >0.00-0.24) and unsatisfactory if (NSE =0.00).

3.4.3 The HEC-SSP Framework

Flood frequency Analysis (FFA) shows the characteristics of a basin and possible extreme flood events. In the present study the FFA was executed using HEC-SSP for the Kabul basin to identify the return period of extreme flood events in the Kabul river. Annual maximum (AM) discharges are the basis for the analysis, as is common practice (Madsen et al., 1997). HEC-SSP is a statistical software package, developed by the US Army Corps of Engineers (http://www.hec.usace.army.mil/software/hec-ssp). The most recent HEC-SSP version has built-in FFA-Bulletin-17B procedures that have been adopted for flow frequency analysis. The FFA-Bulletin-17B procedure produces a probability plot based on the following equation:

$$\boldsymbol{P} = \frac{(\boldsymbol{m}-\boldsymbol{A})}{(\boldsymbol{n}+\mathbf{1}-\boldsymbol{A}-\boldsymbol{B})} \quad \text{Equation 4}$$

where m is the rank of annual maximum flows values with the largest flood equal to 1, n is the number of flood peaks in the data set, while A and B are the constants dependent on which equation is used during the flood frequency analysis procedure. In case of Weibull A and B equal 0, for Median A and B equal 0.3 and for the Hazen method A and B equal 0.5. To provide a conservative recurrence period, in the current study the Median probability plotting position factors (A and B equal 0.3) have been adopted (USACE, 2016).

3.5 Results and Discussion

3.5.1 Present Day Hydrological Modelling and Flood Frequency Analysis

The sensitivity analysis was carried out for 14 different SWAT variables for daily flow using the model sensitivity tool (Table S2). These variables were selected, because they influenced the model's output. Figure S3 shows the influence of the five most sensitive variables t. The most sensitive variable is the curve number (CN_2). A 10% increase in CN_2 increased the flow by 20%. Other sensitive variables have less influence on the model's outputs. The SWAT model was calibrated for these 14 sensitive variables. Other studies (Abbaspour et al., 2015; Choi et al., 2005; Saleh and Du, 2004; Santhi et al., 2001a) adjusted the same model variables.

The model has been calibrated and validated for 2007-2011 and 2012-2015 respectively. The model performance was good as measured and simulated flows correlated well with R^2 ranging between 0.84 and 0.77 for calibration and validation respectively. The NSE was 0.77 for calibration and 0.72 for validation periods. Percent bias (PBIAS) values were 22.2 and 17.7 for calibration and validation respectively (see Figure 3.4). Underestimates can be found for peaks, particularly during the calibration period. Such underestimates are common in hydrological modelling and could be due to flow recording-errors, biases in precipitation data and hydrological modelling uncertainties. However, the timing of the peaks is accurate for the calibration and validation periods and PBIAS is still within the appropriate range. This suggests that the current SWAT model calibration variables can be rightfully used for future flow modelling and flood frequency analyses.

Observed and simulated flows are usually high during June to September every year. This is evident from both calibration and validation time periods. The magnitude of peaks varies from year to year. In the calibration graph (see Figure 3.4 top), for example the peak starts in March and lasts till the end of July. Similarly a similar peak is also observed in validation graph (see Figure 3.4 bottom). This peak occurs from March till August but the intensity of flow differs much.

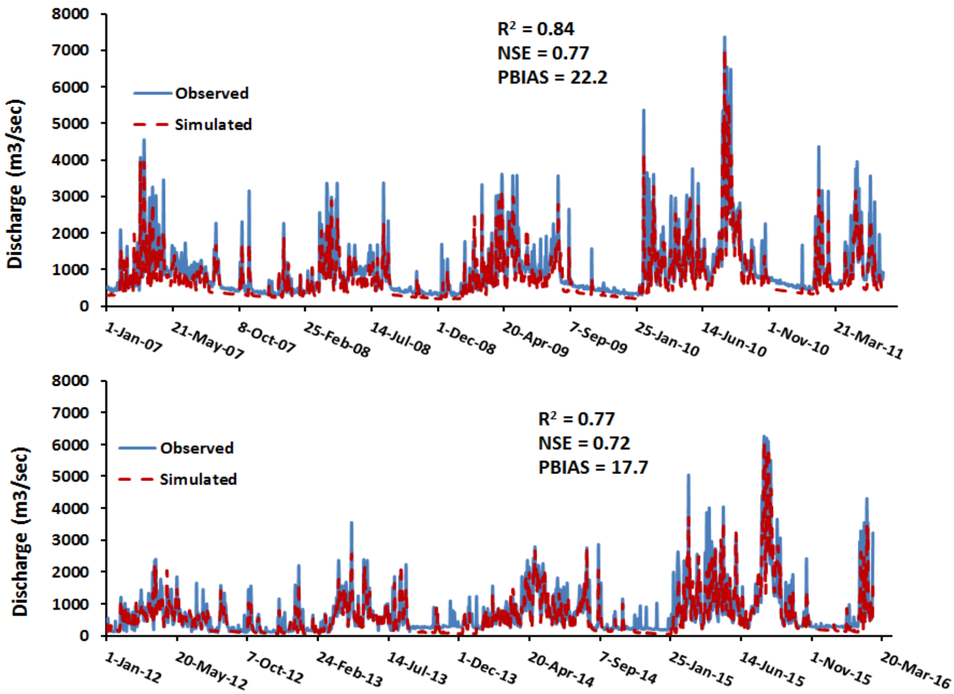

Figure 3.4: Daily observed versus simulated Kabul river discharge for calibration period (2007-2011, top Figure) and validation period (2012-2015, bottom Figure). X-axis shows the time period (years) of observed and simulated discharge, while the Y-axis presents the daily discharge measured in cubic meter per second ($m^3\ s^{-1}$). The blue line showed daily observed flow and dotted red line showed modelled (simulated) discharge for Kabul River.

The HEC-SSP model was used to analyse flood return periods for the study area. In Kabul river especially in its low-land areas, flows that exceeds 2800 $m^3\ s^{-1}$ are declared as floods (FFC, 2016). The highest annual maximum peak flow was recorded in August 2010 (see Figure 3.5). This event has a probability of 0.02%, which equals a 1 in 50 year event.

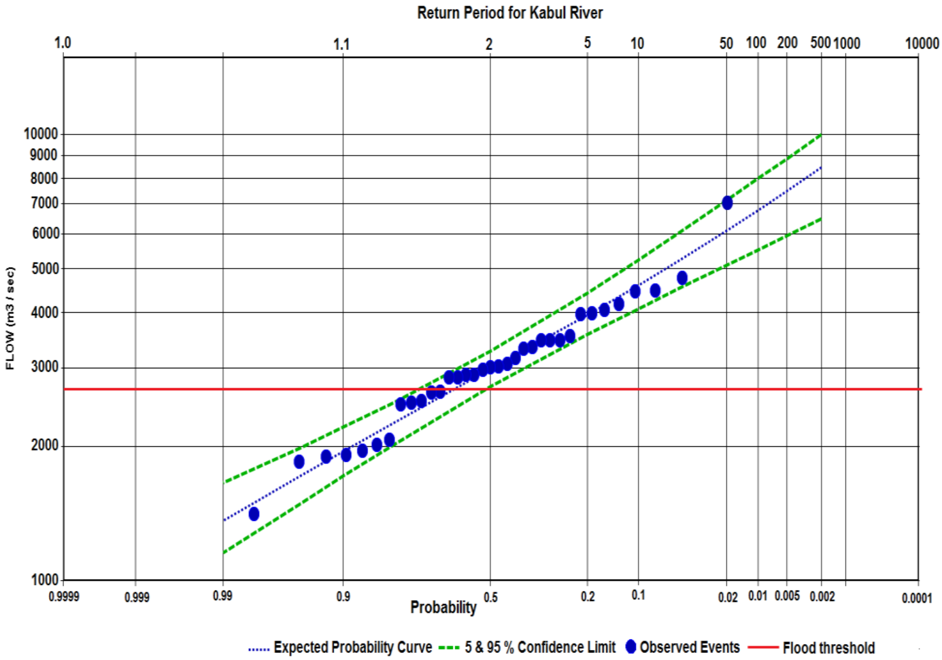

Figure 3.5: Trends of flooding events in Kabul river. The blue dots are the observed flow recorded over the period of 1981-2015. The red box shows higher outlier during this analysis, which was actually the 2010 flood in this region. Y-axis represents the discharge of Kabul River in m^3 s^{-1} while the primary X-axis shows the probability while the secondary X-axis shows the return period of the flooding in years. The red line shows the medium level flood (2800 m^3s^{-1}) as described by the Federal Flood Commission of Pakistan.

3.5.2 Future Discharge and Flood Frequency

Summer monsoon precipitation, snow and glacier melt contribute to the peak flows of the Kabul river (Lutz et al., 2014). In this study temperature and precipitation changes that are based on the four GCMs and two RCPs (RCP4.5 and RCP8.5) scenarios have been used to project changes in the Kabul river flows for the near future (2031-2050) and far future (2081-2100) periods. Mean monthly temperature is expected to rise towards the near and far future periods compared to the contemporary reference period for both RCPs and all GCMs, except INM-CM4, which represents the cold-dry corner of our selected GCMs (see

Figure 3.6 (a-d)). Increased temperatures agree well with other studies (IPCC, 2013; Ridley et al., 2013; Wiltshire, 2014). Mean monthly precipitation also increases towards the near and far future periods for EC-EARTH and MIROC5 GCMs for both RCPs. However, precipitation declines in those periods for INM-CM4 GCM for both RCPs and a mixed response occurs for IPSL-CM5A (see Figure 3.6 (e-h)). Variability is higher for precipitation than for temperature. Ahmad et al. (2015) already observed that winter and autumn precipitation increased in the Swat river (a sub-basin of the Kabul river basin), based on their trend analysis of fifteen climate stations for the period 1961 to 2011. Ridley (2013) and Wiltshire (2014) also project increases in precipitation in the HKH region, including the Kabul river basin, in the mid to end of the 21st century.

Mean monthly modelled flows increases in the near and far future periods compared to the historic flows for most GCMs and both scenarios. Only the IPSL-CM5A climate model shows a slight decline for both future periods and scenarios (see Figure 3.6 (i-l)). In addition, seasonal flow variability could be expected in both future periods compared to the reference period, although flows continue to peak in August for all GCMs and scenarios (see Figure 3.6 (i-l)). Variation in flows could be driven by the following major factors. These are temperature driven variations in (i) precipitation, (ii) snow/glacier melt, (iii) clean ice exposure,(iv) debris-cover thickness and (v) preceding winter snow-fall. Therefore, to determine the main causes of the rise or decline in the Kabul basin's river flows, all these factors are evaluated and discussed below.

Our results suggest an increase in the near and far future flows compared to the contemporary flows for both RCPs and all GCMs except INM-CM4 (see Figure 3.6 (i-l)), where flow temporal variations probably caused by temporal variations in precipitation (see Figure 3.6 (e-h)). Ali et al. (2015) and Rajbhandari et al. (2015) concluded that flows in the nearby Upper Indus Basin indeed depend on the past precipitation variability. Thus, our results agree well with other studies.

In addition to precipitation, temperature variability also agrees well with the flows (see Figure 3.6 a-d and i-l). Dey et al. (1989) showed a strong relation between temperature and snow-melt in the Kabul basin and Archer (2003) argued that summer river flows are mainly derived from the snow-melt of preceding winter snowfall in the Kunhar and Swat basins (sub-basins of the Kabul river basin). Archer's (2003) argument is also complemented by other, more recent studies (see e.g. Lutz et al., 2014; Yu et al., 2013). Therefore, an increase/decrease in temperature drives the increase/decrease in snow-melt during summer months. These arguments and results also agree well with the our study's result for the near and far future, where the rise/decline in temperature and flows are comparable.

The increased flows that we simulate, are also supported by the literature. An increase in winter to early summer temperature probably reduce snowfall and accelerates snow-melt during the early summer months. Additionally, early seasonal snow-melt may also expose clean glacier ice, which can produce more melt during the summer months than the more airy snow. A decline in snow-cover has been observed by Savoskul and Smakhtin (2013) in the Kabul basin between the periods 1960-1990 and 2000-2010. This decline in snow-cover expedited glacier-melt and resulted in a shrinking glacier length. Other studies (see e.g. Bolch et al., 2012; Rankl et al., 2014; Sarıkaya et al., 2013; Sarikaya et al., 2012) observed shrinkage in glacier length in the Hindukush region (including the Kabul basin). Early seasonal snow-melt and exposure of glacier ice, which resulted in a negative glacier mass balance (about -0.3 ± 0.1 m water equivalent per year based on 2003-2008 data analysis by Kääb et al. (2012) and Kääb et al. (2015), likely have supported part of the rising flows during peak summer months in the recent decades (Savoskul and Smakhtin, 2013; Savoskul et al., 2013). However, since the glacier length in the Kabul basin declined as per Randolph Glacier Inventory 5.0 data (Arendt et al., 2015) to only 2.2% of the total basin area (approximately 2,100 km^2), its contribution to rising flows are probably small.

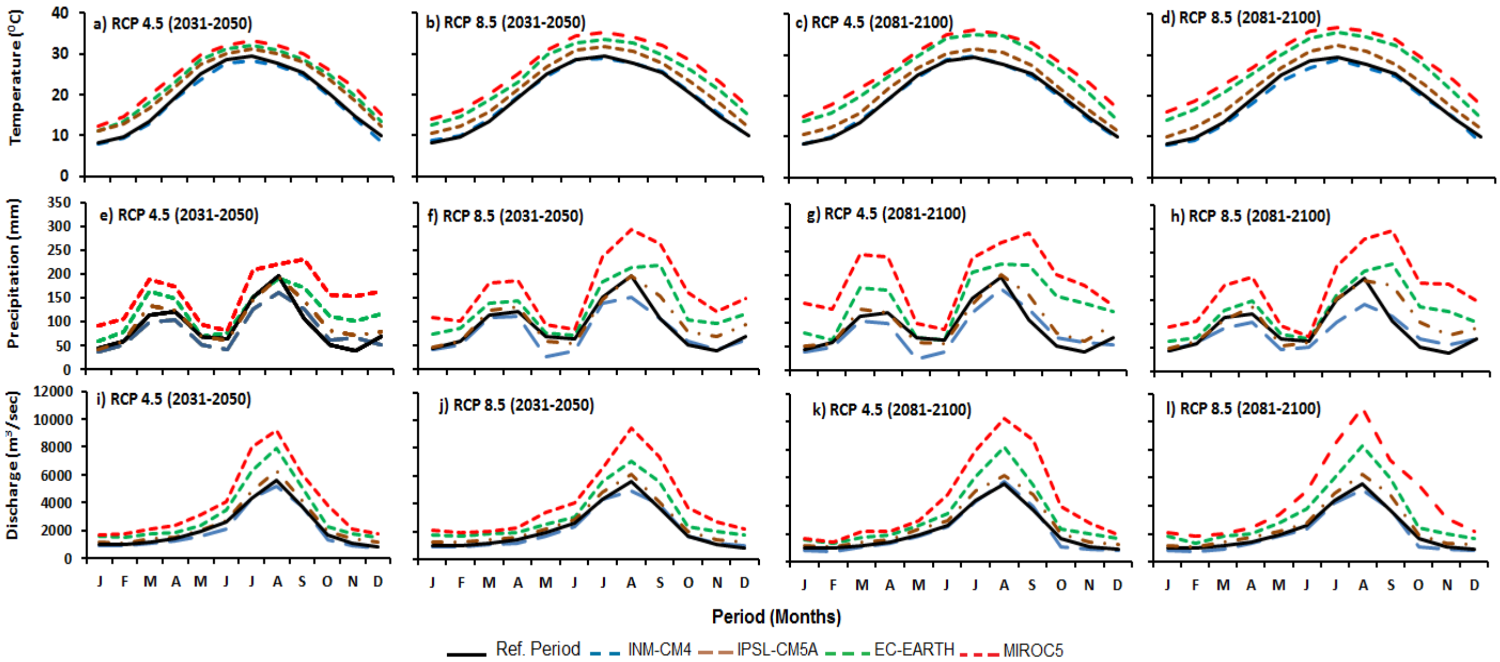

Figure 3.6: Variation in average monthly temperature (a-d), average monthly precipitation (e-h) and average monthly flow (i-l), all based on 20 years data for the Kabul river basin. Comparing reference period (1981-2000) and downscaled scenario data from four selected GCMs under two RCPs 4.5 and 8.5 in near (2031-2050, a, b, e, f, i and j) and far future (2081-2100, c, d, g, h, k and l).

In contrast, Lutz et al. (2014) projected declines in Kabul river flows by the end of 21st century. The main reasons for this contradiction with our results could be the use of different GCMs data, sub-optimal bias correction of GCM data, use of different hydrological models and data from different time periods. The result by Lutz et al. (2014) are part of study for much larger region, while for Kabul basin their results are not supported by literature. Therefore, based on the above results and discussion, an increase (decrease) in flows for the near and far future are caused by an increase (decrease) in precipitation coupled to an increase (decrease) temperature. This enhances (suppresses) snow- and glacier-melt in the Kabul basin.

Increases in extreme precipitation events and a rise in temperature are the major sources of floods in the HKH region (e.g. Din et al., 2014; Hartmann and Buchanan, 2014; Wang et al., 2011). In our study, FFA has been carried out for the near future and far future peak flows. FFA results show an increase in recurrence of peak flows for the near and far future and both RCP scenarios for all GCMs except INM-CM4, which show slight declines in the recurrence periods for both periods and RCPs. The result for MIROC5 provides the most extreme peak flow projection. For this model the recurrence of the historic peak flow (i.e. the 2010 flood) is reduced from 1 in 50 years to 1 in less than 3 years for the near and far future periods and both RCPs. Projections for the other GCMs also suggest an intensification of future peak flows with a substantial reduction in the recurrence intervals during the near and far future periods.

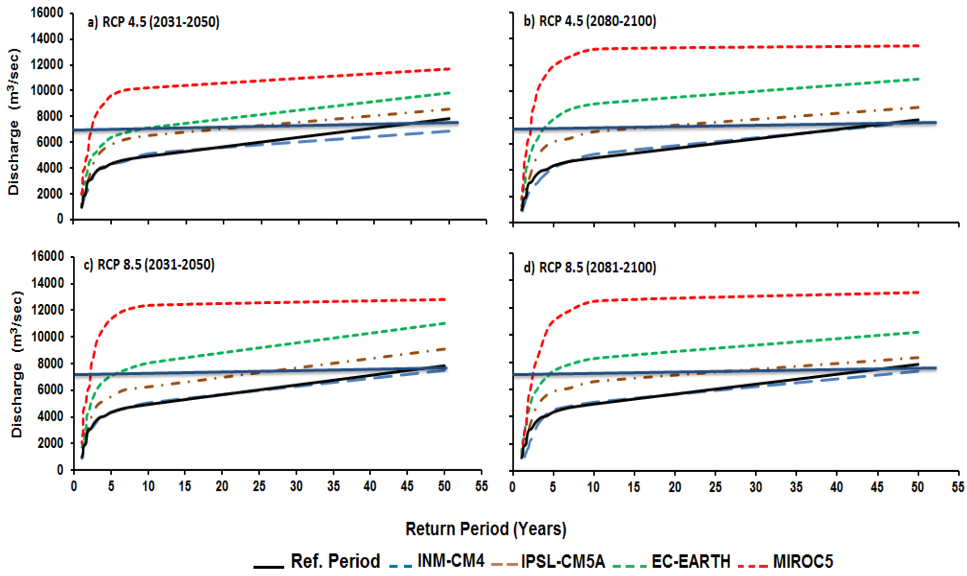

Figure 3.7: Return periods of peak flow in Kabul river (years). Results for four different GCMs for the RCPs 4.5 and 8.5 for the near future (2031-2050, a and c) and far future (2081-2100, b and d) are presented. The horizontal dark blue line shows the magnitude of the most devastating flood in 2010.

FFA estimation is commonly used in hydrology and is usually performed to plan and design various hydraulic structures (Du et al., 2015). Dams and reservoirs could be built to protect the population and infrastructure from floods. In general, small dams are built to be strong enough to withstand a peak flood of a 100 year return period, while agricultural area protection infrastructure is designed for a 15-25 year return period flood (Ali, 2013). When such structures are planned and built, impacts of future climate change should be incorporated. Afghanistan plans to construct 13 dams for irrigation and energy production in the Kabul basin, upstream of the current study's gauging station (FAO Aquastat, 2011). This new infrastructure should consider the changing return periods estimated in this study (see Table S3). That means that small dams should withstand flow up to approximately 15000 m^3/s. Our analysis thus provides insight into the boundary conditions of current and new infrastructure.

Our results can be used to prepare flood inundation plans and to study vulnerability of various infrastructures and land and population at risk (see for example the inundation mapping by Tariq and van de Giessen (2012)). The population in the most affected districts by the 2010 flood (shown in Figure 3.1(c)) is expected to become more vulnerable because of more frequent extreme flows and larger future population (Kc and Lutz, 2014) in the flood plans. Our quantification of vulnerabilities assessment (e.g., Table S3) helps to prepare flood inundation maps, flood mitigation plans and risk assessments.

3.6 Conclusions

Lower Kabul basin in Pakistan is often hit by intensive floods that cause devastating effects in terms of human suffering, economic losses and infrastructural damages. The basin usually receives severe floods when high monsoon rainfall is joined by snow and glacier melt. The basin's average monthly temperature reaches its maximum in July, while precipitation is bimodal with peaks in April and August. April peaks result from the strong influence of western disturbances and August peaks predominantly stem from the Indian summer monsoon. The threshold level of floods is when river flows at Nowshera cross 2800 $m^3 s^{-1}$. The historical (1981-2015) flows reveal that this threshold level is attained more often than every second year except INM-CM GCM that shows lower flood hazards in future. The exceptionally high and most devastating flood of 2010 was a one in 50 years event.

This study revealed substantial changes in hydro-climatology of the basin for both near and far futures. The GCMs MIROC5 and EC-EARTH project consistent increases in mean monthly temperature, precipitation and river flows, while the INM-CM4 projects a slight decline for all three variables. IPSL-CM5A shows a slight increase in temperature and river flows, while for precipitation the response is mixed for RCP4.5 and increases for RCP8.5. These changes in river flow influence the flood frequency. The return periods are in most cases reduced. Depending on the scenario, GCM and period in the future, present day 1 in 50 year events could in the future occur from once in every 3 years to once in every 24 years.

Kabul river is an important part of the Indus river system. The low-altitude and densely populated areas in its downstream reaches are seriously threatened by frequent high-levels of floods. The biggest flood on record, in 2010, influenced a large area and killed over 2000 people. The results and analyses presented in our study indicate the hydrological implications of the projected climate changes in the basin until 2100. These changes have great practical implications for river discharge variation and occurrence of extreme events of floods and droughts. As the flow that caused the 2010 flood is expected to occur much more often in the future, climate proof flood protection measures are essential for the current and future water development and management plans in the Kabul river basin.

Acknowledgement

The authors would like to acknowledge Nuffic, Netherland Fellowship Program (NFP), Government of the Netherlands for providing the PhD fellowship. The Pakistan Meteorological Department (Regional Meteorological Centre, Peshawar) and the Water and Power Development Authority Pakistan are also acknowledged for providing hydro-meteorological data for the current study.

CHAPTER 4

ESCHERICHIA COLI FATE AND TRANSPORT MODELLING IN THE KABUL RIVER BASIN

This chapter is based on:

Iqbal M. Shahid and Nynke Hofstra. *Escherichia coli* fate and transport Modelling in the Kabul River Basin (Submitted)

Abstract

Access to safe water is the primary goal of all development plans, yet population increase coupled with industrialization, urbanization and infrastructural limitations lead to contamination of water resources. This paper focuses on microbial contamination and aims to analyse the fate and transport of *Escherichia coli* in the Kabul River Basin in Pakistan and evaluate the contribution of different sources to these concentrations. The fate and transport of *E. coli* in lower Kabul River are simulated using the Soil and Water Assessment Tool (SWAT) hydrological model coupled with its bacterial sub-model. SWAT is calibrated and validated for the monthly time step using observed *E. coli* concentrations for April 2013 -July 2015. The model results respond well to the observed *E. coli* concentrations in the lower Kabul River; coefficients of determination (R^2) equal 0.72 and 0.70, Nash-Sutcliffe efficiencies (NSE) equal 0.69 and 0.66, and percentages bias (PBIAS) equal 3.7 and 1.9 for calibration and validation respectively. Regional measured and modelled concentrations are very high with peaks of up to 5.2 ^{10}log cfu/100ml in the wet season. Overall, point sources that are comprised of human faeces from the big cities and livestock manure from animal sheds, contribute most (44%) to the *E. coli* concentrations. Also upstream contamination (34%) and non-point sources (22%) contribute substantially. During peak discharge the non-point sources become the most important contributors due to wash-off from the land and diluted point sources. The developed model is capable to assess the fate and transport of *E. coli* concentrations and the main contamination sources in such rivers. Allthoughs such studies are lacking in developing countries, they can be helpful for sanitation management by developing and accessing regional sanitation scenarios.

Keywords: SWAT model, *E. coli* contamination, Fate and transport, Water quality modelling, Kabul River.

4.1 Introduction

Clean and safe water is indispensable for the sustenance of life. Access to safe water is the primary goal of all development plans; yet population increase coupled with industrialization, urbanization and infrastructural limitations lead to contamination of water resources. Among various sources of water contamination, microbial contamination is by far the largest and probably the most serious issue in developing countries (Montgomery and Elimelech, 2007). With recent improvements in living standards, water-quality aspects require more scientific support and public attention. Although waterborne diseases are an international issue, many people in the developing countries are extremely vulnerable due to their increased exposures and poor sanitation facilities (Cann et al., 2013a; WHO, 2009). The World Health Organization estimates that approximately 10% of all diseases worldwide is due to microbiologically contaminated water (Prüss-Üstün et al., 2008). In developing countries, like Pakistan, where the sanitation facilities are poor, the situation of waterborne diseases is alarming. 7% of all deaths in Pakistan are linked to waterborne issues (Azizullah et al., 2011).

Risk of waterborne diseases depends on the concentrations of waterborne pathogens in water resources (Azizullah et al., 2011). The Kabul River Basin in Pakistan is exposed to microbial contamination due to direct disposal of raw sewage from both urban and rural areas and discharge of contaminated effluents from agricultural fields. The situation is worsened by the absence of wastewater treatment plants (WWTP) in this basin. The contaminated surface water is used for irrigation, recreational activities and other domestic purposes. This makes the population prone to the outbreaks of waterborne diseases (Carr and Neary, 2008).

Faecal contamination in the Kabul river is not monitored and little knowledge exists on the distribution of microbes in water resources. To better understand the bacterial contamination in water resources, usually indicator organisms, such as faecal coliform and *E. coli,* are used to estimate the concentration of pathogenic and non-pathogenic microorganisms. Although *E. coli* is not directly correlated to waterborne pathogens, they have been used worldwide to indicate fecal contamination (Wu et al., 2011a). This is because measuring *E. coli* is less expensive and time-consuming compared to other pathogenic microorganisms, such as *Cryptosporidium* and *Rotavirus*. Iqbal et al. (2017a), for example, conducted large-scale sampling in the lower Kabul River Basin and observed very high concentrations of *E. coli* in Kabul river.

To better understand the fate and transport of microbes (pathogenic and non-pathogenic) in water resources, process-based modeling provides a low-cost and effective alternative to sampling (Shirmohammadi et al., 2006). In developing countries where waterborne diseases are endemic, process-based modeling of water quality is rare (Hofstra, 2011). Hydrological models coupled with microbial modules describe the conditions in water resources considering the sources, pathways and decay of waterborne pathogens (Sokolova et al., 2013). Therefore, in this study, we implement a microbial water quality model in the highly contaminated Pakistani Kabul River Basin.

The objective of the current study is to analyse the fate and transport of *E. coli* in the lower Kabul River. The Soil and Water Assessment Tool (SWAT) was calibrated for this river basin using river discharge data from a previous study (Iqbal et al. 2017b). The bacterial transport module available in SWAT (Neitsch et al., 2011; Sadeghi and Arnold, 2002) is then used to simulate the fate and transport of *E. coli* in the catchment and to determine the main contamination sources.

4.2 Data and Methods

4.2.1 Study Site

The basic characteristics of the Kabul River Basin are described in detail by Iqbal et al. (2017b). This study focusses the lower reaches of the basin, which are densely populated and prone to destructive floods. The large cities of Peshawar (2800 people per km^2), Charsadda (900 people per km^2) and Nowshera (1500 people per km^2) are located in this area (Figure 4.1c). The lower Kabul River Basin covers total area of 22,000 km^2. A large number of livestock sheds are present in the area. Manure from these sheds is either used as fertilizer on agricultural fields or disposed directly or indirectly into the river network. The river network also carry untreated sewage effluents from urban and rural settlements to Kabul River. Microbial contamination from agricultural activities, livestock sheds and sewage disposals often result in high microbial concentrations of river. Due to such conditions and disposal practices, the number of *E. coli* detected in the Kabul river are 5.20 log colony forming units (cfu) per 100ml (Iqbal et al., 2017a). The land-use characteristics and soil types of the study area are presented in Table 4.1. The study area is in the sub-tropical zone with a mean annual precipitation of 285 mm (over the period of 2013-2015) and a mean annual surface air temperature of 22.9 ^{0}C.

Table 4.1: Land-use and Soil types used in the SWAT model. Land-use types are from the European space Agency (Arino et al., 2010) and soil types are from the Harmonized World Soil Database (Nachtergaele et al., 2012).

Classification	Area (1000 km^{-2})	Total area %
Lower Kabul Basin	22	100.0
Land-use		
Crop Land	8.3	34.1
Pasture / Range land	5.9	24.8
Urban Area	4.5	21.3
Wetland / Water Bodies	2.2	13.4
Barren land	0.8	6.4
Soil Types		
Leptosol	7.5	30.1
Rock Outcrop	5.0	20.6
Fluvisol	4.3	18.4
Cambisol	2.5	15.8
Calcisol	1.4	8.5
Glaciers	1.1	6.6

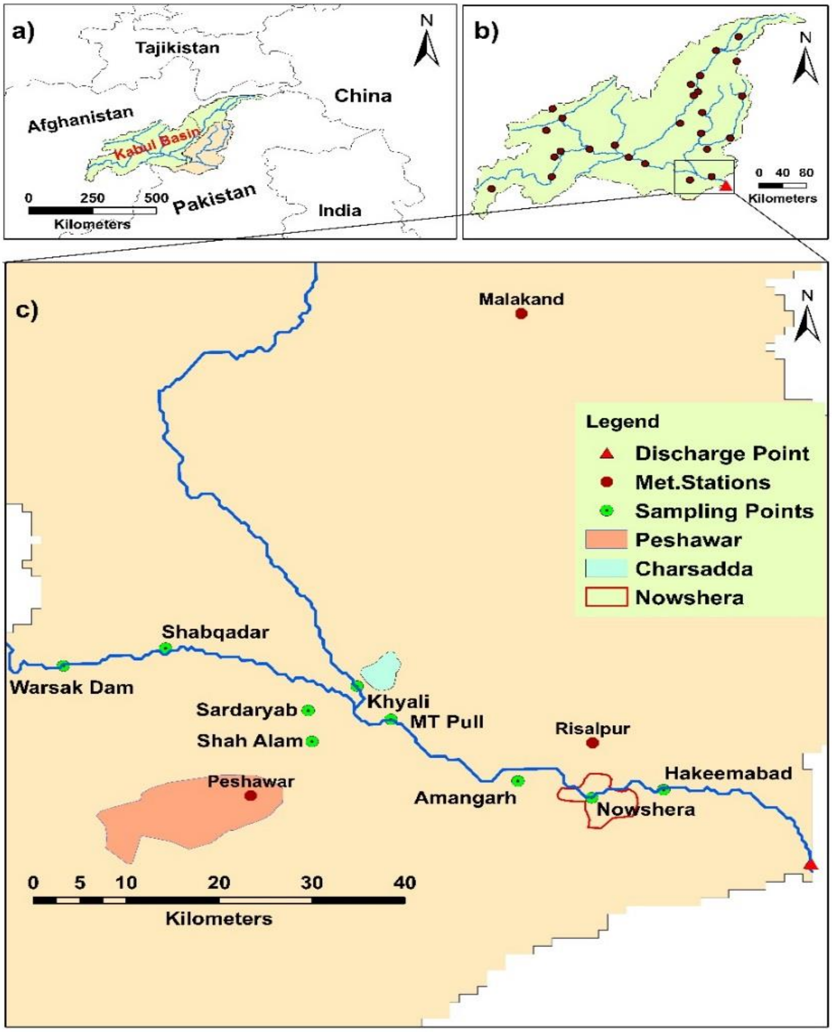

Figure 4.1. Study-area map of the lower Kabul River Basin: a) shows the full basin along with neighboring countries. b) Kabul basin indicating the main branches and meteorological stations, c) shows the downstream area of Kabul basin with urban areas of Peshawar, Charsadda and Nowshera (highlighted). Green points indicate the sampling sites from where water samples were collected, while the black triangle is the rim station where discharge is measured. At this point Kabul river discharges into the Indus river. Sampling points Sardaryab, Shah Alam and Amangarh are not located on the main Kabul river, but on smaller, still important, branches.

4.2.2 Data

4.2.2.1 Water Sampling and Microbiological Data

Water samples were collected from nine locations in Kabul river (see Figure 4.1c), The samples were analysed for microbial concentrations through laboratory tests using the Most Probably Number approach. The sampling strategy, procedures and data are detailed in Iqbal et al. (2017a). Water samples were collected between April 2013 and August 2015. The frequency of sampling during times of flooding (i.e. April to August) was daily and fortnightly samples were taken outside the flooding season. In short, samples were collected in pre-sterilized plastic bottles and transported to the laboratory of the Nuclear Institute for Food and Agriculture for bacterial analysis. For total coliform counts a series of five fermentation tubes of Mackonky broth (Merck) were inoculated with appropriate volumes of ten-fold dilutions of water samples, and incubated at 37 °C for 24 h. Gas-positive tubes were considered positive for the presence of total coliform (Franson, 1995). Gas-positive Mackonky broth tubes were subjected to further analysis for the confirmation of *E. coli*. The tubes were incubated at 44.5°C for 24 hours. Each positive test tube was also exposed to an ultraviolet light lamp. Fluorescence in the tube denoted the presence of *E. coli* (Brenner et al., 1993). *E. coli* concentrations in water samples were recorded with the MPN table (WHO, 1985). During flooding the *E. coli* concentrations ranged from 4.87 to 5.20 log cfu/100ml and outside the flooding season the concentrations ranged from 3.61 to 4.91 log cfu/100ml (Iqbal et al. 2017a). The data were collected from sampling locations (as shown in Figure 1c) and averaged over months to calibrate the model.

4.2.2.2 Topographic, Soil, Land-use and Climatic Data

Watershed boundaries were delineated from the 90m Digital Elevation Model data from the Shuttle Radar Topography Mission (SRTM, available through http://srtm.csi.cgiar.org). Soil data are acquired from the Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database; (Nachtergaele et al., 2012), while land use data developed by the European Space Agency for the year 2009 are used (http://due.esrin.esa.int/page globcover.php; Arino et al. (2010) are used. The climatic data, including precipitation, minimum and maximum surface air temperature, relative humidity, solar radiation and wind speed, at a daily time step for twenty-five years (1981-2015) are acquired from the Pakistan

Meteorological Department (PMD). Discharge data of Kabul River at Attock for the same period and time resolution were acquired from the Water and Power Development Authority (WAPDA).

4.2.2.3 Hydro-Bacteriological Modelling

The SWAT model is used to estimate *E. coli* concentrations in the Kabul river. The concentrations calculated represent the situation at Attock, which is indicated by the triangle in Figure 1c. This is the point where the Kabul river enters the Indus river. *E. coli* concentrations are modelled with a monthly temporal resolution.

4.2.2.4 Hydrological Model

SWAT is semi-distibuted process based model that was developed to quantify the impact of management and climate on water resources, sediment and pollutant load in catchment on a continuous time scale (Abbaspour et al., 2007). Its conceptual basis operates by distributing a watershed into sub-basins. Each sub-basin is linked via stream network and further splits up into hydrological units. The model structure was built with the help of ArcGIS software, which provides graphical information of the watershed and allows for the definition of watershed hydrology.

The SWAT model was calibrated for daily discharge for 2007-2011 and validated for 2012-2015 respectively (Iqbal et al. 2017b). The model evaluation statistics or skill score showed good agreement between measured and simulated results. The coefficient of determination (R^2) was 0.84 and 0.77, Nash-Sutcliffe Efficiency Index (NSE) outcome was 0.77 and 0.72 and percent bias (PBIAS) values were 22.2 and 17.7 for calibration and validation time periods respectively. Based on the model efficiency (Moriasi et al., 2007), overall the model describes the hydrological process of the watershed systems as good (Iqbal et al., 2017b submitted). The model calibrated at a daily time step has been used at the monthly resolution here. Such upscaling in time has been done before and the models perform well at both resolutions (Heathman and Larose, 2007; Thampi et al., 2010a).

4.2.2.5 Bacterial Module

The SWAT bacterial module developed by Sadeghi and Arnold (2002) was used to predict bacterial (i.e. pathogenic and non-pathogenic) loads and concentrations in rivers. The comprehensive bacterial model considers parallel risk evaluation of bacteria loading linked with diverse land-use practices in the basin. Bacteria from each hydrological unit are collected at the sub-basin level and then moved to the watershed main outlet (Benham et al., 2006). The SWAT bacterial model simulates the fate and transport as two different bacteria populations: persistent bacteria (*E. coli* and other pathogens, such as *Cryptosporidium*) and less-persistent bacteria (fecal coliform). The persistent pathogens are considered to have lower decay rates in the natural conditions compared to less-persistent bacteria (Coffey et al., 2007; Jamieson et al., 2004). We focus solely on the persistent bacteria. To account for microbial loads in the catchment, different possible sources of bacterial pollution were included in the model, the point and non-point sources. We model monthly mean *E. coli* concentrations.

Human Sources

The lower Kabul River Basin has over 6.2 million inhabitants living in major cities: Peshawar (2800 people per km^2), Charsadda (900 people per km^2) and Nowshera (1500 people per km^2)) and surrounding villages (Bureau of Statistics, 2016). *E. coli* from raw sewage and domestic wastewater is discharged directly via drains, small streams, irrigation canals and other tributaries to the river, due to the absence of a wastewater treatment plants (WWTP).

The input flows from the sewage were estimated based on the number of people connected to the sewer network and water consumption per person of 95 L/day (WATSAN, 2014). Each household was assumed to be occupied by four persons. We applied an effluent rate of 0.38 m^3/day from each household and an effluent concentration of approximately 1.7×10^6 cfu/100ml as reported by Mara and Horan (2003), Payment et al. (2001) and Baker (1980).

Moreover, surface water resources can be polluted with microorganisms through flood water runoff from the urban settlements of Peshawar, Charsadda and Nowshera (see Figure 4.1c). This flood water can contain faeces from animals that roam around freely or are held in small livestock sheds, such as dogs, asses, horses and camels.

The runoff volume was simulated using the curve number method available in the SWAT model. The runoff curve number was developed by the US Department of Agriculture (USDA, 1986) that is a hydrological variable to predict approximate amount of direct runoff from a precipitation event (Balvanshi and Tiwari, 2014; King et al., 1999). The curve number is based on the soil type, land-use, slope and hydrologic condition. The *E. coli* concentrations in storm water range from 10^3 to 10^4 cfu $100ml^{-1}$ (Marsalek and Rochfort, 2004). In the current study the *E. coli* concentration of 6.5 x10^3 cfu $100ml^{-1}$ was used and included as non-point sources in the model.

Livestock Sources

Livestock manure is another important source of microbial contamination in the Kabul River Basin. Total livestock (cattle/buffalo) in the lower Kabul basin was estimated to be 0.89 million animal units (AU). The total number of sheep and goats present in the area was 1.32 million and 1.15 million respectively (Bureau of Statistics, 2016). Poultry (i.e. chicken) are not included, because these are not kept in the area. The livestock is mostly housed in animal sheds. From the animal sheds the manure is used on the land, for fuel, or is dumped into the river.

The inputs of manure to water resources can be divided into indirect (via surface runoff) and direct (deposited to river) inputs. According to the American Society of Agricultural Engineer (ASAE) (2005) standards, each day the manure production of cows and buffalo's is estimated to be 27 kg of wet manure per day per 650-kg AU, which approximate equals the weight of one animal). The actual manure production by each AU may vary depending on the dietary habit of the animal. An *E. coli* concentration in cow/buffalo manure of $4.2*10^5$ cfu/g is used (Coffey et al., 2010a) (see Table 4.2). That means that each cow or buffalo produces approximately 1.1 x 10^{10} cfu per day.

Approximately 35 kg/ha of manure is applied monthly on the fields (crop lands) (Parmar and Sharma, 2002). The remaining quarter of the manure is used as fuel, while the rest is dumped directly into the river

Table 4.2: *E. coli* concentration in fresh manure and waste.

Type	Animal Weight (kg)	Manure production (kg day^{-1})	Min (cfu/g)	Max (cfu/g)	Geometric Mean (cfu/g)
Sheep/Goat (Collins and Rutherford, 2004; Hutchison et al., 2004; Mara and Horan, 2003; Thurston-Enriquez et al., 2005b)	30 / 50	1.3 / 2.5	$7.8 \cdot 10^2$	$1.6 \cdot 10^7$	$6.6 \cdot 10^4$
Buffalo/Cow (Collins and Rutherford, 2004; Fegan et al., 2004; Hutchison et al., 2004; Mara and Horan, 2003; Meals and Braun, 2006**)**	650	27	$2.3 \cdot 10^5$	$7.5 \cdot 10^5$	$4.2 \cdot 10^5$

Manure application

The fate and transport of the non-point source bacteria is calculated by applying manure from livestock sheds to crop land as fertilizer, adsorption to soil, extraction by runoff, decay and, finally, stream flow. The inputs and outputs of bacteria in the top soil layer can be calculated with the help of the following equation:

$$\Delta_{Bact} = \boldsymbol{Surface_{Loading}} - \boldsymbol{Decay_{Solution}} - \boldsymbol{Decay_{Adsorbed}} - \boldsymbol{Mixed_{Bact}} - \boldsymbol{Bact_{Surf}} - \boldsymbol{Bact_{Perc}} - \boldsymbol{Bact_{Sed}} \qquad \textbf{(Eq. i)}$$

where Δ_{Bact} is the change of bacterial loading in the top 10mm surface soil; $\boldsymbol{Surface_{Loading}}$ is the total bacterial loading deposited on the soil surface in one day; $\boldsymbol{Decay_{Solution}}$ and $\boldsymbol{Decay_{Adsorbed}}$ are the amount of bacteria in the soil solution and adsorbed to soil particles that decayed in one day; $\boldsymbol{Mixed_{Bact}}$ is the amount of bacteria redistributed to deep soil layer by tillage; and $\boldsymbol{Bact_{Surf}}$, $\boldsymbol{Bact_{Perc}}$ and $\boldsymbol{Bact_{Sed}}$ are the loadings of bacteria transported by surface runoff, runoff percolating through the soil and moving sediments.

Tillage

During the tillage operation bacteria from the top 10mm are mixed with the soil and can be lost to the lower soil layer. When bacteria reach to second layer of the soil, they become unavailable for transport via surface runoff.

Surface Runoff

The movement of bacteria from the soil layer (top 10mm) to the river with sediment is calculated as a function of the amount of bacteria attached to the sediment, the sediment yield based on runoff and the enrichment ratio for bacteria. The SWAT user manual (Neitsch et al., 2002) describes all these equations. SWAT considered direct inputs of bacteria from watershed system as point sources. Per sub-basin one point source is assigned by default. Hence, integrating all the point source from the sub-basin in the watershed by a single discharge outlet and the associated bacterial concentration is important. This is usually done at the main outlet of the watershed.

The movement of bacteria from the soil solution of the soil layer (top 10mm) to the river due to surface runoff is a function of runoff amount and soil bacteria contact. The SWAT model simulates the bacterial transport during surface runoff similar to the soluble phosphorus movement and is based on pesticide equations suggested by Leonard and Wauchope (Knisel, 1980; Pierson et al., 2001). The strength of this association is embedded in the bacteria-soil partitioning coefficient (BACTKDQ):

$$\boldsymbol{Bact_{Surf}} = \frac{\boldsymbol{Bact_{solution} * Q_{surf}}}{\boldsymbol{P\beta * depth * BACTKDQ}} \qquad \textbf{(Eq. } \boldsymbol{ii}\textbf{)}$$

where $\boldsymbol{Bact_{Surf}}$ is the bacterial amount transported through runoff [cfu/m^2], $\boldsymbol{Bacteria_{solution}}$ is a number of bacteria in the top 10mm of soil layer [cfu/m^2], $\boldsymbol{Q_{surf}}$ is the volume of surface runoff [mm], $\boldsymbol{P\beta}$ is the bulk density [Mg/m^3], and $\boldsymbol{BACTKDQ}$ is the bacterial-soil partitioning coefficient [m^3/Mg]. $\boldsymbol{BACTKDQ}$ is expected to be independent from the type of bacteria simulated by the SWAT model, land-use and soil type. There is no range of values given for this variable. The SWAT model took 175 for phosphorus as default (Neitsch et al., 2002), however, the value is 100 in the Agricultural Policy Extender (APEX) model (Williams et al., 2008) . Therefore the value between 100-200 is a rational start for the calibration of bacterial movement.

Upstream inputs

Another important source of bacterial contamination in the lower part of the Kabul River Basin is the input bacterial load from upstream part (above Warsak Dam, see Figure 1c) of the river. The observed concentrations at the Warsak sampling point have been used as input into the model.

River concentrations

In the river the bacteria mass balance is presented by the following equation:

$$\Delta_{\boldsymbol{Stream-bact}} = \boldsymbol{Bact_{Surf} - Bact_{Sed} + Direct_{Inputs} - Decay_{Stream} - Bact_{Flow}} \qquad \textbf{(Eq. iii)}$$

where $\Delta_{\boldsymbol{Stream-bact}}$ is the change of bacteria loading in stream in one day; $\boldsymbol{Bact_{Surf}}$ *and* $\boldsymbol{Bact_{Sed}}$ are the loadings of bacteria in solution and adsorbed to soil particles transported by surface runoff. $\boldsymbol{Direct_{Inputs}}$ are the bacteria loading directly discharged in to river by wastewater treatment plant (if any); $\boldsymbol{Decay_{Stream}}$ is the number of bacteria decayed during one day, and $\boldsymbol{Bact_{Flow}}$ is the number of bacteria transported out of reach by stream flow.

Decay

Bacteria are considered to be dissolved pollutants and changes in the river concentration can be calculated with the first-order decay equation (chick's law) proposed by Mancini (1978) and revised by Moore et al. (1989) to model fecal bacteria decay. Decay rates can be determined with the following equation.

$$C_t = C_0 * e^{-k_{20} t_\theta *^{(T-20)}} \quad \textit{(Eq. iv)}$$

where C_t is the bacterial concentration in the river at time t, [count per 100ml] C_0 is the initial bacterial concentration [count per 100ml] K_{20} is the first order die off rate at 20^0C [per day] t is the exposure time in [days] $t\theta$ is temperature adjustment factor (*THBACT* in SWAT model), T is expressing ambient temperature [^{0}C]. Both $t\theta$ and K_{20} are user specified. In SWAT K_{20} is specified to be 20^0C per day for *E. coli*. Reddy et al.(1981) described the decay rates for fecal coliforms and fecal streptococci (i.e. the average die-off rates were 1.14 per day and 0.41 per day respectively). They also described that microbial die-off increased with decrease in soil moisture, pH (range of 6-7) and with 10^0C rise in temperature the die-off rates increased approximately two times.

4.2.3 Model Calibration Procedures

The SWAT bacterial module was calibrated (April 2013 to June 2014) and validated (August 2014 to July 2015) for monthly mean *E. coli* concentration. The SWAT bacterial model was calibrated with the SWAT Calibration Uncertainties Program (SWAT-CUP) (Abbaspour, 2015) while using the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour et al., 2004; Abbaspour et al., 2007). To determine the variables that need to be calibrated, the variables to which the *E. coli* concentrations are most sensitive were included in a sensitivity analysis. A one-factor-at-a-time (OAT) sampling method Morris, (1991), was applied in the Sequential Uncertainty Fitting SUFI-2 algorithm SWAT-CUP automatic sensitivity analysis tool (Abbaspour, 2012). This robust method has been extensively used in modelling, despite its long calculation times (Van Griensven et al., 2002). The sensitivity analysis was also performed to evaluate how the simulated output was influenced by the input variables. To that extent, individual variables were changed by 10% of the initial value (keeping all other input variables constant), and the effect on the *E. coli* concentration was examined. For the calibration of the model, the values of the most sensitive variableswere adjusted between ranges that were preset in the SWAT model and are based on earlier worldwide studies. The optimum values were set and subsequently used in the model. For validation, the simulated output was compared with measured *E. coli* data. Model evaluation statistics were calculated during both calibration and validation.

4.2.4 Model Evaluation Statistics

The model evaluation statistics or skill score were carefully chosen so that they were 1) robust to several models and climatic conditions and 2) established and recommended in available literature (Moriasi et al., 2007). Model evaluation statistics used to evaluate the measured vs predicted data includes the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). The coefficient of determination (R^2) values shows how measured vs predicted values track a best-fit line. This R^2 can range from zero (no correlation) to one (perfect correlation) (Maidment, 1993). The Nash-Sutcliffe Efficiency Index (NSE) indicates how reliably measured values matched with predicted values (Nash and Sutcliffe, 1970). This index ranges from negative infinite (poor) to 1.0 (perfect model). The NSE values have been widely used for the assessment of hydrological models (Wilcox et al., 1990). Generally, model simulations are called satisfactory when NSE> 0.50, R^2> 0.60 and -25%<PBIAS<25%. Negative values of PBIAS indicate that the model overestimates flow while positive values of PBIAS indicate underestimated flow (Gupta et al., 1999). Moriasi et al (2007) categorized the model capabilities as excellent (NSE ≥ 0.90), very good (NSE= 0.75-0.89), good (NSE= 0.50-0.74), fair (NSE= 0.25-0.49), poor (NSE = 0.0-0.24) and unsatisfactory if (NSE < 0.0).

4.3 Results

4.3.1 Bacterial Calibration and Validation

The bacterial model was sensitive to 12 variables. These have been calibrated according to the values in Table 4.2. The outcome of sensitivity analysis shows that the precise value of these variables can considerably affect model outcome. For example, the bacteria-soil partitioning coefficient (BACTKDQ), the bacterial percolation coefficient (BACTMIX) and the temperature adjustment factor for die-off (THBACT) are the most sensitive variables that affect *E. coli* concentrations. The result of sensitive analysis are shown in Figure S4. When the value of THBACT is increased or decreased by 10%, the overall model output was changed by +17% and -15% respectively. The other two variables were similarly sensitive.

The coefficients of determination (R^2) are 0.72 and 0.70, Nash-Sutcliffe Efficiency Index (NSE) are 0.69 and 0.66 and the percent bias (PBIAS) for the bacterial model are 3.7 and 1.9 for calibration and validation respectively. This means that the performance of the model can be classified as good. The outcome of the simulated monthly values were compared with averaged monthly observed values for *E. coli* (Figure 4.2). The SWAT model overall produces results with slightly too low variability. This is a standard artefact seen in microbiological modelling. In general, the trend in model predictions follows the observed patterns and the values showed good agreement between simulated and measured *E. coli* concentrations.

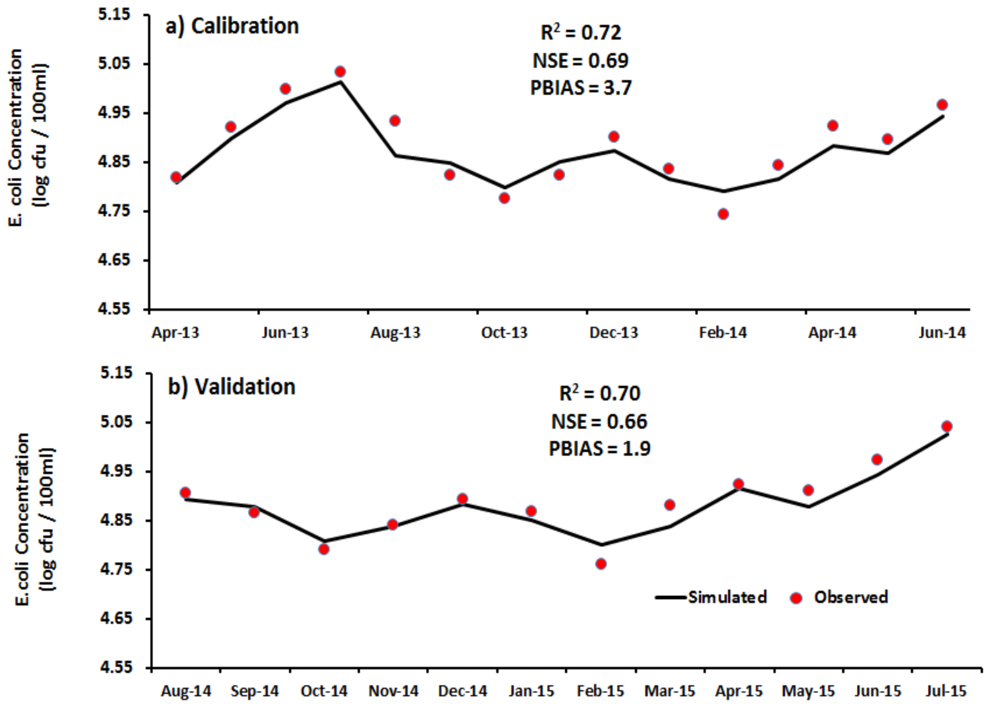

Figure 4.2: *E. coli* concentration calibration and validation results for Kabul river basin.

4.3.2 *E. coli* Source Estimation

Figure 2 shows that the monthly mean *E. coli* concentrations in Kabul river are high. They range from $6.5*10^4$ cfu/100ml to $1.1*10^5$ cfu/100ml. This water is certainly unsuitable for bathing. The concentrations strongly exceed the US-EPA daily (single sample) bathing water quality standards of 235 cfu/100ml. Concentration peaks were observed during the flooding months of April to August 2013, 2014 and 2015.

To estimate the contributions of contamination sources to the overall *E. coli* concentrations, point and non-point sources of contaminations were simulated separately and their share in the total load was calculated for the total simulation period (April 2013 to September 2015). 44% of total *E. coli* concentration originates from the point source in the watershed.

Non-point sources contribution accounts for 22% and *E. coli* loads from above Warsak account for 34% of the total loads in the watershed system (Figure 4.3). The point sources include untreated sewage and direct deposition of manure. The major point source of pollution is sewage from Peshawar (14%) followed by sewage from Nowshera (12%) and manure from Amangarh (11%). Also the contribution from Charsadda is substantial (7%). Crops and pasture are the most important non-point sources at 10% and 7% respectively. Flood water runoff was included in the model as non-point source and contributes 5%.

Table 4.3: Selected variables and their final calibrated values for the SWAT-Model to simulate *E. coli* concentrations.

Variables	**Range of values**	**Fitted Value**
Bacterial Percolation Coefficient (BACTMIX)	7-20	16.42
Bacteria Soil Partition Coefficient (BACTKDQ)	150-200	*177.17*
Bacterial partition coefficient in manure (BACTKDDB)	0-1	*0.79*
Die-off factor for persistent bacteria in soil Solution (per day; WDPQ)	0-1	*0.41*
Die-off factor for persistent bacteria adsorbed to soil particles (per day; WDPS)	0-1	*0.74*
Fraction of manure applied to land areas that have active colony forming units (BACT_SWF)	0-1	*0.89*
Growth factor for persistent bacteria in soil solution (per day; WGPQ)	0-1	*0.47*

Growth factor for persistent bacteria absorbed to soil particles (per day; WGPS)	0-1	*0.33*
Groundwater delay (*GW_DELAY*)	30-100	*41.93*
Minimum daily bacteria loss for persistent bacteria (BACTMINP)	0-5	*3.15*
Saturated hydraulic conductivity (*SOL_K*)	0-4	1.37
Temperature adjustment factor for bacteria Die-off/growth (THBACT)	1-1.18	*1.08*

The concentration and also the contribution from the sources varies over the study period (Figure 4.4). The relative contribution of non-point sources is higher in flooding months (April – August). The reason for that is high precipitation increases the runoff of manure from the fields. In these cases this effect weighs up to the dilution that could also occur with increased precipitation and flow. At times of non-flooding, the chances of surface runoff from agricultural land are reduced due to low precipitation, that increases the contribution from point sources due to constant input load to the river.

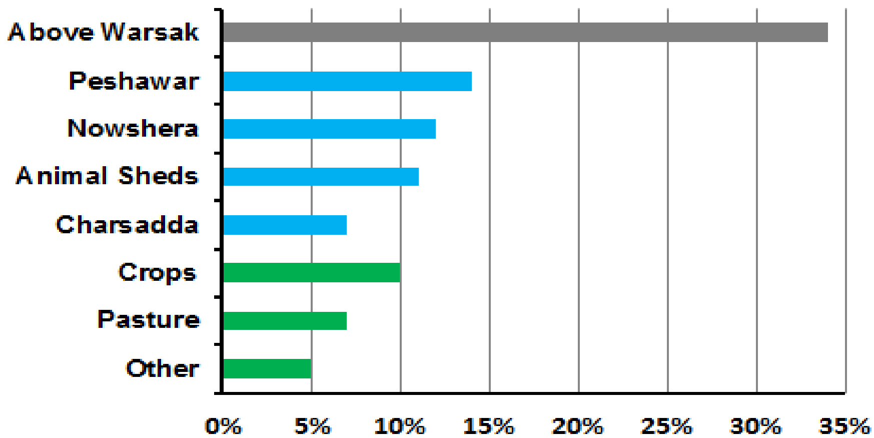

Figure 4.3: The share of E.coli sources from upstream and downstream areas of Kabul River Basin in the E.coli load. The blue colour shows the E.coli concentrations from point sources including animal sheds and human settlements. The green colours shows the E.coli concentrations from non-point sources and the grey area represents the load from above Warsak (upstream settlements that contribute point and non-point sources).

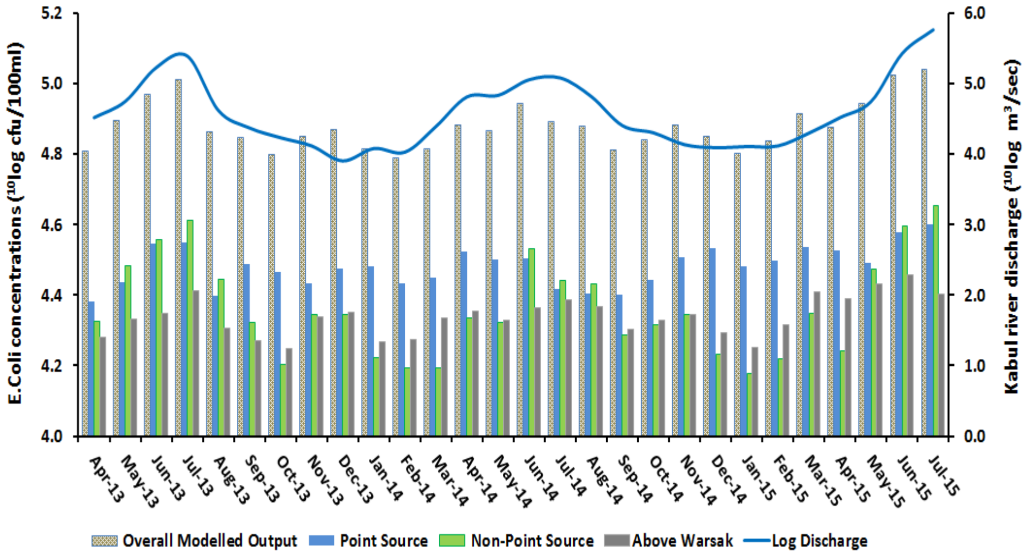

Figure 4.4: The overall *E. coli* concentration in Kabul river along with the river discharge specified for above Warsak, point source and non-point source contributions.

4.4 Discussion

In this paper we modelled the *E. coli* concentrations in Kabul River water and analyzed the contribution of contamination sources. The SWAT model was used in this study. The most sensitive variables in this study were the bacteria-soil partitioning coefficient (BACTKDQ), the bacterial percolation coefficient (BACTMIX), and the temperature adjustment factor for die-off (THBACT). These variables were calibrated together with nine other variables.

Model validation showed that the model performs well. The NSE values for monthly *E. coli* concentrations were 0.69 and 0.66 for calibration and validation respectively. Other studies using the SWAT model find similar NSE values, although these are not always fully comparable due to different temporal resolutions and the use of a more generic faecal coliform bacteria. Benham et al (2006), for example, find NSE values of 0.63 and 0.61 for their calibration and validation period for monthly faecal coliform bacteria for the Shoal Creek

Watershed in Missouri; US. Chin et al. (2009) find an NSE of 0.73 for daily *E. coli* concentrations in an experimental watershed in Georgia, US; and Parajuli et al. (2009) find NSE values from -2.92 – 0.71 for daily source-specific faecal coliform bacteria concentrations in the Upper Wakarusa watershed in Kansas, US. Coffey et al. (2010a) applied the SWAT model to predict the transport of *E. coli* and found NSE values from 0.78 – 0.59 at Fergus catchment in Ireland. Similarly, Coffey et al. (2013) also applied the SWAT model and find NSE values from -0.42 - 0.29 for daily *E. coli* concentrations at Kilshanvey catchment at Ireland. Bougeard et al. (2011) coupled the SWAT model with hydrodynamic model MARS 2D to predict the *E. coli* concentrations at the Daoulas catchment in France. They found R^2 of 0.99 for river water quality and 0.89 for shellfish quality. Kim et al. (2010) also applied the SWAT model to predict streambed *E. coli* concentrations released and deposited on sediment resuspension at Little Cove Creek watershed in Pennsylvania. They found that surface runoff carried large numbers of *E. coli* to the river. Our study is, as far as we are aware, the first one on microbial modelling with the SWAT model in a developing subtropical country. The comparison above shows that our calibration and validation results are satisfactory and the modelling outcomes are reliable.

The Kabul river contains very high *E. coli* concentrations. It can be classified as 'grossly polluted' (Medema et al., 2009a) with all observed and simulated values larger than 10000 cfu/100ml. US-EPA's (2001) single sample bathing water quality standard (235 cfu/100 ml for *E. coli*) is strongly violated year around. The simulated and observed results presented considerable spatiotemporal variations. The highest concentrations peaks were observed at times of monsoon (June to August) with associated high surface-air temperature that causes snow/glacier melt and flooding. While the concentration in January and February is around 3.8 ^{10}log cfu/100ml, the peak concentrations reach up to 5.2 ^{10}log cfu/100ml in August. This suggests that peak concentrations of *E. coli* appear during substantially high flow due to increased surface runoff from land to water resources in the lower Kabul River basin. Modelling thus enables us to better understand the source of these higher concentrations. In some months with high concentrations (e.g. June – August 2013, 2014 and 2015), the non-point sources contributed relatively more to the total loads as during these months monsoon precipitation coincides with snow and glacier melt that causes floods. While, in other months point sources appear to contribute more because of constant load to river. Higher microbiological concentrations during monsoon periods (i.e. high precipitation events) and high river flow (due to snow/glacier melt) were also observed in other studies (Ouattara et al., 2013; Schilling et al., 2009a). The reason for this is that high precipitation increases the runoff of manure from the fields. In these cases this effect weighs up to the dilution that could also occur with increased precipitation and flow. An important mechanism t in these regions is that flooding of agricultural land will wash large amounts of manure into the river. Our modeled peaks could thus be a slight underestimate. At times of non-flooding, the chances of surface runoff from agricultural land are reduced because of low precipitation. Meanwhile, a constant input of bacterial loads from cities and livestock sheds occurs and this increases the contribution from point sources to the river.

These outcomes showed that, overall, total loads from direct sewage and manure discharges and upstream concentrations (i.e. above Warsak) contributed most to the total concentrations (34% and 44% respectively; Figure 3). Chin et al. (2009) also found high concentrations of faecal coliforms in a river in Georgia, US, due to direct inputs of pollutants. Diffuse emissions were less important, although they still contributed around 22%. Comparatively lower contribution from non-point sources was also observed by others (Ouattara et al., 2013; Sokolova et al., 2012).

The loads from Peshawar contribute most out of the point sources. The population of Peshawar is large (3.13 million people) and nearly everyone is connected to the sewer. Unfortunately, the wastewater treatment plant has been broken since the extreme 2010 flood. Also Nowshera and Charsadda (1.77 and 1.37 million people respectively) are large cities without functioning wastewater treatment systems. The animal sheds in the basin, which are mostly located in Amangarh (see Figure 4.1c), also strongly contribute to the total concentrations. Livestock numbers in the basin are large (0.89 million) and especially cows emit relatively large amounts of *E. coli* in their manure. Approximately 20% of total manure collected from livestock sheds is used on the land and 25% is sold as fuel, about 55% of this manure is deposited on the river side and enters the river quickly (Nisar et al., 2003).

Modelling studies have inherent uncertainties. For instance, some processes could be omitted, calibrations may not provide as satisfying results as hoped for, or input data are lacking. The SWAT model performs fine for the Kabul River Basin. However, Figure 2 shows that the model slightly overestimates low concentrations and underestimates high concentrations. The lower estimates of peak concentrations are directly related to the too low estimate of peak discharge, as explained in Iqbal et al (2017b). Such low estimate is standard in hydrological modelling (Döll et al., 2003). The low underestimates of peak concentrations could also be partly related to the free moving animals in the basin, such as dogs, asses, camels and horses. These animals are present, but limited in numbers and precise data are not available. During extreme precipitation events more of their excreta may reach the river. In urban areas these animals have been included in an urban runoff fraction. However, these are ignored in rural areas. As the numbers of these animals are generally low in the basin, excluding them in the current study should not affect our outcomes substantially. The too high estimates of the low flow could cause by a too high overestimate of the direct inputs of sewage. Although the sewage is not treated, it does have a long residence time in the drains and the irrigation canals and during this period decay can occur. Similarly, the manure from the animal sheds will stay on the river banks for a while before it enters the river. Also then decay can occur. The assumptions that we have used in this model, are based on available data and insights. The model quality can be classified as good and therefore the results are likely robust.

The microbial water quality in Kabul river is very poor. While the population does like to bathe in the river or use the water for other purposes, the water is not safe to do so. Together with *E. coli*, other pathogens will be present and these can cause disease. Thorough sewage and manure management is thus required to improve this situation. The provincial government of Khyber Pukhtunkhwa, Pakistan (EPA-KP, 2014) has already started to reconstruct and establish new wastewater treatment plants for cities. Treatment will also become compulsory for other urban settlements and industries. To better understand the sources of the poor water quality and its high health risks, and to assess the impact of interventions, modelling provides opportunities. The SWAT bacterial model developed in this study could be a dependable assessment tool that can be used by water and public health managers to obtain information in controlling the widespread microbiological contamination of Kabul River.

4.5 Conclusions

The objective of this study was to analyse the fate and transport of *E. coli* in the lower Kabul River Basin and to provide improved understanding of the influence of different processes involved in *E. coli*'s transport to water resources. The highly sensitive variables for pathogen modelling, *BACTKDQ, BACTMIX* and *THBACT,* show that the presence of *E. coli* likely lead to higher *E. coli* concentrations at the watershed outlet. The model performance was good. High and low concentrations were slightly underestimated. Mean monthly *E. coli* concentrations were high and range from $6.5*10^4$ cfu/100ml to $1.1*10^5$ cfu/100ml. Point source of contamination contributed to 44%. Non point souces contribution accounted for approximately 22% while *E. coli* from above Warsak accounted for 34% of the total conentration in the watershed system. *E. coli* concentration peaks were observed during the flooding months of July-August 2013, 2014 and 2015. To improve the surface water quality in Kabul River, the focus should thus be on wastewater treatment and prevention of the direct manure loads from livestock sheds.

Based on the outcomes of this modelling study, the upstream concentrations and point source of microbial pollution were found to be the major contributor in contaminating the surface-water resources in the Kabul River Basin. The developed model could be useful in future studies on assessing the impacts of socioeconomic developments and climate change on *E. coli* concentrations. Such modelling study can provide useful information to water managers to improve the surface-water quality and to protect humans from waterborne diseases, which still are the leading cause of death in developing countries like Pakistan.

Acknowledgements

The authors would like to acknowledge Nuffic (NFP), Government of the Netherlands for providing the Ph.D. fellowship. Thanks to Professor Dr. Raghavan Srinivasan and Dr. Karim Abbaspour for their support of the SWAT model setup and variables selection for pathogen modelling. Special thanks to Professor Dr Rik Leemans (Wageningen University and Research) and Confidence Duku for critical review and correction of this manuscript.

CHAPTER 5

THE IMPACT OF SOCIOECONOMIC DEVELOPMENT AND CLIMATE CHANGE ON *E. COLI* CONCENTRATIONS IN KABUL RIVER, PAKISTAN

This chapter is based on:

Iqbal M. Shahid, Islam M. M. Majeed, and Nynke Hofstra. The impact of socioeconomic and climate-change on *E. Coli* concentrations in Kabul River, Pakistan (Submitted)

Abstract

Microbial pollution is a major problem worldwide. High concentrations of *Escherichia coli* have also been found in the mainstream and tributaries of the Kabul river in Pakistan. Such *E. coli* concentrations vary with varying socioeconomic variables, such as population and livestock densities, urbanization, sanitation and treatment of wastewater and manure, and climate-change aspects, such as floods and droughts. In this paper, we assess future *E. coli* concentrations in the Kabul river using the Soil and Water Assessment Tool (SWAT) with newly developed scenarios that are based on the most recent shared socioeconomic and representative concentration pathways (RCPs and SSPs) developed for the Intergovernmental Panel on Climate Change (IPCC). Scenario_1 has moderate population and livestock density growth, planned urbanization and strongly improved wastewater and manure treatment, and moderate climate change. Scenario_2 has strong population and livestock density growth, moderate urbanization, slightly improved wastewater treatment, no manure treatment and strong climate change. In Scenario_2 *E. coli* concentrations are strongly increased to 158% and 201% of the baseline concentrations by the 2050s and 2100s respectively. In Scenario_1, *E. coli* concentrations are reduced to 70% and 81% of the baseline concentrations by the 2050s and 2100s. When additional treatment is added to Scenario_1, the *E. coli* concentrations are reduced even further to 5%, 7% and 0.6% of the baseline concentrations when additional tertiary treatment, manure treatment or both have been applied respectively. This study is the first to apply combined socioeconomic 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* and other pathogen concentrations in Pakistan's rivers is possible, but requires stringent waste water treatment and manure management measures.

Keywords: Global change, Scenario analysis, *Escherichia coli,* Hydrological modelling, Bacterial modelling.

5.1 Introduction

Safe and clean water is essential for healthy life. However, due to the increasing pressure of population growth, urbanisation and lack of sanitation it is difficult to sustain. Water contamination due to microbiological contaminants (e.g. bacteria, viruses or parasites) impairs the water quality in water systems. Waterborne pathogens causes waterborne diseases like diarrhoea, which is the fourth leading cause fo dealth in children under five years of age (UN, 2015). Waterborne diseases are linked to waterborne pathogen concentrations in water systems (Azizullah et al., 2011; Saeed and Attaullah, 2014). To analyse the microbial contamination in water systems, usually indicators, such as fecal coliforms and Escherichia coli (*E. coli*), are used in water systems (Coffey et al., 2007; Odonkor and Ampofo, 2013). Although *E. coli* is not usually pathogenic, its presence indicates faecal contamination, possible presence of pathogenic microorganisms and therefore health risk (Wu et al., 2011b). High concentrations of *E. coli* are found in the main stream and tributaries of Kabul river in Pakistan (Iqbal et al., 2017a). Bathing water criteria are violated year round and floods strongly increase concentrations. This indicates a high health risk for the population, who use the contaminated water for bathing, cleaning and other domestic activities. This study focuses on *E. coli* concentrations in Kabul river in Pakistan.

Concentrations of *E. coli* in surface water systems vary with varying socioeconomic variables, such as population growth, urbanization 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 micro-organisms to the water system, a sewer without treatment emits large amounts (Ahmed et al., 2002; Graham and Polizzotto, 2013). An increasing population increases the pressure on sanitation systems. Moreover, climate change induced extreme precipitation may increase emissions to surface water through an increased amount of sewer overflows and manure runoff from the land. Increased precipitation may also increase the dilution and therefore reduce the surface water concentrations (Boxall et al., 2009; Rose et al., 2001a; Whitehead et al., 2009). The net impact of the different socioeconomic and climate processes on microbial contamination of surface water is understudied (Hofstra and Vermeulen, 2016a).

To assess the impact of socioeconomic and climate change on *E. coli* concentrations in surface water systems, models together with scenario analysis can be applied (Hofstra, 2011). Scenario analysis explores future developments in complex systems. Scenario analysis is a 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 population is at risk of water security. Climate change impacts on water quality have been discussed by Jalliffier-Verne et al. (2016), who applied a hydrodynamic model to simulate the transport of fecal contaminants from combined sewer system overflows affecting drinking water quality at Quebec, Canada. They used climate change scenarios and found up to 87% increase in *E. coli* concentrations, depending on future climate and socioeconomic 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 the surface water is 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 pre-treated. 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 scenario analyses, climate change scenario were used. Also Whitehead et al. (2015) and Jin et al. (2015) study impacts of climate and socioeconomic development on water quantity and quality separately. Only few studies highlight the importance of combined socioeconomic and climate change impacts on water quality. For instance, Borris et al. (2016) perform a scenario analysis for storm water quality (suspended solids and heavy metals) in Sweden and Zhuo et al. (2016) studied the impact of socioeconomic and climate changes on the water availability for agricultural activities. Thus far no studies other than the present study and Islam et al (2017) have assessed the impacts of combined socioeconomic development and climate change on microbial water quality.

Our study therefore aims to assess future changes in the *E. coli* concentrations in the surface water of Kabul river in Pakistan. Such a study is particularly important for this river, because very high *E. coli* concentrations of were found in one of our previous studies (Iqbal et al., 2017a).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 with the Soil and Water Assessment Tool (SWAT) model (Section 2.2) that has been calibrated and validated for hydrology and monthly *E. coli* concentrations before (Iqbal et al., 2017b; Iqbal and Hofstra, 2017c). This scenario approach helps 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.

5.2 Data and Methods

5.2.1 Study Area

Our study was conducted in the Kabul River Basin (Figure 5.1). The characteristics of this watershed have been described in detail by Iqbal et al. (2017b)The river basin covers 92600 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 temperatures, more and more snow melts quickly and precipitation patterns change. The resulting increased runoff increases the discharge of the Kabul river and this causes floods. At times of flooding, many microorganisms are carried from the land and contaminate the river. Mean monthly river flows observed at the Attock rim station indicate that four fifths of the annual flows occur during the April-September months with a peak in August (Iqbal et al., 2017b). Most people in the river basin are connected to a sewer but wastewater treatment is lacking. 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. The Kabul River therefore carries many untreated sewage effluents and manure from urban and rural settlements.

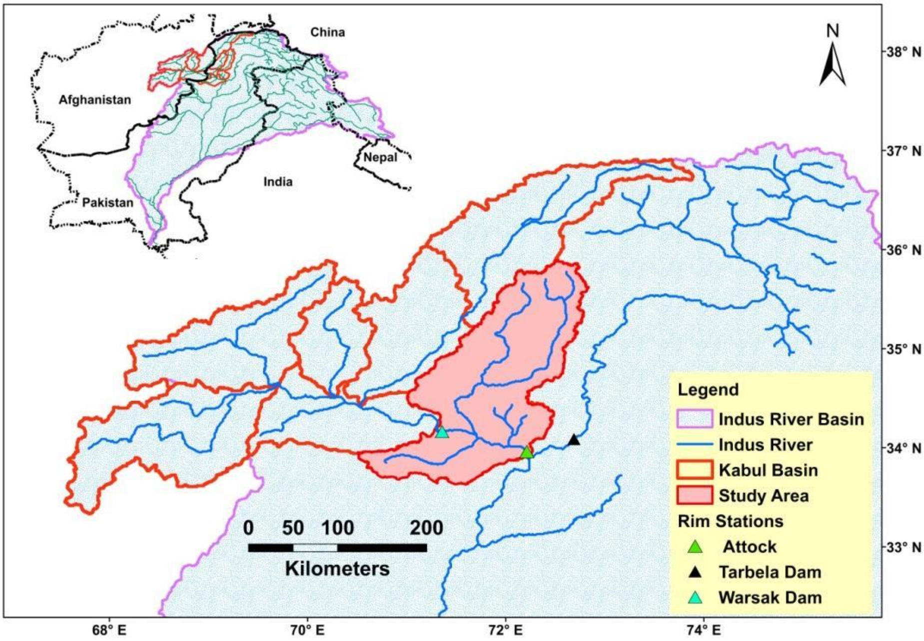

Figure 5.1: Study map of the Kabul River Basin, the geography of the basin in Afghanistan and Pakistan, and the major tributaries of Kabul river. The triangles are the RIM stations where discharge is measured. At the green triangle Kabul river discharges into the Indus river.

5.2.2 Water Quality Modelling

The SWAT hydrological model together with its bacterial sub-model (Sadeghi and Arnold, 2002) was used to analyse the fate and transport of *E. coli* in the lower Kabul River Basin. The model was previously calibrated and validated for hydrology (Iqbal et al. 2017b) and *E. coli* (Iqbal and Hofstra, 2017c). The modelling results correspond well to measured concentrations in the Kabul River. The coefficients of determination (R^2) were 0.72 and 0.70, Nash-Sutcliffe efficiencies (NSE) were 0.69 and 0.66 and percentages bias were 3.7 and 1.9 for *E. coli* concentration calibration and validation respectively. Humans connected to sewers and livestock in animal sheds are point sources of contamination, while runoff from urban and agricultural land is the diffuse (i.e. non-point) source of contamination in the Kabul River Basin.

5.2.3 Scenario Analysis

To analyse the joint impacts of changes in socioeconomic development and climate on the *E. coli* concentrations, two scenarios have been developed. These scenarios are based on existing scenarios developed for the IPCC and include specific assumptions for the Kabul River Basin that are in line with the storylines. The scenarios were developed for the periods 2040-2060 (i.e. the 2050s) and 2080-2100 (i.e. the 2100s).

Since 2006, the climate change research community has established a new scenario framework (Ebi et al., 2014; Moss et al., 2010; O'Neill et al., 2014; Van Vuuren et al., 2014). The new scenarios comprise two basic elements: i) Shared Socioeconomic Pathways (SSPs) and (ii) Representative Concentration Pathways (RCPs). The SSPs comprise narratives and quantifications of possible socioeconomic developments. They have been structured around challenges to climate change mitigation and adaptation (O'Neill et al., 2014). The socioeconomic variables that have been quantified include, for example, population, livestock production, urbanisation and GDP. The RCPs explore trajectories for the development of emissions and concentrations disturbing the radiative forcing of the climate system over time (Van Vuuren et al., 2011b). Such disturbance in radiative forcing leads to changes in, among others, temperature and precipitation. In this paper we use combined SSP and RCP scenarios. Specific SSPs produce greenhouse gas emissions that can lead to one or more RCP. This results in a scenario matrix. Every cell in the scenario matrix portrays a reasonable course of emission and concentration and is compatible with socioeconomic development pathways (Kok, 2016; Van Vuuren et al., 2014).

In this study, we only use two SSP-RCP combinations for the Kabul River Basin: SSP1 with RCP4.5 as the basis for Scenario_1 and SSP3 with RCP8.5 as the basis for Scenario_2. The SSP-RCP combinations chosen are plausible for this region. The combination SSP1 with RCP4.5 is often used. Scenario_1 is a scenario with a sustainability focus leading to limited climate change (i.e. adheres to the well-below 20C target). Strong socioeconomic improvements are required for the Kabul River Basin and when the rest of the world also limits its greenhouse gas emissions, limited climate change is reasonable. Scenario_2 portrays large changes in climate by combining SSP3 with RCP8.5, which is globally not a common combination. In SSP3 society is so destructive that greenhouse gas emissions are not high enough to reach the radiative forcing of 8.5 w/m2 (Riahi et al., 2011). However, while the world overall could be on a socioeconomic pathway that has very strong greenhouse gas emissions (e.g. SSP5), the Kabul River Basin could well be in a situation with war and poverty. So, combining SSP3 with RCP8.5 is a plausible combination for this region. While several SWAT model variables have been collated for the 2050s and 2100s from the SSPs and RCPs, also specific assumptions were made. These assumptions were made in line with the SSP narratives for Scenario_1 and Scenario_2. Table 5.1 summarises the data and the assumptions made for these scenarios that are detailed in Sections 2.3.1 and 2.3.2.

5.2.3.1 Socioeconomic Changes

E. coli concentrations are influenced by socioeconomic changes. Scenario_1 is based on SSP1, which is called: "Sustainability – taking the green road" and emphasises human well-being, sanitation, education and improved water quality at the cost of long-term economic growth. In SSP1, population growth is moderate and urbanization is well planned (Jiang and O'Neill, 2015). This scenario, with its dominant assurance characteristics to accomplish growth and steady movement towards less resource-intensive lifestyles, leads to relatively low challenges for climate-change mitigation. Advances in human well-being alongside robust and flexible international and regional institutions also suggest low challenges to climate change adaptation.

Scenario_2 is based on SSP3. SSP3 is called: "Regional rivalry – a rocky road" and in the scenario the focus is on regional progress. Policy gradually shifts towards national security concerns, along with limited investment in education and other developments, such as slow economic growth, elevated poverty, health care, safe water, improved sanitation and interest on environmental issues declines (O'Neill et al., 2015). Economic development is low and inequalities persist, especially in developing countries. The population growth is high in developing countries with unplanned urbanization. The partial development on overall population growth and less income growth leads to high challenges to climate change adaptation for many groups in all regions (O'Neill et al., 2015). Regional rivalries cut down the support for international organizations and progress associated towards development goals.

To perform the scenario analysis, model input variables should be adjusted for these two future narratives. The population numbers, urbanisation rate and change in livestock production have been taken from the SSP database (available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome; accessed 23rd November 2016). These data are country data that we have downscaled. For population, the numbers for Pakistan and Afghanistan have been distributed over a 30 arc-second grid, using current and future country population, current and future urbanisation rates and the Land scan population database for 2010 (Bright et al., 2011). We assume that urban areas become more densely populated, but do not expand. Current livestock numbers in the study area obtained from the Bureau of Statists, Khyber Pukhtunkhwa (BSKP, 2016) have been adjusted with the percentage change in livestock production obtained from the SSP database. We assume that all livestock species increase by the same percentage, even though that is not necessarily realistic. At present there are no SSP data available for the different livestock species. We assume changes in population and livestock numbers, but we do not assume changes to the amount of *E. coli* they emit in their faeces.

Other input variables for the model have been quantified in line with the story lines for the SSPs. We make our own assumptions for sanitation, wastewater and manure treatment for our own scenarios. At present, most of the population living in urban and rural settlements in Kabul River Basin are connected to the sewage system (WATSAN, 2014). For both scenarios the assumption is that the percentages connected will increase from 90 to 99%. At present, there is no wastewater treatment, because the 2010 floods destroyed the systems (EPA-KP, 2014). Primary treatment systems are currently developed. For Scenario_2 we therefore assume some degree of primary treatment. As Scenario_1 is much more focussed on sustainable development, we assume that nearly all wastewater will be treated, with some degree of two level wastewater treatment (primary and secondary) by the 2050s and three level treatment (primary, secondary and tertiary) by the end of the century (see Table 5.1). Manure treatment will also reduce *E. coli* concentrations. We assume that in Scenario_1 most of the manure collected from livestock sheds is treated with an anaerobic digester prior to its use as fertilizer. In Scenario_2 the situation remains the same as today and no manure is treated. We assume changes to the sewage and manure treatment overall, using present removal rates in the treatment systems. We do not account for possible technological advancements in *E. coli* removal in the treatment systems that could occur for Scenario_1. Land-use change could also influence the *E. coli* concentrations in Kabul river. These should have been taken from the

SSP database. Unfortunately, SSP land use change data was thus far unavailable. We therefore used RCP land use data, as explained below.

5.2.3.2 Climate Change

E. coli concentrations will also be influenced by future climate change. Future climate projections for a given level of radiative forcing are uncertain due to numerous factors, such as climatic variations and regional climate-response patterns (Christensen et al., 2007; Meehl et al., 2007). We therefore use temperature and precipitation data from an ensemble of four different climate models. These climate models are INM-CM4, IPSL-CM5A, EC-EARTH, MIROC5 and they have been chosen for their earlier proven performance in the region as explained by Iqbal et al (2017b). The scenario data have been collected from the Earth System Grid Federation Portal (http://cmip-pcmdi.llnl.gov/cmip5/; https://esgf-data.dkrz.de/search/cmip5/) and have been downscaled using a delta change approach with quantile to quantile correction (Liu et al., 2015), as explained in more detail in Iqbal et al (2017b).

For Scenario_1 RCP4.5 is used, with a moderate increase and later stabilisation of greenhouse gas concentrations. RCP4.5 leads to a worldwide 0.9 – 2 ºC increase in surface air temperature by the 2050s compared to the 2000s and 1.1 – 2.6 ºC increase by the late 21st century (Thomson et al., 2011). In the Kabul River Basin mean surface air temperature increases by 3.1 ºC by the late 21st century, until 26 ºC. Total annual precipitation is expected to increase by 20% by the late 21st century, until 341 mm/year (See Table 5.1). More extreme precipitation will occur.

For Scenario_2 RCP8.5 is used. This scenario shows a strong increase in greenhouse gas concentrations, and therefore temperature. RCP8.5 leads to a worldwide 1.4 – 2.6 ºC increase by the 2050s and 2.6 – 4.8 ºC increase by the 2100s (Riahi et al., 2011). In the Kabul River Basin the temperature increases are also much stronger than for Scenario_1. The mean surface air temperature is expected to increase by 5.2 ºC to 28.1 ºC by the late 21st century. Precipitation is expected to increase by 25% until 356 mm/year (see Table 5.1). Precipitation is expected to become much more extreme in the future.

RCP land use change data have been used, as these were, as far as the authors were aware, the only land use change data available. Land use data for scenario analysis were acquired from RCP database (available on https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome#intro) for the 2050s and 2100s. For RCP4.5 the landuse data developed by the MiniCAM modeling team was selected. For RCP8.5 the landuse data developed by the MESSAGE modeling team was utilized to create the projected landuse data for the Kabul River Basin. In Scenario_1 agricultural areas (crop land and pasture), forest area and barren lands have been converted to urban settlements, while in Scenario_2 the agricultural land and urban settlement expand and forest area and barren land are reduced. Details are available in Table 5.1.

Table 5.1: Population growth, urbanization, sanitation, wastewater treatment, land-use, livestock numbers and projected climate variables for Scenarios_1 and 2 for the 2050s and 2100s for the Kabul River Basin.

	Base year	**Scenario_1**		**Scenario_2**	
Scenario features	**1990-2010**	**2050s**	**2100s**	**2050s**	**2100s**
Population (million)	21.17	33.33	31.9	46.05	79.36
Urban population (%)	35.9	70.1	90.5	41.9	50.0
Connected to sewer (%)	90	99	99	99	99
Sewage treatment (%) based on connected to sewage system					
Primary (removal rate: 90%)	0	65	60	50	65
Secondary (removal rate: 99%)	0	20	20	0	0
Tertiary (removal rate: 99.9%)	0	0	10	0	0
No treatment (no removal)	100	15	10	50	35
Projected Livestock number (million)					
Cattle (cow + buffalo)	0.89	1.17	1.06	1.46	1.88
Goats	1.15	2.91	2.54	3.01	4.41
Sheep	1.32	3.61	3.01	3.98	5.01
Manure treatment (%)					
Anaerobic digester (removal rate: 90%)	0	45	80	25	35
No treatment	100	55	20	75	65
Climate Variables (Ensemble mean)					
Total annual precipitation (mm)	285	328	370	341	356
Mean annual surface air temperature (^{0}C)	22.9	24.8	26.0	25.9	28.1

Projected Land use change (%)					
Agricultural Land	33.1	29.8	25.8	36.4	37.6
Forest area	20.8	17.9	15.8	14.6	11.8
Urban / Built-up area	21.3	29.4	36.4	27.9	30.2
Water / Snow or Ice	13.4	14.2	14.6	13.9	13.6
Barren / Sparsely vegetation	11.4	8.7	7.4	7.2	6.8

5.3 Results

Figure 2 shows the *E. coli* concentrations at Attock (near the inlet to the Indus River) for Scenarios_1 & 2 for the 2050s and 2100s along with baseline *E. coli* concentrations. Baseline monthly mean concentrations are high and vary between 4.62 and 4.93 (log cfu /100ml) Human point sources account for 29%, livestock point sources for 15% and total non-point sources for 22% of the total concentration, and the remaining 34% of the concentrations are coming from upstream of Warsak. Scenario_1, with moderate population growth, planned urbanization, strong sanitation and wastewater and manure treatment improvements, shows substantial reduction in *E. coli* concentration by the 2050s and 2100s of 70% and 83% respectively. Overall, the point sources account for 19.7% and 16.3%, while non-point sources account for 46.8% and 44.3% and concentrations from above Warsak for 33.5% and 38.4% by the 2050s and 2100s respectively (Figure 2). *E. coli* concentrations are reduced in Scenario_1 to well below the USEPA bathing water quality standards. On average the concentration of *E. coli* is 95 cfu/100ml, which is low compared to the USPEA daily, single sample bathing water standards for *E. coli* in water samples (235 cfu/100ml (Kinzelman et al., 2003; USEPA, 2001).

Figure 5.2 also shows that with strong sanitation improvements in Scenario_1 concentrations of *E. coli* from point sources (human settlements and livestock sheds) are reduced, but non-point sources (livestock grazing and other agricultural activities) still strongly contribute to *E. coli* concentrations, despite some manure treatment in an anaerobic digester. Livestock are important as they act as both point and non-point source of contamination. To control the *E. coli* concentrations from livestock sources all the manure collected from livestock sheds should be treated (see Figure 5.3, Scenario_1b). In that case, the concentrations are 46% of those of Scenario_1 or 7% of the baseline concentrations. Also human emissions could be reduced further when tertiary treatment is applied in the full basin. Then the total concentrations are then 35% of Scenario_1 (see Figure 5.3, Scenario_1a). When both human and livestock emissions are reduced throughout the basin (see Figure 5.3, Scenario_1c), *E. coli* concentrations are 4% of Scenario_1 and 0.6% of the baseline concentrations.

The *E. coli* concentrations are expected to increase for Scenario_2 (Figure 5.2) by the 2050s and 2100s and are expected to be 158 % and 201% of baseline *E. coli* concentrations respectively. The point sources of contamination increase to 138% and 189%, non-point sources of contamination increase the concentrations to 112% and 167%, and above Warsak concentration increase to 125% and 177% of baseline *E. coli* concentrations by the 2050s and 2100s respectively in Scenario_2. In the future, major contributors to *E. coli* concentrations are expected to be point sources due to increased population growth, unplanned urbanization and limited wastewater treatment facilities, followed by expanded agricultural activities where untreated manure is used as organic fertilizer in the Kabul River Basin or dumped directly into the river.

Figure 5.4 presents the projected *E. coli* concentrations and variability among the outputs from the different General Circulation Models (GCMs). Projections of surface air temperature, precipitation and river discharge were different for all GCMs for the 2050s and 2100s. The GCMs were chosen for their characteristics and show a spread in climate responses. While the GCM INM-CM4 projects a relatively cold and dry future, IPSL-CM5A projects a cold and wet future. The GCMs EC-EARTH and MIROC5 project relatively warm futures. EC-EARTH projects a dryer future than MIROC5 Iqbal et al. (2017b). Together these models provide a spread in future *E. coli* concentrations. Under colder conditions the concentrations are expected to be lower than under warmer conditions and under dryer conditions they are expected to be lower than under wetter conditions. While the spread over the four GCMs is in the order of 0.5 – 1 log-unit, the changes in *E. coli* concentrations all have the same sign, so we see decreases for Scenario_1 and increases for Scenario_2.

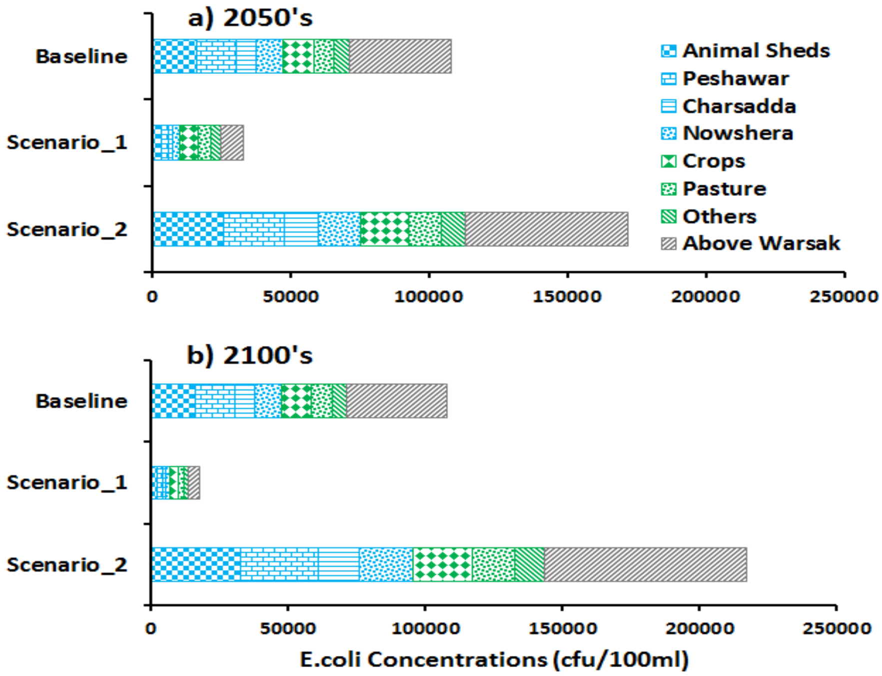

Figure 5.2: Total *E. coli* concentration in Kabul river averaged over the basin for a) near future 2050s, b) far future 2100s, Concentrations are averaged over the four runs using the different GCM climate data. Point sources are depicted in blue, non-point sources in green and contribution of above Warsak concentrations in grey. The patterns indicate the contributions of various sub-sources of point and non-point contamination.

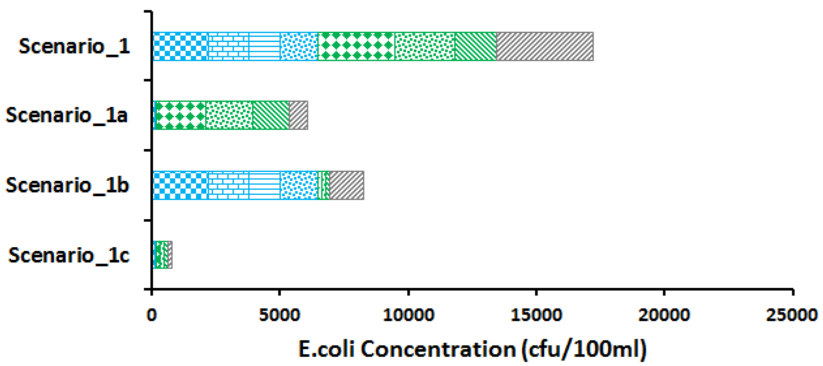

Figure 5.3: Three variants of Scenario_1 compared with Scenario_1 concentrations for 2100.

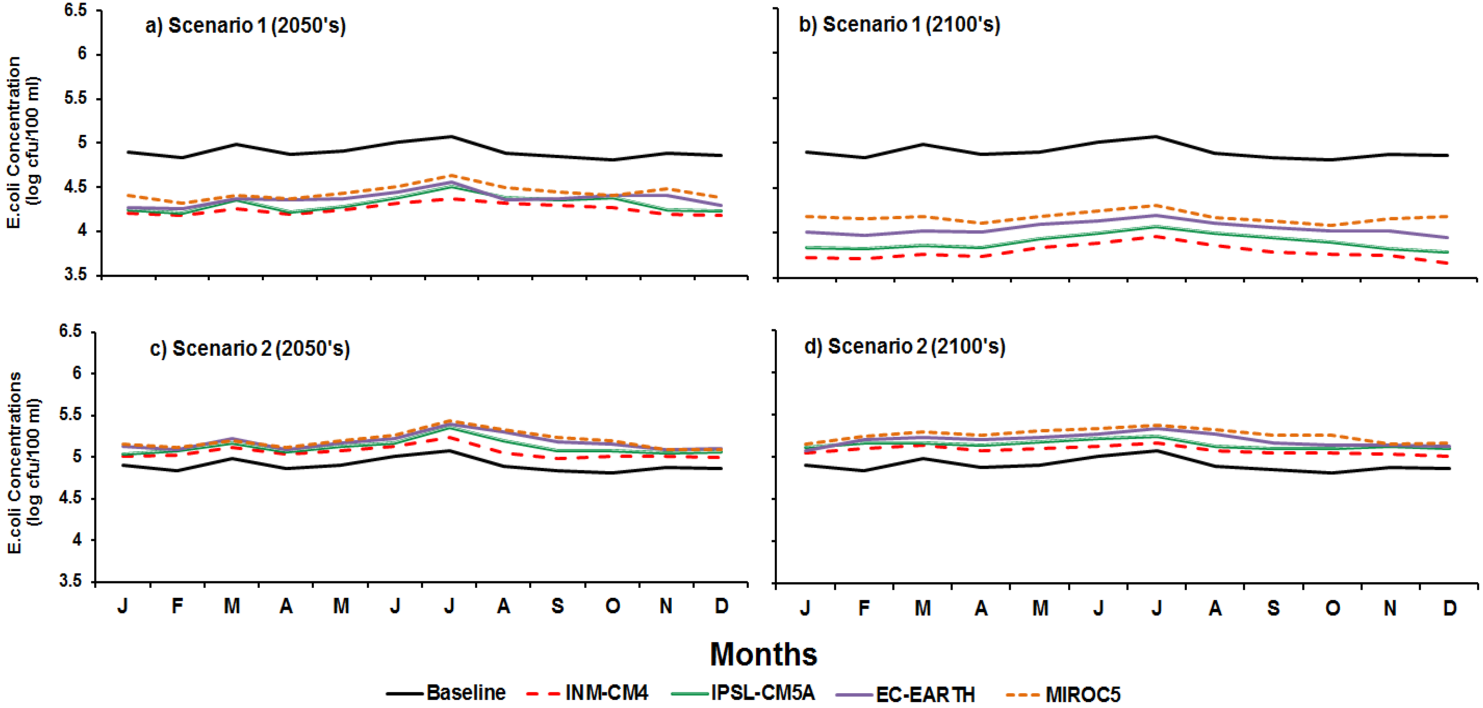

Figure 5.4: Variability in total *E. coli* concentration in surface water of the Kabul river while applying GCMs (INM-CM4, IPSL-CM5A, EC-EARTH, and MIROC5) for Scenario_1 and Scenario_2.

5.4 Discussion

In this paper we used comprehensive socioeconomic and climate change scenario analysis to assess future concentrations of *E. coli* in Kabul river. We find that *E. coli* concentrations are reduced in Scenario_1 and non-point livestock sources are relatively important for contamination of Kabul river, whereas in Scenario_2 *E. coli* concentrations are higher than baseline concentrations, due to point sources. In the future we expect that if the sanitation situation is improved via installation of highly advanced wastewater and manure treatment plants the contamination to water sources would be reduced and the quality of water in the Kabul river would be much improved. When wastewater and manure treatment are combined for the full basin (Scenario_1c), the total concentrations will be strongly reduced. These results are in line with our expectations. Currently, partly due to broken wastewater treatment systems, the *E. coli* concentrations are very high and strongly related to human inputs. When stringent measures are put in place, the concentrations could be reduced significantly.

Hydrological models coupled with bacterial modules are the best available tools to better understand the fate and transport of microbes from land to the river, as they take into account all the possible routs of contamination (Benham et al., 2006). The Soil and Water Assessment Tool (SWAT) is a watershed-scale model. It has been widely used for modelling watershed hydrology at a continuous timescale. The SWAT bacterial model has also been used before for various watersheds worldwide to better understand the fate and transport of different pathogenic and non-pathogenic micro-organisms (Coffey et al., 2010a; Coffey et al., 2012; Sadeghi and Arnold, 2002; Tang et al., 2011). The model has been tested on a watershed in Missouri (USA) for *E. coli* and fecal coliforms (Baffaut and Benson, 2003). Likewise, Parajuli (2007) has tested the SWAT microbial for a watershed in Kansas (USA). The model performed well in all of these studies (R^2 and NSE equal 0.5 – 0.74). In addition to the SWAT model several other bacterial model have been used to better understand the fate and transport of different bacterial species globally, such as Watershed Assessment Model (WAM View) (Tian et al., 2002), Hydrologic Simulation Program in FORTRAN (HSPF) (Desai et al., 2011; Fonseca et al., 2014), WATFLOOD/SPL (Dorner et al., 2006), SENEQUE-EC model consists of the hydro-ecological SENEQUE/RIVERSTRAHLER model (Ouattara et al., 2013) and World Qual, Part of WaterGAP3 (Reder et al., 2015). Most of these models require many computing resources, which is an issue for modelling studies in data sparse developing countries like Pakistan. In such conditions the SWAT model is a good choice as it can be run with minimum datasets for accurate modelling studies in those part of the world and the results are comparable with other models (Devia et al., 2015).

Although SWAT is capable of simulating the influence of future socioeconomic and climate change scenarios on *E. coli* concentrations, so far no studies have done that. Few studies have focused on scenario analysis. For instance Coffey et al. (2010b) explored the influence of improvement of wastewater treatment and direct deposition reduction and found a 91% reduction of *E. coli* concentration to water sources from direct deposition and an 82% reduction from improved wastewater treatment system in the area. We found even slightly stronger reductions, with a 95% reduction for concentrations caused by direct deposition and a 93% reduction for concentrations caused by improved wastewater treatment and when both direct deposition and wastewater treatment were improved even a 99% reduction in *E. coli* concentration was observed in this study (see Figure 3). We most likely find much stronger reductions, because our river is more polluted at present, compared to the Irish catchment modelled by Coffey et al. (2010a).

To assess the *E. coli* concentrations in the future, we performed a scenario analysis. For Scenario_1 and 2 the most recent socioeconomic and climate change scenarios have been used that have been developed for the IPCC. Most other case studies used RCP4.5 and RCP8.5 as the two emission scenarios. RCP6.0 is barely used as RCP4.5 and RCP8.5 overlap and cover the range of RCP6.0. The RCP selection is strongly limited by the availability of GCMs runs. For instance, most of the GCMs have data for RCP4.5 and RCP8.5 (Kok, 2016). The GCMs selected by Iqbal et al. 2017b did not have data available for RCP2.6. This was one of reasons that RCP2.6 was not selected in the current study. Using the two reasonably extreme scenarios enables exploration of the spread of the *E. coli* concentrations in the future. Simultaneously, the spread should not be seen as the full spread of plausible futures. To get a better understanding of the full spread, a full SSP-RCP matrix with the full GCM ensemble should be run. However, as the sign of the change in *E. coli* concentrations are the same for the different GCMs and as the two most extreme SSPs have been used, the added value of such an intensive model exercise is questionable.

We analysed changes in *E. coli* concentrations in the surface water of Kabul river using scenario data. For the Kabul River Basin population growth, urbanization, livestock numbers and future land use data were acquired from SSP and RCP databases (explained in Section 2.3.2). The data were acquired for Pakistan and downscaled to the Kabul River Basin. No data were available for sanitation, wastewater and manure treatment. Assumptions for these variables were made in line with the SSP storylines. In future studies, these variables could possibly be linked to other indicators, such as the GDP in the region that is also available through the SSP community. In addition, at present communities responsible for the SSP data using integrated assessment models are still finalising their model outputs. While we did use the most recently released data of October 2016, more and newer data may become available in the near future.

Until now, no combined socioeconomic and climate change scenario analysis was performed for *E. coli* concentrations in surface water. This study proves that such scenario analyses are valuable to anticipate future changes and get a better understanding of what is required to improve the current poor quality. This study can be used as an example for others to apply similar tools to their own basin.

This paper focuses on *E. coli* rather than waterborne pathogens. This has the limitation that we cannot simply use the results to estimate health risk for the population and changes in this health risk due to socioeconomic development and climate change. The method applied here, could, though, also be applied for pathogens. Using the modelling approach described here for pathogens, together with risk assessment in the future would improve our understanding of the future changes to human health risk. Such knowledge has already been requested for years (Campbell-Lendrum et al., 2009; Checkley et al., 2000; Hofstra, 2011; Semenza and Menne, 2009). Such papers would strongly contribute to the health risk chapter in IPCC's assessment report, which has thus far been very limited for waterborne disease. Overall, we could make the crude assumption that lower (higher) *E. coli* concentrations also means lower (higher) pathogen concentrations and thus lower (higher) health risk for the population. Scenario_1c should be the way forward to deal with the plausible changes and reduce the health risk for the population. Reaching concentrations as estimated by Scenario_1c is very important to achieve the sustainable development goals that aim to improve the water quality.

5.5 Conclusions

In this paper, we assess future *E. coli* concentrations in surface water using two scenarios based on the new IPCC scenario matrix approach with the SWAT model. Socioeconomic variables together with climate change impacts will alter the *E. coli* concentrations in the basin. We found changes in mean monthly *E. coli* concentrations in surface water for the 2050s and 2100s for Scenario_1, its three variants Scenario_1a,1b,1c, and Scenario_2. In Scenario_2, with strong human and livestock population growth and limited wastewater and manure treatment improvements, *E. coli* concentrations increase by the 2050s and 2100s and are expected to be 158% and 201% of baseline concentrations respectively. In Scenario_2 the point source contribution increases by 38% and 89% and non-point source contribution increases by 12% and 67% for the 2050s and 2100s respectively. Point sources were already the most important source and are expected to become relatively more important for this scenario. For Scenario_1, with moderate population growth, planned urbanization and strong wastewater and manure treatment improvements, total *E. coli* concentrations by the 2050s and 2100s are expected to reduce to 30% and 19% of the baseline concentrations. *E. coli* concentrations are further reduced with three variants Scenario_1a (maximum wastewater treatment), Scenario_1b (maximum manure treatment) and Scenario_1c (both) to 35%, 46% and 4% of the Scenario_1 concentrations by the 2100s respectively, or 5%, 7% and 0.6% of the baseline concentrations. This shows that strong improvements in treatment will help to reduce the concentrations of *E. coli* in the Kabul River Basin.

Our scenario analysis demonstrates that in addition to anticipated climate change, socioeconomic variables play a substantial role in microbiological contamination of water sources and they need to be considered in the future whenever water quality and related health risks are evaluated by water managers. This study is the first to combine socioeconomic and climate scenarios to study the microbial water quality. The study provides an understanding of possible future changes and shows that stringent measures for human sewage and livestock manure are required to improve the water quality in the Kabul River Basin.

Acknowledgement

The authors would like to acknowledge Nuffic (NFP), Government of the Netherlands for providing the Ph.D. fellowship. Special thanks to Professor Dr. Rik Leemans (Wageningen University and Research) for review and correction of this manuscript.

CHAPTER 6

SYNTHESIS

6.1 Introduction

This PhD thesis quantifies the impact of socioeconomic development and climate change on *Escherichia coli* concentrations in surface water resources in the Kabul River Basin, which is part of the Hindukush-Karakoram-Himalayas (HKH). Safe and clear water has always been important for healthy human societies. Yet the water resources on which they rely, are becoming progressively contaminated with microorganisms. Over one billion people worldwide were using contaminated drinking water in 2007 (WHO, 2007). By 2012, this number was reduced by a quarter (UNICEF and WHO, 2012) and this trend continued. Although the Millennium Development Goal for safe drinking water was achieved in 2015 (Rose, 2015), too many people still suffer from contaminated drinking water.

The deteriorating water quality is mainly caused by insufficient sanitation and wastewater treatment facilities, particularly in regions where access to safe and clean water is limited. Microbial contaminants, like bacteria, protozoa and viruses, pose human health hazards. Waterborne pathogens cause waterborne diseases, such as diarrhea. Diarrhea is worldwide the second leading mortality cause in children under the age of five (WHO, 2013). Substantial reductions in diarrhea were reported for improved water quality (Arnold and Colford, 2007; Clasen et al., 2007; Cutler and Miller, 2005; Fewtrell et al., 2005). In 2015, 90% of the global population had access to an improved drinking-water resources, compared to 75% in 1990 (WHO, 2016).

Improved water quality alone, however, is not enough to always guarantee safe drinking water. Increased concentrations of waterborne pathogens in water resources can occur during heavy precipitation events, by increased contaminated surface runoff and resuspension of pathogens in sediments (Funari et al., 2012; Hofstra, 2011). The pathways through which changes in hydro-climatic variables influence waterborne pathogen concentrations in surface water, are relatively well understood, but their net effects are poorly quantified (Hofstra, 2011). To analyse the microbial contamination in water resources, indicators, such as faecal coliforms and *Escherichia coli* (*E. coli*), are often used in water resources (Odonkor and Ampofo, 2013).

Flash floods occur every year in the HKH. The region receives intense monsoon precipitation that coincides with snow and glacier melt in the Himalayas. The Kabul River Basin suffers from similar floods and is the regional basin that is most vulnerable to climate change. Climate change causes more floods to occur and to become more frequent and intense (Tariq and van de Giesen, 2012). Usually, during the floods, pathogen concentrations increase as livestock manure and insufficiently treated sewage flushes into the river. This occurs especially in developing countries where wastewater treatment and manure controls are limited (Conn et al., 2012). Consequently, more diarrheal cases are recorded after floods (Hashizume et al., 2008). Concentrations of pathogen and associated health risk are also related to the socioeconomic developments. This thesis explores the relationship between changes in hydro-climatic variables (i.e. precipitation, surface-air temperature, water temperature and river discharge) and socioeconomic factors (i.e. population growth, animal numbers, urbanization, land-use changes and sanitation) with *E. coli* concentrations in the Kabul River Basin. My research aimed to **Quantifying the Impact of Socioeconomic Development and Climate Change on *Escherichia coli* Concentrations in the Pakistani Kabul River Basin.** It combines measurements, statistics and statistical and process-based modelling with comprehensive scenarios (assessing socioeconomic development and climate-change pathways). This objective was defined by four research questions (RQs) in Chapter 1 (Table 6.1) and the questions were addressed (Chapter 2 to 5).

The approach used in this thesis to assess changes in the Kabul River Basin is summarised in Figure 1.3. To address RQ1, I applied a correlation analysis and a regression model to better understand the relationship between hydro-climatic variables and *E. coli* concentrations in surface and drinking water resources. Climatic data were acquired from the Pakistan Meteorological Department, while I collected water temperature and *E. coli* concentration data from the selected locations (explained in Chapter 2). To address RQ2, I quantified the climate-change effects on the river flows and the flood return periods. A process-based hydrological model (Soil and Water Assessment Tool (SWAT)) is coupled with a flood frequency analysis model (i.e. HEC-SSP) and state of the art Intergovernmental Panel on Climate Change (IPCC) climate-change scenarios (i.e. the Representative Concentration Pathways, RCPs) were applied to determine future flood return periods (Chapter 3). The hydrological model was calibrated with the discharge data that was acquired from the Water and Power

Development Authority Pakistan. To answer RQ3, the hydrological SWAT model was coupled with the bacterial sub-model to determine the fate and transport of *E. coli* in surface water (Chapter 4). To address RQ4, the model was used and scenario analysis was conducted in which the latest Shared Socioeconomic Pathways (SSPs) were combined with IPCC's RCPs to project *E. coli* concentrations under changing climatic and socioeconomic conditions (Chapter 5). Sections 6.2 to 6.5 summarise the main answers to these four research questions, reflect on the robustness and innovation of these answers and discussed them in a broader scientific and societal context.

The thesis' main findings are summarized in Table 6.1. Each section first summarizes the answer to each RQ followed by the reflection and discussion. Additionally, my thesis' contribution to advance science is presented in Section 6.6 and an outlook for further research in Section 6.7. Finally the thesis' potential impact to solve societal issues is presented in Section 6.8.

Table 6.1: Summary of the main finding of four research questions to address the main them of PhD study.

Research Question		Main Findings
RQ.1	What is the impact of hydro-climatic variables on concentration level, sources and pathways of *E. coli* in the Kabul river at flooding and non-flooding times? (Chapter 2)	• All of the surface water samples exceeded USEPA bathing water standards due to the presence of high concentrations of *E. coli*. Similarly, 95% of the drinking water samples were exceeded the WHO standards of drinking water quality. Hence, water from the Kabul river and drinking water from Nowshera is not fit for drinking or bathing. • The linear regression model explains 61% of the variation in *E. coli* concentrations in surface water resources and 55% in drinking water resources of the Kabul River Basin while considering the hydro-climatic variability. Surface air and water temperature, precipitation and discharge of Kabul river were positively correlated with the *E. coli* concentrations in water resources • Anticipated climate-change, with projected increased precipitation and surface air temperature, is expected to increase *E. coli* concentrations in water resources of the Kabul River Basin. Waterborne pathogens like *Cryptosporidium* may respond in the same way to climate-change and this could be a threat to the population living in this region.
RQ2	What would be the impact of climate-change on return periods of floods in the Kabul River Basin? (Chapter 3)	• This study revealed substantial changes in the hydro- climatology of the Kabul River Basin. Four climate models were selected. MIROC5 and EC-EARTH project consistently increase mean monthly temperature, precipitation, and river flows, while INM-CM4 projects a slight decline for all three variables. IPSL-CM5A shows a slight increase in temperature and river flows, while its precipitation response is similar for RCP4.5 and increases for RCP8.5. • The return periods of floods will be reduced in most cases. Depending on the scenario, climate model and period in the future, present day 1-in-a-50-year events could in the future occur from once in every 3 years to once in every 24 years.
RQ3	How can the observed *E. coli* concentrations be adequately modelled with the SWAT model? (Chapter 4)	• The SWAT model includes point and non-point contaminant sources of *E. coli* and compared well with the observed *E. coli* concentrations. • Humans and livestock are the major contributors to *E. coli* concentration in water resources followed by agricultural activities (where livestock manure is used as fertilizer) in the Kabul River Basin. Based on pathogen source estimation point sources were identified to be the major source of pollution (44%), while nonpoint (diffuse) sources (22%) were slightly less significant and above Warsak (upstream) Kabul river also contributes (34%) to the concentration.

RQ4	What are the future projections of *E. coli* concentrations in Kabul river, when comprehensive socioeconomic and climate-change scenario analysis is performed? (Chapter 5)	• We developed two future scenarios based on existing scenarios developed for the IPCC and own assumptions. Future scenarios were found to have a significant impact on *E. coli* concentrations in the Kabul River Basin. A less sustainable future resulted in a deterioration of microbial water quality due to socioeconomic changes, such as higher population growth, land use change and variations in precipitation patterns. However, microbial water quality was found to improve under a sustainable climate and an improved sewage treatment. • In Scenario_1, *E. coli* concentrations are reduced to 70% and 81% by respectively the 2050s and 2100s. When additional treatment is added to Scenario_1, the *E. coli* concentrations are reduced even further to 5%, 7% and 0.6% of the current concentrations when additional tertiary treatment, manure treatment or both have been applied respectively. • In Scenario_2 *E. coli* concentrations are strongly increased to 158% and 201% by respectively the 2050s and 2100s. All climate models show the substantial variability and elevated concentration of *E. coli* in water resources of the Kabul River Basin.

6.2 *E.coli* concentrations and hydro-climatic variables (RQ1)

RQ1 was answered in two steps to assess surface water quality in Pakistan. First, water samples were collected to determine the *E. coli* concentrations during flooding and non-flooding periods. This sampling considered the sources and pathways of the different contaminations. Water samples were collected from the selected locations (Figure 2.1). The measured *E. coli* concentrations (mean ranges from 4.70 to 4.90 log cfu per 100ml) for all the sampling locations along the Kabul river. The measured *E. coli* concentration in the drinking water samples (mean ranges from 2.10 to 2.22 log cfu per 100ml). High *E. coli* concentrations are observed. Sanitation facilities are lacking and raw sewage and manure are dumped directly into the Kabul river and these sources contaminate the river's surface water. Microorganisms probably also enter surface waters through runoff from agricultural land (vegetables, cereal crops etc.), where not only livestock manure is used to fertilize land (Medema and Schijven, 2001). The river's surface water is generally unfit to swim or bath. Our samples show that during the sampling period, all samples exceeded the USEPA bathing water-quality standards (Kinzelman et al., 2003) and all samples violated the WHO criteria (WHO, 2008a) for drinking water quality.

Second, I statistically analysis the impact of hydro-climatic variables on *E. coli* concentrations. The detailed sources and pathways through which the water resources are contaminated, were comprehensively combined into a conceptual diagram (Figure 1.3). The statistical (linear-regression) model and a correlation analysis were applied to quantify these impacts (Chapter 2). For the microbial analysis, surface and drinking water samples were collected and climatic data were acquired from the Pakistan Meteorological Department and the Water and Power Development Authority Pakistan (i.e. Precipitation, surface air temperature and Kabul river discharge). Chapter 2 identified several statistically significant variables that best explained the observed variation in *E. coli* contamination levels. The surface air and water temperature, precipitation and river discharge data were positively correlated with the *E. coli* concentrations. This shows that precipitation increases the surface runoff and this transports pathogens to the river. Water temperature was not expected to be positively correlated because a temperature increase enhances the inactivation rate of *E.*

coli. For example, Garzio-Hadzick et al. (2010) also found that increasing surface-air temperatures stimulate the inactivation of *E. coli*. But my study area was situated in the subtropics where high surface air temperatures and monsoon precipitation coincide (i.e. from June to September). Other studies from tropical zones, however, also reported a positive correlation with water temperature for example, (Huang et al., 2008; Kelly-Hope et al., 2007; Koirala et al., 2008). After a heavy precipitation event, the *E. coli* concentrations swell quickly to high levels and remain high for several days (Hong et al., 2010). The relationship with river discharge is likely attributed to similar mechanisms as the precipitation effect, but discharge also depends on bacteria sources from the upstream areas (Kelman et al., 2011; Vermeulen and Hofstra, 2014).

The regression model explains 61% of the *E. coli* variability in surface water and 55% in drinking water resources, even when other factors, such as location and land-use variables are ignored. The waterborne pathogens behave similarly and concentrations could increase with increased precipitations and surface-air temperatures.

6.3 Climate-change Impacts and Future Floods in the Kabul River Basin (RQ2)

RQ2 was answered by application of the SWAT hydrological model coupled with a flood frequency model (i.e. HEC-SSP) that was used to analyse the flood frequency using the state-of-the-art IPCC climate-change scenarios for the near future (i.e. 2031-2050) and far future (i.e. 2081-2100). These scenarios were adopted for the Kabul River Basin to better understand the future climate-change impacts on projected floods and their return periods. Flood frequency analysis is generally performed to plan and design hydrological structures (e.g. dams and bridges) but can also provide information on flood return periods. The most recent global climate-models (GCMs), that can provide data for future flood frequency analysis, were prepared by the Fifth Coupled Model Intercomparison Project (Taylor et al., 2012). This CMIP5 daily climate data from four selected GCMs were downloaded from the Earth System Grid Federation Portal (http://cmip-pcmdi.llnl.gov/cmip5/; https://esgf-data.dkrz.de/search/cmip5/). Lutz et al. (2016b) evaluated most of the available GCMs for the HKH region and suggested the eight most suitable GCMs for this region. Four selected GCM data were downscaled using the delta change approach with quantile to quantile correction (Liu et al. (2015)), which is used often in this field. The method is also in line with Arnell et al (2003)… etc (Arnell et al., 2003; Diaz-Nieto and Wilby, 2005; Hawkins et al., 2013; Räty et al., 2014), who also use the delta change method for bias correction of GCM data in their studies. The downscaled data were used to project future Kabul river flows. These are obtained by forcing the SWAT model with bias-corrected GCM output for the RCP4.5 and RCP8.5 climate-change scenarios. Summer monsoon precipitation, snow and glacier melt contribute to the peak flows of the Kabul river (Lutz et al., 2014). Surface-air temperature is expected to rise in the future periods for both RCPs and in all GCMs, except for the INM-CM4 GCM that shows slight decline. Increased temperatures that result from bias corrected GCM data agree well with those of other studies (IPCC, 2013; Ridley et al., 2013; Wiltshire, 2014). Ridley (2013) and Wiltshire (2014) also project precipitation increases in the HKH region during this century. Dey et al. (1989) strongly related temperature and snow-melt in the Kabul basin, while Archer (2003) argued that summer river flows mainly stem from the snow-melt of preceding winter snowfall in the Kunhar and Swat basins (sub-basins of the Kabul River Basin). This argument is also supported by more recent studies (Lutz et al., 2014; Yu et al., 2013). The GCMs MIROC5 and EC-EARTH consistently increase precipitation and river discharge, while these two variables slightly decline in the INM-CM4 GCM. The IPSL-CM5A GCM slightly increases temperature and river discharge, while its precipitation is neglectable for RCP4.5 and increases for RCP8.5. Results indicate an increase in extreme precipitation events (Figure 3.7). Increased extreme precipitation events are major flood triggers in the HKH region (Din et al., 2014; Hartmann and Buchanan, 2014; Wang et al., 2011). These anticipated climate changes in the Kabul River Basin thus very likely lead to more floods with shorter return periods (Figure 3.8).

The largest recorded flood occurred in 2010, influenced a large region and killed over two thousand people. The threshold level for floods is 2800 $m^3 s^{-1}$ at Nowshera in the Kabul river (FFC, 2016). The historical flows (determined for the period 1981 to 2015) reveal that this threshold level is exceeded more often than every second year. The exceptionally high and most devastating flood of 2010 was a one in fifty-year event. The flood-frequency analysis shows that the present day's one-in-a-fifty-year event could occur in the future between once in every 3 years (i.e. EC-EARTH and MIROC5 GCM and RCP4.5) to once in every 24 years (i.e. IPSL GCM and RCP8.5). To conclude, the future climate-change projections substantially increase precipitation and surface air temperature in the Kabul river and consequently its future discharge. This enhances the regional floods and reduces return periods. In the future we may thus expect more waterborne diseases in the Kabul River Basin due to these larger and more frequent floods and continued lack of sanitation facilities and manure management. This analysis of current and future river flows can help decision makers and water managers to anticipate climate-change impacts and adaptation possibilities in the basin. Our approach to project flood-return periods can be helpful for similar regions that have similar hydro-climatological conditions.

6.4 Modelling *E. coli* Fate and Transport (RQ3)

RQ3 was answered with the calibrated SWAT bacterial model. The scientific literature shows that different hydrological models have been coupled with a bacterial module to understand the fate and transport of bacteria (*E. coli*) in different watersheds worldwide. For example, Hydrological Simulation Program FORTRAN (HSPF). This model was developed and applied to model fate and transport of faecal indicators in watersheds to quantify the concept of the Total Maximum Daily Load and source identification (Benham et al., 2006) also an improved version of WATFLOOD (Wu et al., 2009) was used to simulate fate and transport of pathogens for the purpose of source identification in watersheds used for drinking water supply and to determine the magnitude of fecal indicator contributions from sediment. Both the SWAT bacterial model and HSPF simulate water quality in a watershed. The SWAT model's ability to evaluate microbial risk has been assessed to be high compared to the HSPF model (Benham et al., 2006). Most of the bacterial modelling studies were done in developed countries (e.g. Bougeard et al., 2011; Coffey et al., 2010a; Ferguson et al., 2007; Fraser et al., 1998; Haydon and Deletic, 2006b; Kim et al., 2010; Medema et al., 2009b; Parajuli et al., 2009).

The Kabul River Basin receives intense monsoon precipitation. This together with snow and glacier melt, produces flash floods (Chapter 3). During floods the concentration of *E. coli* increases in surface water resources as manure and raw sewage flushes into the river. We, for the first time, performed bacterial modelling study in a developing country. Our model results agree well with our measured *E. coli* concentrations (Figure 4.2). Based on the pathogen source estimations, point sources are identified to be the most important pollution source, including pollution from upstream areas (above measuring point Warsak) followed by non-point sources (Figures 4.3 & 4.4). Our validated bacterial model is then used to simulate projected *E. coli* concentrations in a comprehensive scenario analysis (Chapter 5). Different factors that determine the fate and transport of *E. coli* are selected using a one-at-a-time sensitivity analysis (Table 4.2). We found that the Bacteria Soil Partition Coefficient (*BACTKDQ),* Bacterial Percolation Coefficient *(BACTMIX)* and Temperature adjustment factor for bacteria Die-off/growth (*THBACT)* are the most sensitive parameters..

Uncertainty is present during every step in any environmental study. Uncertainty can be due to inherent randomness, measurement errors, systematic errors due to sampling biases (these are difficult to quantify), natural variability and model uncertainty (Narsimlu et al., 2015). For example some relevant processes could be omitted from a model; calibrations may not provide satisfying results or input data are lacking. The SWAT model performs satisfactorily for the Kabul River Basin. The model slightly overestimates low concentrations and underestimated high concentrations. The underestimation of the peak concentrations is directly related to the underestimation of peak discharge, as explained in Chapter 3. Such underestimation is standard in hydrological modelling (Döll et al., 2003). The outcomes of the study showed that, overall, total loads from direct sewage and manure discharges and upstream concentrations (above Warsak) had the largest contribution to the total concentrations (34% and 44% respectively) (see Figure 4.3). Point sources of pollution are a serious issue in the Kabul River Basin. This is in line with other studies, such as Liu and Chan (2015) who conducted a modelling study for faecal coliform at the Danshui River basin of northern Taiwan and found that during low water discharges the faecal coliform concentrations from point sources were substantial. Chin et al. (2009) also found high concentrations of fecal coliforms in the river in Georgia, US, due to direct inputs of pollutants. Likewise, Arnone and Walling (2007) discussed the concerns by water resource managers that inadequately treated sewage compellingly contribute to microbiological pollutants in water resources. Hooda et al. (2000) reviewed the water-quality concerns and found that especially point sources from local livestock sheds are a serious source in UK livestock farming areas. Non-point emissions were also important, as it contributed around 22%. Comparatively lower contribution from non-point sources were also observed by Ouattara et al. (2013) and Sokolova et al. (2012). Modelling the fate and transport of faecal contaminants can be useful approach in water quality and health risk assessments. Such knowledge can help to protect populations that are exposed to contaminated water in developing countries. The validated SWAT model is an effective tool to assess future impacts of socioeconomic developments and climate change on *E. coli* fate, transport and dynamics. Our study also emphasises the need for wastewater treatment and manure management before dumping (waste) into the Kabul river.

6.5 Impact of Socioeconomic Development and Climate Change on *E. coli* Concentrations (RQ4)

RQ4 was answered with the help of two scenarios developed by myself that are based on the new scenario matrix proposed to IPCC by a team of scientists in 2006 (Kriegler et al., 2012; O'Neill et al., 2014) and own assumptions. The matrix integrates the socioeconomic SSPs with the various radiative-forcing levels of the RCPs to create comprehensive new scenarios. To assess the impacts of socioeconomic development and climate change on *E. coli* concentrations in the surface waters of the Kabul river, we implemented the scenarios in the model. Although this is standard practice in most other climate impact studies, it has thus far not been applied to assess changes in *E. coli* or waterborne pathogen concentrations.

Scenario_1 links the socioeconomic narrative by SSP1 with the radiative forcing of RCP4.5, while Scenario_2 integrates SSP3 and RCP8.5. Although these two scenarios are based on existing IPCC scenarios, we included specific assumptions for the Kabul River Basin. These assumptions are in line with the original narratives. We simulated the scenarios for the periods 2040 to 2060 (i.e. the 2050s) and 2080 to 2100 (i.e. the 2100s). Scenario_1 focusses on sustainability that leads to a limited climate change (i.e. adheres to the well-below 2^0C target from the Paris Agreement). Strong socioeconomic improvements, including wastewater treatment, are required for the Kabul River Basin when the rest of the world limits its greenhouse gas emissions. Scenario_2 portrays large changes in climate by combining RCP8.5 with SSP3. In the SSP3 society, greenhouse gas emissions are not high enough to reach the radiative forcing of 8.5 W/m^2 (Riahi et al., 2011). Currently, most of rural and urban populations in the Kabul River Basin are connected to a sewage system. For both scenarios we assume that the percentages connected will increase from 90 to 99%. At present, no wastewater treatment exists, partly because the 2010 floods destroyed the available plants (EPA-KP, 2014) and primary treatment plants are currently constructed to treat the collected wastewater from the sewage systems. We assumed excellent and poor wastewater and manure treatment for 2050s and 2100s for Scenario_1 and Scenarion_2 respectively (see Table 5.1).

The impacts of changes in hydro-climatic variables on *E. coli* concentrations were explained in Chapter 2. Few studies (e.g. Moss et al., 2010) assessed how impacts of climate-change influence human lifestyles, changes in technology, and allow policies to cope with these impacts. Vörösmarty et al. (2010) for example, analysed the importance of freshwater stress in the face of climate change and found that three quarters of the world's population is at risk of local or regional increased water insecurity. Concentrations of *E. coli* in water resources vary with changing socioeconomic factors and climate-change impacts. Projected changes in *E. coli* concentrations in the Kabul river depend on the climate-change impacts on river flows besides changes in precipitation and surface air temperature (as explained in Chapter 3).

Mostly the socioeconomic scenarios have been developed for the world as a whole. Translating these global scenarios to national, regional or local scenarios to assess impacts, adaptation possibilities and vulnerabilities is difficult because every region is unique. For this study, two plausible combinations are made of the global SSPs and RCPs. These combinations make sense for the Kabul River Basin. For example, the SSP3 rivalry narrative in the Kabul River Basin could be plausible when the world then keeps emitting carbon as in SSP5 ('Taking the Highway"), then RCP8.5 could well be possible. Combining SSP1 and RCP4.5 is also a plausible choice for the world, now including the Kabul River Basin. More importantly, combinations that are impossible globally, range among the most interesting, challenging, and useful ones regionally (Kok, 2016). Such analyses are primarily required in those areas where projected climate-change impacts are on the extreme.

Our pioneering scenario research is presented in Chapter 5, where the new scenario matrix is used for a scenario analysis of microbial water quality. For Scenario_1, the *E. coli* concentrations are reduced compared to current concentrations. We further elaborated three variants of Scenario_1as Scenario_1a,1b and 1c. *E. coli* concentrations are reduced to a greater extent in all three variants when compared to Scenario_1 and current concentrations. We assumed that wastewater is treated with tertiary treatment systems and that manure is collected from livestock sheds treated through either compositing or aerobic digesters prior to using it as organic fertilizer on agricultural fields. In contrast, Scenario_2 has very limited wastewater and manure handling services. Here the concentrations of *E. coli* increased more than the current concentrations. Projected concentrations of *E. coli* along with variability among the different GCMs for the Kabul River Basin were observed. All GCMs showed half to one log increase in *E. coli* concentration for future. The *E. coli* concentrations are reduced substantially throughout the year for Scenario_1 for all GCMs for 2050s and 2100s, while for Scenario_2 they always increased. Our scenario analysis suggests that these changes are mostly, but not entirely, driven by population increases. Other elements, such as expanded agricultural activities, limited sanitation and wastewater treatment, also substantially contribute to elevated *E. coli* concentrations in the Kabul River Basin. This study emphasises and advocates the need for substantial improvements in sanitation, wastewater and manure treatment systems in the Kabul River Basin to assure future *E. coli* concentrations in water resources inside the limits of WHO and USEPA for drinking and bathing water quality. Our study's outcome can provide information to support decisions by policy makers and water managers, who want to reduce *E. coli* concentrations and the risk of waterborne diseases in the Kabul River Basin.

6.6 Implication of this thesis for health risks through waterborne disease

In the Kabul River Basin waterborne diseases are a serious problem and were the third leading cause of death in children under the age of five and elderly people (Azizullah et al 2011). One of the major reasons for such high incidence of waterborne diseases is the use of contaminated water. The river's water is used for bathing, washing and other domestic uses, and the surface water quickly replenishes the ground water that is used for drinking. This basin is vulnerable to frequent annual flash floods that are aggravated by climate change. Such floods increases the exposure of the population to contaminated surface water and collect additional pollution from flooded land and sewage systems. In this thesis we studied the microbial water quality of the river basin, with the motivation that waterborne disease is a large problem in this basin and that the impacts of global environmental change (i.e. changes in land use, climate and biodiversity) on the waterborne diseases is currently ignored. Although assessing health risks was not the thesis' objective, it is an additional argument to perform this research. I reflect in this Section on how my research can be used to address these risks.

Numerous pathogens, such as viruses and harmful bacteria, are present in water resources. In Pakistan, pathogens, such as S*almonella typhi, Para typhi, Vibrio Cholera, Enterococci and Cryptosporidium,* are common in surface water resources. Analysing the concentrations of these pathogens requires time and financial resources, and those are sparse in developing countries, like Pakistan. Thus, to analyse the microbiological contamination in water resources, indicators, like faecal coliform and E. coli, are frequently used. Although E. coli is not pathogenic, their presence indicates the potential presence of other harmful microorganisms (Odonkor and Ampofo, 2013). Therefore, E. coli can easily be linked to the health risks. For instance, in The Netherlands swimming health risk can be related to E. coli concentrations (Joosten et al., 2017). However, such relationships are not directly applicable to Pakistan, because the risks profiles strongly differ here.

Chapter 2 revealed that the *E. coli* concentrations in Kabul basin's drinking and surface water are always extremely high. Doubtlessly, also many pathogens are present in the water. The present health risks are therefore already very high. This is indicated by the observed high burden of diarrhoeal disease (Nabeela et al., 2014). The floods in the basin generally also lead to diarrheal disease outbreaks. For Scenario_2 (where no or limited sanitation and manure management facilities are present), E. *coli* concentrations increase considerably. As pathogens follow comparable fate and transport routes, pathogen concentrations can also be expected to increase. When the health risks are already very high, a small increase in concentrations due to climate change (i.e. an increase in floods) may not alter these risks much. However, in Chapter 5 (see Section 5.3 and Figure 5.3) we simulated a huge reduction in the concentrations for other scenarios. The concentrations can be reduced to below bathing water standards (i.e. 235 cfu/100ml (USEPA, 2001)) and when exposure remains the same, the dose and therefore the health risks may also decrease. Under these conditions, however, increased flooding due to climate change can increase the risks under such possible improved management conditions. Our study explores this.

To further study the health risk due to waterborne pathogens in Kabul river. ideally, a similar study for pathogens would be performed to measure and model their concentrations. These concentrations can then be direct input in Quantitative Risk Assessment (QMRA) models that enable quantification of the risk and burden of disease for the population. Unfortunately, measuring pathogens is expensive. An approach could be to use the currently calibrated model for bacterial pathogens in the basin. However, you would want to do that first for a basin with large data availability to ensure this is a reasonable approach. The use of the approach for pathogens and the link to QMRA are avenues to explore further.

6.7 Scientific contribution

E. coli concentration in water resources are associated with climate variabilities (i.e. variability in precipitation and surface-air temperature). For example, an increase in precipitation events, *E. coli* concentrations will likely be reduced due to dilution. But if the precipitation is high and causes floods that flushes the untreated sewage and manure via increased surface and sub-surface runoff, these floods will eventually increase the *E. coli* concentrations. Decreases in precipitation may also increase *E. coli* concentrations as most microorganisms are continuously emitted from wastewater and manure (Atherholt et al., 1998). Likewise, increased surface-air temperature probably increase the inactivation rate of these pathogens (An et al., 2002b). However, the net effect of climate variability on pathogen concentrations remains unclear (Vermeulen and Hofstra, 2013). In a few studies, a single climate variable (either precipitation or surface-air temperature) is linked with the *E. coli* concentrations (see, for example, Table

1.1). This PhD thesis quantifies the combined effect of socioeconomic development and climate-change impacts on *E. coli* concentrations in the Kabul River Basin. Robust estimates were obtained with both statistics (regression modelling and correlation analysis) and process-based modelling (SWAT). This study successfully assessed the effects of climate change in river flows and *E. coli* concentrations.

Chapter 3 explains that the Kabul River Basin is confronted with natural calamities like floods, which cause loss of human and animal lives, and economic losses. Due to climate change, this basin would expect more intense and frequent floods in the future. An integrated modelling approach with flood-frequency analysis were applied for the first time for the Kabul River Basin with the latest climate-change scenarios. Climate-change impacts on flood return periods in the low lying regions of the Kabul River Basin were demonstrated in Chapter 3. These results are relevant to the broader scientific community, as they show that regional impacts from other studies (Lutz et al., 2014), who suggest declining future discharges in the Kabul river, are probably unfounded when the hydrology is thoroughly assessed at the river-basin scale. To better understand the fate and transport of microbial contaminants in surface water of the lower Kabul River Basin, the combined hydrological-bacterial model was applied. I initiated modelling the fate and transport of *E. coli* considering point and non-point sources to explain the contribution of these sources to contamination levels. The data availability for *E. coli* modelling in the Kabul River Basin is poor. I and my co-authors have used the SWAT bacterial model, and their results provides valuable information on *E. coli*'s fate and transport. Our research opens the field for new scientific endeavours to apply such models to simulate trends in harmful pathogenic microorganisms (e.g. *Cryptosporidium and Rotavirus)*, in regions where sanitation facilities are poor and surface water is highly polluted. Our modelling study for the Kabul River Basin can be considered as a successful example for other studies. Lessons learned from such variety of new studies will increase the usefulness for water managers and policy makers, and guide them in managing their watersheds.

Model-based scenarios proved to be a useful tool to assess the impact of socioeconomic development and climate change on *E. coli* concentrations in surface water. Despite their inherent uncertainties and limitation, models help to estimate future changes in the concentration of waterborne pathogens under changing conditions (e.g. due to climate-change) (Hofstra, 2011). The Kabul River Basin is densely populated. Most people are not connected to a sewage treatment system and raw sewage is directly discharged into the Kabul river. Concurrently, local farmers apply large quantities of manure on their croplands as fertilizer. This elevates the concentrations of microorganisms in different water resources through direct manure release and also indirectly via runoff from agricultural fields. We implemented the most recent scenarios (a combination of socioeconomic developments and climate-change pathways as developed for IPCC) in a calibrated and validated hydrological-bacterial model for projected *E. coli* concentrations in the Kabul River Basin (explained in Chapter 5). We demonstrated that future advances in waste-water and manure treatment will convincingly reduce *E. coli* concentrations in the Kabul River Basin.

Overall, our study is one of the first regional studies that assesses the impacts of socioeconomic development and climate change on *E. coli* concentrations in surface water. The subsequent changes in water quality by micro-organisms is quantified by statistical and process-based modelling approaches. The comprehensive scenario analysis coupled with the modelling results help to identify the research gaps in water contamination sources, the linking pathways to surface water and the consequently emerging waterborne diseases. These gaps are addressed in the next section.

6.8 Future outlook for further research

This PhD thesis focused on socioeconomic development and climate-change impacts on *E. coli* concentrations in the Kabul River Basin and determined potential future trends in waterborne diseases. . Water quality has gained little attention compared to water availability issues. Nevertheless, water quality issues are serious and need to be addressed. Around two-thirds of the population has access to municipal water supply but this is not always safe (National Water Policy Pakistan, 2012; Vörösmarty et al., 2010). The focus of this thesis was limited to assessing socioeconomic developments and climate changes on the *E. coli* concentrations in Kabul river. The research has highlighted many new research avenues to explore.

The current water quality in the Kabul River Basin is poor and unfit for drinking, because manure and untreated sewage are directly released to the surface water.

The potable water supplied in the basin is violating the standards set by WHO (Chapter 2). Consumption of contaminated water increases the risk of waterborne disease outbreaks. The prevalence of waterborne disease is influenced by climate change and hydro-climatic variables. In Chapter 2, a linear regression model was used to understand the relationship between hydro-climatic variables and *E. coli* concentration in these local water resources. Using different statistical methods (e.g. time series analysis or multivariate tests) in addition to the linear regression model to get more insight in the relationship between hydro-climatic variables and *E. coli* or waterborne pathogens, such as *Cryptosporidium* in surface and drinking water resources. Pakistan is a developing country and confronted with annually recurring floods that cause huge losses (Chapter 3) due to poor flood management and inadequate flood protection plans. The National Engineering Services of Pakistan (NESPAK) have developed the new fourth national flood protection plan in collaboration with the Dutch Deltares Institute (Ebrahim, 2015). In Chapter 3, the return periods of floods were calculated by using four GCMs to understand the impact of anticipated climate-change. We used their climate-change scenarios for a flood frequency analysis by downscaling the GCMs data. Our selected and further developed hydrological-bacterial model provided robust results, even with the limited datasets. Our results will help water managers to understand how future floods may change and therefore help them to effectively manage them, by anticipating more frequent flood return period. Our results can likely be extrapolated to other part of the country. Further research can be conducted with the application of flood routing models, like HEC-RAS, to make flood indentation maps for projected floods. In addition, if data would become available at a higher spatial and temporal resolutions and over longer periods, more detailed models (e.g. VIC (Liang et al., 1994) and SPHY (Terink et al., 2015)) can be applied. These models could, for example, simulate the changes in the flows from snow and glacier melt better. Additionally, instead of deriving regional scenarios from global scenario developments and models, Regional Climate Models could also be used to better represent anticipated climate-change in this region. Unfortunately, no regional model that used the RCP scenarios exist for the Kabul River Basin.

Chapter 4 applied the SWAT bacterial model to model the fate and transport of *E. coli* in surface water resources of the Kabul river. The model's simulations agreed well with observed concentrations. The surface-water resources are contaminated by many different water quality variables, such as waterborne pathogens (Hofstra, 2011; Hofstra et al., 2013; Vermeulen and Hofstra, 2013), heavy metals (Förstner and Wittmann, 2012; UNEP, 2016), nutrients (Strokal and Kroeze, 2013), plastics (Koelmans et al., 2016) and chemicals (de Almeida Azevedo et al., 2000). Similar to *E. coli*, all these pollutants are transported through water resources (Schwarzenbach et al., 2006). Human activities substantially contribute to microbial pollution by, for example, rapid urbanisation and disposal of raw sewage because the lack of sanitation (Vermeulen et al., 2015a; Vermeulen et al., 2015b). Agricultural activities also contribute to increased water pollution, such as leaching of nutrients (Nitrogen and Phosphorus) and pesticides via surface and sub-surface runoff (Chau et al., 2015). The final water polluting sector is industry, whose waste contains heavy metals (e.g. zinc, cadmium, lead and arsenic) and chemicals. Retention times differ for different pollutants. For example, the retention time of heavy metals is long as they are absorbed in sediments, while pathogens are short lived. These different retention times must be considered in integrated water pollution modelling for river basins. The calibrated SWAT model can also be applied to model pathogenic microorganism (Coffey et al., 2010a; Coffey et al., 2013) and the other pollutants, such as chemicals, heavy metals and nutrients. The SWAT has thus far not been used for plastics.

Application of the SWAT bacterial model for current and future water-quality assessment in a large-scale basin, such as the Indus river is also important to get more realistic projections of large-scale water availability and quality for water managers. Abbaspour et al. (2015) applied the SWAT model from a small watershed scale to the continental scale (Europe). They simulated both water quantity and water quality aspects (but no pathogens). Likewise, several other studies (Arnold et al., 1998b; Cao et al., 2006; Lobmeyr et al., 1999; Santhi et al., 2001b; Srinivasan et al., 1998; Thampi et al., 2010b) used SWAT for water quantity (hydrology) for various river basins in the world. However, no applications exist for the Indus River Basin. The Kabul river originates from Afghanistan and enters Pakistan and sustains the life of people in both countries. It is one of the largest tributary of the Indus river. Due to lack of sanitation facilities and manure management, the Kabul river carries large concentrations of microbiological contaminants to the Indus river. Different modelling studies on water quantity have been conducted for the Indus River Basin (Akhtar et al., 2008; Faran Ali and de Boer, 2008; Fowler and Archer, 2006; Immerzeel et al., 2010; Lutz et al., 2014; Rajbhandari et al., 2015; Tahir et al., 2011). Expanding ours water quality modelling to the whole of the Kabul river (upstream and downstream) and the Indus River Basin would be interesting. Microorganisms, pollutants and other water quality parameters should be included. Such integrated water quantity and quality study will help to identify current and future environmental and health issues and find solutions to them. This is urgently needed for the Indus River Basin.

In Chapter 5, we used the new scenario matrix approach and integrated the socioeconomic developments with climate-change pathways to project future *E. coli* concentrations in surface waters. In the low laying areas of the Kabul River Basin, wastewater treatment plants are present (i.e. only primary treatment level) but after the extreme 2010 flood most plants are broken and currently under construction. Several new projects are also in progress. These include installation of wastewater treatment facilities (mostly primary treatment levels) and manure treatment facilities. Such facilities are now legally mandatory to improve the water quality in the region (Bagel, 2016; EPA-KP, 2014). Figure 6.2 exemplifies the divergence between the current and future status with improved sanitation, sewer water and manure treatment facilities. These facilities contribute to reduced *E. coli* concentrations. These pathways can solve compromised water qualities. Figure 6.2 also demonstrates that in current situation where no or limited sanitation and manure management facilities are present (i.e. Scenario_2) the *E. coli* concentrations are high and violate the USEPA and WHO standards. The modelling and scenario approach is flexible and can easily be specified for sub-basins, extended to other waterborne pathogens and other pollutants. Also other scenarios can be analysed, such as more detailed land-use change scenarios and management scenarios. Additionally, the approach can serve as a basis for the development of improved climate-change adaptation plans, which can maybe limit future floods damages and preserve water resources from flood-driven contamination. The tool could be adapted so that it can be utilized by regional experts to assess health risks.

6.9 This thesis' impact

This PhD thesis provides a base for devising optimal coping strategies that are essential for the sustainability of hydrological resources under socioeconomic development and climate change. The results of our research are extremely important to assess alternative water-quality management options. It supplements past research on the impact of climate-change on water resources and incorporates current water-quality aspects. This study adds and generates new information and knowledge for the Kabul River Basin (e.g. simulated and observed *E. coli* concentrations, comprehensive scenario analysis and quantified impacts of floods on *E. coli* concentrations). In addition, the outcome of our scenario analysis can likely be used for other pollutants, such as nutrients, pesticides and heavy metals. Our results are important for policy makers and could help them to understand how to protect people from microbiological pollution impacts. Our study can be a step to improve the water quality of the Kabul River Basin by providing guidelines for water managers. It helps to select options and develop plans and strategies. For example, several regions of the HKH are affected by climate change. This alters regional river flows (Lutz et al., 2014). The Kabul River Basin is part of the HKH and is exposed to frequent flooding (Chapter 3). Earlier floods increased health burdens to the Pakistani of the low lying regions of the Kabul River Basin. This PhD project is very relevant to the national and international priority areas for research on the impact of socioeconomic development and climate change on waterborne pathogens concentrations in water resources. Considering the future return periods of floods water resource managers can propose better flood protection plans to safeguard surface-water qualities in the basin. Likewise, sources of pollution (explained in Chapter 4) can be monitored and compared to trends in the sustainability scenarios of Chapter 5. It can provide guidance, so that many more people would have access to good quality of water and sanitation. This helps to achieve several of the Sustainable Development Goals.

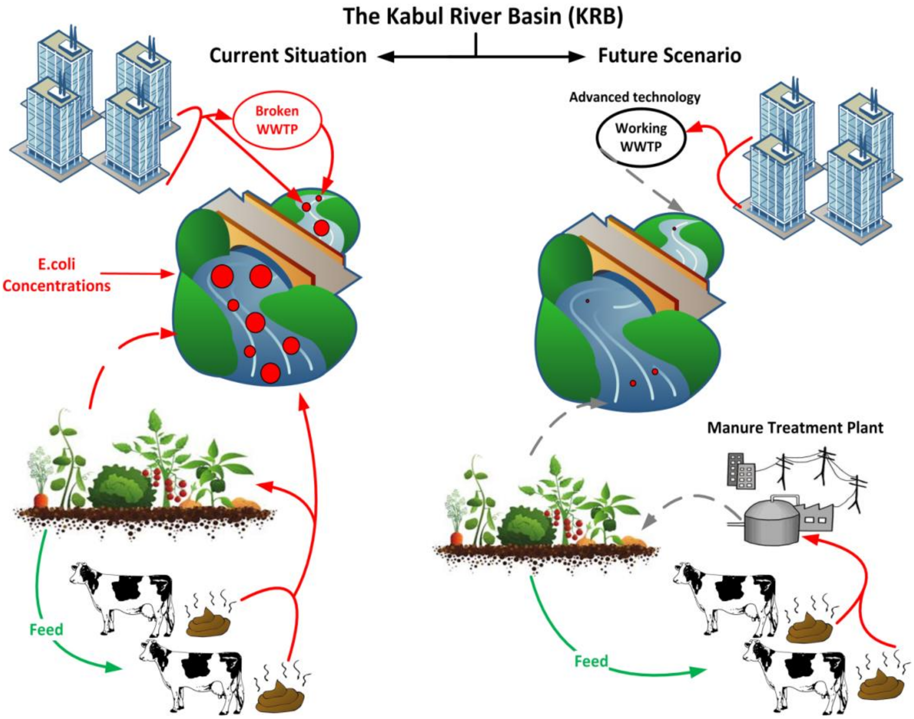

Figure 6.1: Scenarios illustrate future conditions in the Kabul River Basin. Reduced *E. coli* concentrations are caused by improved sanitation, sewer water and manure handling. The Red lines indicate direct contaminations; grey lines the runoff or treated wastewater to water bodies; and green arrows shows the animal feeds.

During our study, we limit ourselves to develop the science only, but we highlighted the potential important link to policies on water quality. The studied Kabul River Basin needs wastewater-treatment and manure-management policies. This is one of the reason that microbial contamination in water resources and burden of waterborne diseases are high. This PhD thesis could serve as a start to make new regional advances and technologies that would help to improve the existing surface water quality. Currently, I am exploring opportunities to continue study these issues in close collaboration with policy makers and regional NGOs to ensure that my PhD findings can be utilized to design new policies in, for example, designing new hydrological structures (e.g. dams, reservoirs) that store excess water during flood events. Such stored water can be used later to overcome the water scarcity issues of my country. Likewise, the findings of this thesis would be helpful to identify and monitor microbiological pollution sources, and to reduce pollutants, to collect wastewater and get it treated by tertiary treatment plants, and develop manure applications for fertilizers after treatment in anaerobic digesters. All this would reduce microorganisms reaching water resources. I hope that my PhD research serves as an example for other regions which flood annually and where microbiological water pollution monitoring is needed to improve future water quality.

Bibliography

Abbaspour, K., 2012. SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs-A User Manual EAWAG: Swiss Federal Institute of Aquatic Science and Technology. Zurich, Switzerland.

Abbaspour, K., Johnson, C., Van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone Journal 3(4) 1340-1352.

Abbaspour, K.C., 2015. SWAT-CUP Manual - Soil and Water Assessment Tool.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology 524(0) 733-752.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology 333(2) 413-430.

Abia, A.L.K., Ubomba-Jaswa, E., Momba, M.N.B., 2015. Impact of seasonal variation on Escherichia coli concentrations in the riverbed sediments in the Apies River, South Africa. Science of The Total Environment 537 462-469.

Adingra, A., Kouadio, A., Blé, M., Kouassi, A., 2012a. Bacteriological analysis of surface water collected from the Grand-Lahou lagoon, Cte divoire. African Journal of Microbiology Research 6(13) 3097-3105.

Adingra, A.A., Kouadio, A.N., Ble, M.C., Kouassi, A.M., 2012b. Bacteriological analysis of surface water collected from the Grand-Lahou lagoon, Cote d'ivoire. African Journal of Microbiology Research 6(13) 3097-3105.

Ahmad, I., Tang, D., Wang, T., Wang, M., Wagan, B., 2015. Precipitation trends over time using Mann-Kendall and Spearman's rho tests in Swat River Basin, Pakistan. Advances in Meteorology 2015.

Ahmed, K., Khandkar, Z., Lawrence, A., Macdonald, D., Islam, M., 2002. An investigation of the impact of on-site sanitation on the quality of groundwater supplies in two peri-urban areas of Dhaka, Bangladesh. Assessing risk to groundwater from on-site sanitation:

scientific review and case studies. British Geological Survey Commissioned Report CR/02 N 79.

Akhtar, M., Ahmad, N., Booij, M., 2008. The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios. Journal of Hydrology 355(1) 148-163.

Ali, A., 2013. Indus Basin floods: mechanisms, impacts, and management. Asian Development Bank.

Ali, M., Kim, D.R., Yunus, M., Emch, M., 2013. Time series analysis of cholera in Matlab, Bangladesh, during 1988-2001. Journal of Health, Population and Nutrition 31(1) 11.

Ali, S., Li, D., Congbin, F., Khan, F., 2015. Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. Environmental Research Letters 10(1).

Amisah, S., Nuamah, P.A., 2014. Spatial and Temporal Variations in Microbiological Water Quality of the River Wiwi in Kumasi, Ghana. Water Quality, Exposure and Health 6(4) 217-224.

An, Y.-J., Kampbell, D.H., Breidenbach, G.P., 2002a. Escherichia coli and total coliforms in water and sediments at lake marinas. Environmental Pollution 120(3) 771-778.

An, Y.-J., Kampbell, D.H., Peter Breidenbach, G., 2002b. *Escherichia coli* and total coliforms in water and sediments at lake marinas. Environmental Pollution 120(3) 771-778.

Angel, M.V., 1982. Ocean trench Conservation. The Environmentalist 2(1) 1-17.

Aragonés, L., López, I., Palazón, A., López-Úbeda, R., García, C., 2016. Evaluation of the quality of coastal bathing waters in Spain through fecal bacteria Escherichia coli and Enterococcus. Science of The Total Environment 566 288-297.

Archer, D., 2003. Contrasting hydrological regimes in the upper Indus Basin. Journal of Hydrology 274(1) 198-210.

Arendt, A., A. Bliss, T. Bolch, J.G. Cogley, A.S. Gardner, J.-O. Hagen, R. Hock, M. Huss, G. Kaser, C., Kienholz, W.T.P., G. Moholdt, F. Paul, V. Radić, L. Andreassen, S. Bajracharya, N.E. Barrand, M., Beedle, E.B., R. Bhambri, I. Brown, E. Burgess, D. Burgess, F. Cawkwell, T. Chinn, L.

Copland,, B. Davies, H.D.A., E. Dolgova, L. Earl, K. Filbert, R. Forester, A.G. Fountain, H. Frey, B. Giffen, N., Glasser, W.Q.G., S. Gurney, W. Hagg, D. Hall, U.K. Haritashya, G. Hartmann, C. Helm, S. Herreid, I., Howat, G.K., T. Khromova, M. König, J. Kohler, D. Kriegel, S. Kutuzov, I. Lavrentiev, R. LeBris,, S.Y. Liu, J.L., W. Manley, R. Marti, C. Mayer, E.S. Miles, X. Li, B. Menounos, A. Mercer, N. Mölg, P., Mool, G.N., A. Negrete, T. Nuimura, C. Nuth, R. Pettersson, A. Racoviteanu, R. Ranzi, P., Rastner, F.R., B. Raup, J. Rich, H. Rott, A. Sakai, C. Schneider, Y. Seliverstov, M. Sharp, O., Sigurðsson, C.S., R.G. Way, R. Wheate, S. Winsvold, G. Wolken, F. Wyatt, N. Zheltyhina, 2015. Randolph Glacier Inventory-A Dataset of Global Glacier Outlines: Version 5.0, pp. 1-63.

Arino, O., Ramos, J., Kalogirou, V., Defourny, P., Achard, F., 2010. GlobCover 2009 (http://due.esrin.esa.int/files/GLOBCOVER2009_Validation_Report_2.2.pdf) Accessed 10 May 2016.

Arnell, N., Hudson, D., Jones, R., 2003. Climate change scenarios from a regional climate model: Estimating change in runoff in southern Africa. Journal of Geophysical Research: Atmospheres 108(D16).

Arnold, B.F., Colford, J.M., 2007. Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. The American journal of tropical medicine and hygiene 76(2) 354-364.

Arnold, J., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2009. Soil and Water Assessment Tool (input /output document).

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998a. Large area hydrologic modeling and assessment - Part I: Model development. J. Am. Water Resour. As. 34(1) 73-89.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998b. Large area hydrologic modeling and assessment part I: Model development1. Wiley Online Library.

Arnone, R.D., Walling, J.P., 2007. Waterborne pathogens in urban watersheds. Journal of Water and Health 5(1) 149-162.

Arshad Ali, N.B., Shahid Iqbal, Jamila Begum, Ghazala Nosheen, 2012. Assessment of quality of water in Kabul River, Nowshera city, Pakistan. ARCH. ENVIRON. SCI. 6 62-67.

ASAE, 2005. Manure Production and Characteristics, Americal Society of Agricultural Engineering.

Atherholt, T.B., LeChevallier, M.W., Norton, W.D., Rosen, J.S., 1998. Effect of rainfall of Giardia and Crypto. American Water Works Association. Journal 90(9) 66.

Auld, H., MacIver, D., Klaassen, J., 2004. Heavy rainfall and waterborne disease outbreaks: the Walkerton example. Journal of Toxicology and Environmental Health, Part A 67(20-22) 1879-1887.

Azizullah, A., Khattak, M.N., Richter, P., Hader, D.P., 2011. Water pollution in Pakistan and its impact on public health--a review. Environ Int 37(2) 479-497.

Baffaut, C., Benson, V.W., 2003. A bacteria TMDL for Shoal Creek using SWAT modeling and DNA source tracking. Total Maximum Daily Load TMDL Environmental Regulations II 35-40.

Bagchi, S., 2007. Disease outbreaks in wake of Southeast Asia floods. Canadian Medical Association Journal 177(6) 560-560.

Bagel, P.M., 2016. Pakistan Radies National Water Policy Program, the thirdpole.

Baker, J., 1980. Agricultural areas as nonpoint sources of pollution. Agricultural areas as nonpoint sources of pollution. 275-311.

Balvanshi, A., Tiwari, H.L., 2014. A Comprehensive Review of Runoff Estimation by the Curve Number Method. International Journal of Innovative Research in Science, Engineering and Technology 3 17480-17485.

Bengston, L., 1981. Snowmelt-generated runoff in urban areas, Urban stormwater hydraulics and hydrology: proceedings of the Second International Conference on Urban Storm Drainage, held at Urbana, Illinois, USA, pp. 15-19.

Benham, B.L., Baffaut, C., Zeckoski, R.W., Mankin, K.R., Pachepsky, Y.A., Sadeghi, A.M., Brannan, K.M., Soupir, M.L., Habersack, M.J., 2006. Modeling bacteria fate and transport in watersheds to support TMDLs. Transactions of the ASABE 49(4) 987-1002.

Bergstrom, S., 1976. Development and application of a conceptual runoff model for Scandinavian catchments.

Beven, K., Kirkby, M., Schofield, N., Tagg, A., 1984. Testing a physically-based flood forecasting model (TOPMODEL) for three UK catchments. Journal of Hydrology 69(1-4) 119-143.

Beven, K., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrological Sciences Journal 24(1) 43-69.

Bi, P., Cameron, A.S., Zhang, Y., Parton, K.A., 2008. Weather and notified Campylobacter infections in temperate and sub-tropical regions of Australia: an ecological study. Journal of Infection 57(4) 317-323.

Boithias, L., Choisy, M., Souliyaseng, N., Jourdren, M., Quet, F., Buisson, Y., Thammahacksa, C., Silvera, N., Latsachack, K., Sengtaheuanghoung, O., Pierret, A., Rochelle-Newall, E., Becerra, S., Ribolzi, O., 2016. Hydrological Regime and Water Shortage as Drivers of the Seasonal Incidence of Diarrheal Diseases in a Tropical Montane Environment. PLoS Neglected Tropical Diseases 10(12).

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., 2012. The state and fate of Himalayan glaciers. Science 336(6079) 310-314.

Borris, M., Leonhardt, G., Marsalek, J., Osterlund, H., Viklander, M., 2016. Source-Based Modeling Of Urban Stormwater Quality Response to the Selected Scenarios Combining Future Changes in Climate and Socioeconomic Factors. Environ Manage 58(2) 223-237.

Bougeard, M., Le Saux, J.C., Pérenne, N., Baffaut, C., Robin, M., Pommepuy, M., 2011. Modeling of Escherichia coli fluxes on a catchment and the impact on coastal water and shellfish quality1. Wiley Online Library.

Boxall, A.B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P.D., Haygarth, P.M., Hutchinson, T., Kovats, R.S., Leonardi, G., 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. Environmental Health Perspectives 117(4) 508.

Boyer, D.G., Kuczynska, E., Fayer, R., 2009. Transport, fate, and infectivity of Cryptosporidium parvum oocysts released from manure and leached through macroporous soil. Environmental Geology 58(5) 1011-1019.

Brenner, K.P., Rankin, C.C., Roybal, Y.R., Stelma, G.N., Scarpino, P.V., Dufour, A.P., 1993. New medium for the simultaneous detection of total coliforms and Escherichia coli in water. Applied and environmental microbiology 59(11) 3534-3544.

Bright, E.A., Coleman, P.R., Rose, A.N., Urban, M.L., 2011. LandScan 2010, digital raster data. Oak Ridge National Laboratory: Oak Ridge, TN.

Britton, E., Hales, S., Venugopal, K., Baker, M.G., 2010. Positive association between ambient temperature and salmonellosis notifications in New Zealand, 1965–2006. Australian and New Zealand journal of public health 34(2) 126-129.

Bruhn, L., Wolfson, L., 2007. Citizens Monitoring Bacteria: A Training Manual for Monitoring E. coli. Michigan State University, East Lansing, MI.

BSKP, 2016. Bureau of Statistics, Khyber Pukhtunkhwa, Agricultural report. Institure of Statistics.

Bureau of Statistics, 2016. Khyber Pukhtoonkhwa Bureau of Statistics (http://kpbos.gov.pk/) Accessed 18th July 2016: Khyber Pukhtoonkhwa.

Bush, K.F., O'Neill, M.S., Li, S., Mukherjee, B., Hu, H., Ghosh, S., Balakrishnan, K., 2014. Associations between extreme precipitation and gastrointestinal-related hospital admissions in Chennai, India. Environmental Health Perspectives 122(3) 249-254.

Byappanahalli, M.N., Shively, D.A., Nevers, M.B., Sadowsky, M.J., Whitman, R.L., 2003. Growth and survival of Escherichia coli and enterococci populations in the macro-alga Cladophora (Chlorophyta). FEMS Microbiology Ecology 46(2) 203-211.

Campbell-Lendrum, D., Bertollini, R., Neira, M., Ebi, K., McMichael, A., 2009. Health and climate change: a roadmap for applied research. The Lancet 373(9676) 1663-1665.

Campbell, G.S., 1985. Soil physics with BASIC: transport models for soil-plant systems. Elsevier.

Cann, K., Thomas, D.R., Salmon, R., Wyn-Jones, A., Kay, D., 2013a. Extreme water-related weather events and waterborne disease. Epidemiology and Infection 141(4) 671.

Cann, K., Thomas, D.R., Salmon, R., Wyn-Jones, A., Kay, D., 2013b. Extreme water-related weather events and waterborne disease. Epidemiology and Infection 141(04) 671-686.

Cann, K.F., Thomas, D.R., Salmon, R.L., Wyn-Jones, A.P., Kay, D., 2013c. Extreme water-related weather events and waterborne disease. Epidemiology and Infection 141(4) 671-686.

Cao, W., Bowden, W.B., Davie, T., Fenemor, A., 2006. Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrological Processes 20(5) 1057-1073.

Carlton, E.J., Eisenberg, J.N.S., Goldstick, J., Cevallos, W., Trostle, J., Levy, K., 2014. Heavy rainfall events and diarrhea incidence: The role of social and environmental factors. American Journal of Epidemiology 179(3) 344-352.

Carr, G.M., Neary, J.P., 2008. Water quality for ecosystem and human health. UNEP/Earthprint.

Chau, N., Sebesvari, Z., Amelung, W., Renaud, F., 2015. Pesticide pollution of multiple drinking water sources in the Mekong Delta, Vietnam: evidence from two provinces. Environmental Science and Pollution Research 22(12) 9042-9058.

Checkley, W., Epstein, L.D., Gilman, R.H., Figueroa, D., Cama, R.I., Patz, J.A., Black, R.E., 2000. Effects of EI Niño and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children. The Lancet 355(9202) 442-450.

Cherkauer, K.A., Bowling, L.C., Lettenmaier, D.P., 2003. Variable infiltration capacity cold land process model updates. Global and Planetary Change 38(1) 151-159.

Chin, D.A., Sakura-Lemessy, D., Bosch, D.D., Gay, P.A., 2009. Watershed-Scale Fate and Transport of Bacteria. ASABE 52(1) 145-154.

Cho, K.H., Pachepsky, Y.A., Kim, J.H., Kim, J.-W., Park, M.-H., 2012. The modified SWAT model for predicting fecal coliforms in the Wachusett Reservoir Watershed, USA. Water Research 46(15) 4750-4760.

Choi, I., Munster, C., Victor, D., White, R., Stewart, G., Richards, C., 2005. Calibration and validation of the SWAT model on a field-scale watershed for turfgrass sod establishment. Watershed Management to Meet Water Quality Standards and Emerging TMDL (Total Maximum Daily Load) Proceedings. ASAE Publication(701P0105).

Chou, W.C., Wu, J.L., Wang, Y.C., Huang, H., Sung, F.C., Chuang, C.Y., 2010. Modeling the impact of climate variability on diarrhea-associated diseases in Taiwan (1996-2007). Sci Total Environ 409(1) 43-51.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R.K., Kwon, W., Laprise, R., 2007. Regional climate projections. Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11 847-940.

Chu, Y., Tournoud, M., Salles, C., Got, P., Perrin, J., Rodier, C., Caro, A., Troussellier, M., 2013. Spatial and temporal dynamics of bacterial contamination in South France coastal rivers: focus on in-stream processes during low flows and floods. Hydrological Processes.

Clasen, T., Schmidt, W.-P., Rabie, T., Roberts, I., Cairncross, S., 2007. Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. Bmj 334(7597) 782.

Cloete, T.E., 2004. Microbial waterborne pathogens. IWA Publishing, London.

Cloete, T.E., Cloete, T.E., 2004. Microbial waterborne pathogens. Iwa publishing.

Coffey, R., Cummins, E., Bhreathnach, N., Flaherty, V., Cormican, M., 2010a. Development of a pathogen transport model for Irish catchments using SWAT. Agricultural Water Management 97(1) 101-111.

Coffey, R., Cummins, E., Cormican, M., Flaherty, V.O., Kelly, S., 2007. Microbial exposure assessment of waterborne pathogens. Human and Ecological Risk Assessment 13(6) 1313-1351.

Coffey, R., Cummins, E., O' Flaherty, V., Cormican, M., 2010b. Pathogen Sources Estimation and Scenario Analysis Using the Soil and Water Assessment Tool (SWAT). Human and Ecological Risk Assessment: An International Journal 16(4) 913-933.

Coffey, R., Dorai-Raj, S., O'Flaherty, V., Cormican, M., Cummins, E., 2012. Modeling of Pathogen Indicator Organisms in a Small-Scale Agricultural Catchment Using SWAT. Human and Ecological Risk Assessment: An International Journal 19(1) 232-253.

Coffey, R., Dorai-Raj, S., O'Flaherty, V., Cormican, M., Cummins, E., 2013. Modeling of Pathogen Indicator Organisms in a Small-Scale Agricultural Catchment Using SWAT. Human and Ecological Risk Assessment: An International Journal 19(1) 232-253.

Collins, R., Rutherford, K., 2004. Modelling bacterial water quality in streams draining pastoral land. Water Research 38(3) 700-712.

Conn, K.E., Habteselassie, M.Y., Blackwood, A.D., Noble, R.T., 2012. Microbial water quality before and after the repair of a failing onsite wastewater treatment system adjacent to coastal waters. Journal of Applied Microbiology 112(1) 214-224.

Cutler, D., Miller, G., 2005. The role of public health improvements in health advances: the twentieth-century United States. Demography 42(1) 1-22.

Dastager, S.G., Borade, S., Dhawde, R., Maloo, A., Gajbhiye, S., Ram, A., 2015. Assessment of enteric bacterial indicators and correlation with physico-chemical parameters in Veraval coast, India.

de Almeida Azevedo, D., Lacorte, S.l., Vinhas, T., Viana, P., Barceló, D., 2000. Monitoring of priority pesticides and other organic pollutants in river water from Portugal by gas chromatography–mass spectrometry and liquid chromatography–atmospheric pressure chemical ionization mass spectrometry. Journal of Chromatography A 879(1) 13-26.

Delpla, I., Baurès, E., Jung, A.V., Thomas, O., 2011. Impacts of rainfall events on runoff water quality in an agricultural environment in temperate areas. Science of The Total Environment 409(9) 1683-1688.

Desai, A., Rifai, H.S., Petersen, T.M., Stein, R., 2011. Mass balance and water quality modeling for load allocation of Escherichia coli in an urban watershed. Journal of Water Resources Planning and Management 137(5) 412-427.

Devia, G.K., Ganasri, B.P., Dwarakish, G.S., 2015. A Review on Hydrological Models. Aquatic Procedia 4 1001-1007.

Dey, B., Sharma, V., Rango, A., 1989. A test of snowmelt-runoff model for a major river basin in western Himalayas. Hydrology Research 20(3) 167-178.

Diaz-Nieto, J., Wilby, R.L., 2005. A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the River Thames, United Kingdom. Climatic Change 69(2) 245-268.

Din, K., Tariq, S., Mahmood, A., Rasul, G., 2014. Temperature and Precipitation: GLOF Triggering Indicators in Gilgit-Baltistan, Pakistan. Pakistan Journal of Meteorology 10(20).

Döll, P., Kaspar, F., Lehner, B., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology 270(1) 105-134.

Dorner, S.M., Anderson, W.B., Slawson, R.M., Kouwen, N., Huck, P.M., 2006. Hydrologic modeling of pathogen fate and transport. Environmental Science & Technology 40(15) 4746-4753.

Dorner, S.M., Huck, P.M., Slawson, R.M., 2004. Estimating potential environmental loadings of Cryptosporidium spp. and Campylobacter spp. from livestock in the Grand River watershed, Ontario, Canada. Environmental Science & Technology 38(12) 3370-3380.

Du, T., Xiong, L., Xu, C.-Y., Gippel, C.J., Guo, S., Liu, P., 2015. Return period and risk analysis of nonstationary low-flow series under climate change. Journal of Hydrology 527 234-250.

Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B.C., Riahi, K., 2014. A new scenario framework for climate change research: background, process, and future directions. Climatic Change 122(3) 363-372.

Ebrahim, Z.T., 2015. Pakistan's New Plan to Embrace Floods https://www.dawn.com/news/1197349, The Dawn. Dawn News Agency: Pakistan.

Effler, E., Isaäcson, M., Arntzen, L., Heenan, R., Canter, P., Barrett, T., Lee, L., Mambo, C., Levine, W., Zaidi, A., 2001. Factors contributing to the emergence of Escherichia coli O157 in Africa. Emerging infectious diseases 7(5) 812.

Engel, B., Storm, D., White, M., Arnold, J., Arabi, M., 2007. A hydrologic/water quality model application 1. JAWRA Journal of the American Water Resources Association 43 1223-1236.

EPA-KP, 2014. AN ACT to provide for the protection, conservation , rehabilitation and improvement of the environment, for the preventation and control of pollution, and promotion of sustainable development in the Province of the Khyber Pakhtunkhwa. Provincial Assembly KP: Govenment Press, Khyber Pukhtunkhwa.

Faran Ali, K., de Boer, D.H., 2008. Factors controlling specific sediment yield in the upper Indus River basin, northern Pakistan. Hydrological Processes 22(16) 3102-3114.

Fegan, N., Vanderlinde, P., Higgs, G., Desmarchelier, P., 2004. The prevalence and concentration of Escherichia coli O157 in faeces of cattle from different production systems at slaughter. Journal of Applied Microbiology 97(2) 362-370.

Ferguson, C., Croke, B., Beatson, P., Ashbolt, N., Deere, D., 2007. Development of a process-based model to predict pathogen budgets for the Sydney drinking water catchment. Journal of Water and Health 5(2) 187-208.

Fernández, M.Á.L., Bauernfeind, A., Jiménez, J.D., Gil, C.L., El Omeiri, N., Guibert, D.H., 2009. Influence of temperature and rainfall on the evolution of cholera epidemics in Lusaka, Zambia, 2003–2006: analysis of a time series. Trans R Soc Trop Med Hyg 103(2) 137-143.

Fewtrell, L., Kaufmann, R.B., Kay, D., Enanoria, W., Haller, L., Colford, J.M., 2005. Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. The Lancet infectious diseases 5(1) 42-52.

FFC, 2016. Federal Flood Comission Annual Flood Report http://www.ffc.gov.pk/ (Accessed 6 May 2017).

Fonseca, A., Botelho, C., Boaventura, R.A., Vilar, V.J., 2014. Integrated hydrological and water quality model for river management: A case study on Lena River. Science of The Total Environment 485 474-489.

Förstner, U., Wittmann, G.T., 2012. Metal pollution in the aquatic environment. Springer Science & Business Media.

Fowler, H., Archer, D., 2006. Conflicting signals of climatic change in the Upper Indus Basin. Journal of climate 19(17) 4276-4293.

Frankenberger, J., 1995. E.Coli and Indiana Lakes and Streams (https://engineering.purdue.edu/SafeWater/watershed/ecoli.html) Accessed 7 May 2017. Purdue Entension Safe Water.

Franson, M.A.H., 1995. American public health association American water works association water environment federation. Methods 6 84.

Fraser, R.H., Barten, P.K., Pinney, D.A., 1998. Predicting stream pathogen loading from livestock using a geographical information system-based delivery model. Journal of Environmental Quality 27(4) 935-945.

Frischmann, P., 2011. Water Strategy Final Kabul River Basin Report: Australia.

Funari, E., Manganelli, M., Sinisi, L., 2012. Impact of climate change on waterborne diseases. Ann Ist Super Sanità 48(4) 473-487.

Garzio-Hadzick, A., Shelton, D., Hill, R., Pachepsky, Y., Guber, A., Rowland, R., 2010. Survival of manure-borne E. coli in streambed sediment: Effects of temperature and sediment properties. Water Research 44(9) 2753-2762.

Gassman, P.W., Arnold, J.J., Srinivasan, R., Reyes, M., 2010. The worldwide use of the SWAT Model: Technological drivers, networking impacts, and simulation trends, 21st Century Watershed Technology: Improving Water Quality and Environment Conference Proceedings, 21-24 February 2010, Universidad EARTH, Costa Rica. American Society of Agricultural and Biological Engineers, p. 1.

Gerba, C.P., Smith, J.E., 2005. Sources of pathogenic microorganisms and their fate during land application of wastes. Journal of Environmental Quality 34(1) 42-48.

Gibson, C., Stadterman, K., States, S., Sykora, J., 1998. Combined sewer overflows: a source of Cryptosporidium and Giardia? Water Science and Technology 38(12) 67-72.

Glass, R.I., Becker, S., Huq, M.I., Stoll, B.J., Khan, M., Merson, M.H., Lee, J.V., Black, R.E., 1982. Endemic cholera in rural Bangladesh, 1966–1980. American Journal of Epidemiology 116(6) 959-970.

Graham, J.P., Polizzotto, M.L., 2013. Pit latrines and their impacts on groundwater quality: a systematic review. Environmental Health Perspectives 121.

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. Journal of Hydrologic Engineering 4(2) 135-143.

Hagemann, S., Chen, C., Clark, D., Folwell, S., Gosling, S.N., Haddeland, I., Hannasaki, N., Heinke, J., Ludwig, F., Voss, F., 2013. Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth System Dynamics 4 129-144.

Hamby, D., 1994. A review of techniques for parameter sensitivity analysis of environmental models. Environmental monitoring and assessment 32(2) 135-154.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied engineering in agriculture 1(2) 96-99.

Hartmann, H., Buchanan, H., 2014. Trends in extreme precipitation events in the indus River Basin and flooding in Pakistan. Atmosphere-Ocean 52(1) 77-91.

Hashizume, M., Armstrong, B., Hajat, S., Wagatsuma, Y., Faruque, A.S., Hayashi, T., Sack, D.A., 2007. Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups. International journal of epidemiology 36(5) 1030-1037.

Hashizume, M., Faruque, A.S., Wagatsuma, Y., Hayashi, T., Armstrong, B., 2010. Cholera in Bangladesh: climatic components of seasonal variation. Epidemiology 21(5) 706-710.

Hashizume, M., Wagatsuma, Y., Faruque, A.S., Hayashi, T., Hunter, P.R., Armstrong, B., Sack, D.A., 2008. Factors determining vulnerability to diarrhoea during and after severe floods in Bangladesh. Journal of Water and Health 6(3) 323-332.

Hata, A., Katayama, H., Kojima, K., Sano, S., Kasuga, I., Kitajima, M., Furumai, H., 2014. Effects of rainfall events on the occurrence and detection efficiency of viruses in river water impacted by combined sewer overflows. Science of The Total Environment 468-469 757-763.

Hawkins, E., Osborne, T.M., Ho, C.K., Challinor, A.J., 2013. Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. Agricultural and forest meteorology 170 19-31.

Haydon, S., Deletic, A., 2006a. Development of a coupled pathogen-hydrologic catchment model. Journal of Hydrology 328(3) 467-480.

Haydon, S., Deletic, A., 2006b. Development of a coupled pathogen-hydrologic catchment model. Journal of Hydrology 328(3–4) 467-480.

Heathman, G., Larose, M., 2007. Influence of scale on SWAT model calibration for streamflow, MODSIM 2007 International Congress on Modelling and Simulation, Christchurch, New Zealand, pp. 2747-2753.

Herrador, B.R.G., De Blasio, B.F., MacDonald, E., Nichols, G., Sudre, B., Vold, L., Semenza, J.C., Nygård, K., 2015. Analytical studies assessing the association between extreme precipitation or temperature and drinking water-related waterborne infections: a review. Environmental Health 14(1) 29.

Hofstra, N., 2011. Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. Current Opinion in Environmental Sustainability 3(6) 471-479.

Hofstra, N., Bouwman, A.F., Beusen, A.H.W., Medema, G.J., 2013. Exploring global Cryptosporidium emissions to surface water. Science of The Total Environment 442(0) 10-19.

Hofstra, N., Vermeulen, L.C., 2016a. Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. International Journal of Hygiene and Environmental Health 219(7, Part A) 599-605.

Hofstra, N., Vermeulen, L.C., 2016b. Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. Int J Hyg Environ Health 219(7) 599-605.

Hong, H., Qiu, J., Liang, Y., 2010. Environmental factors influencing the distribution of total and fecal coliform bacteria in six water storage reservoirs in the Pearl River Delta Region, China. Journal of Environmental Sciences 22(5) 663-668.

Hooda, P., Edwards, A., Anderson, H., Miller, A., 2000. A review of water quality concerns in livestock farming areas. Science of The Total Environment 250(1) 143-167.

Howard, G., Calow, R., Macdonald, A., Bartram, J., 2016. Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action, Annual Review of Environment and Resources, pp. 253-276.

Huang, D., Guan, P., Guo, J., Wang, P., Zhou, B., 2008. Investigating the effects of climate variations on bacillary dysentery incidence in northeast China using ridge regression and hierarchical cluster analysis. BMC Infectious Diseases 8(1) 1.

Hutchison, M., Walters, L., Avery, S., Synge, B., Moore, A., 2004. Levels of zoonotic agents in British livestock manures. Letters in Applied Microbiology 39(2) 207-214.

Ibekwe, A.M., Lesch, S., Bold, R., Leddy, M., Graves, A., 2011. Variations of indicator bacteria in a large urban watershed. Transactions of the ASABE 54(6) 2227-2236.

Ihekweazu, C., Barlow, M., Roberts, S., Christensen, H., Guttridge, B., Lewis, D., Paynter, S., 2006. Outbreak of E. coli O157 infection in the south west of the UK: risks from streams crossing seaside beaches. Eurosurveillance 11(4) 128-130.

IIASA., ISRIC., ISSCAS., FAO., JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Immerzeel, W., Pellicciotti, F., Bierkens, M., 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nature geoscience 6(9) 742-745.

Immerzeel, W.W., Van Beek, L.P., Bierkens, M.F., 2010. Climate change will affect the Asian water towers. Science 328(5984) 1382-1385.

Inam, A., Clift, P.D., Giosan, L., Tabrez, A.R., Tahir, M., Rabbani, M.M., Danish, M., 2007. The geographic, geological and oceanographic setting of the Indus River. Large rivers: geomorphology and management 333-345.

IPCC, 2013. The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. K., Tignor, M., Allen, SK, Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, PM, Eds 1535.

IPCC, 2007a. :Summary for Policymakers In: Solomon, S., D. Qin, M. Manning,Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.) (Ed.), In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Iqbal, M.S., Ahmad, M.N., Hofstra, N., 2017a. The Relationship between Hydro-climatic variables and E. coli concentrations in surface and drinking water resources in the Kabul River Basin Pakistan. Wageningen University and Research Centre: Wageningen.

Iqbal, M.S., Dahri, Z.H., Querner, E.P., Khan, A., Hofstra, N., 2017b. The Impact of Climate Change on Flood Frequency and Intensity in the Kabul River Basin. Wageningen University and Research Centre: Wageningen.

Iqbal, M.S., Hofstra, N., 2017c. Escherichia Coli Fate and Transport Modelling in the Kabul River Basin. . Wageningen University and Research Centre: Wageningen.

Islam, M., Sharker, M., Rheman, S., Hossain, S., Mahmud, Z., Uddin, A., Yunus, M., Osman, M., Ernst, R., Rector, I., 2009. Effects of local climate variability on transmission dynamics of cholera in Matlab, Bangladesh. Trans R Soc Trop Med Hyg 103(11) 1165-1170.

Islam, M.M.M., Hofstra, N., Islam, A., 2017a (Submitted). The Impact of Environmental Variables on Faecal Indicator Bacteria in the Betna River Basin, Bangladesh.

Jalliffier-Verne, I., Leconte, R., Huaringa-Alvarez, U., Heniche, M., Madoux-Humery, A.-S., Autixier, L., Galarneau, M., Servais, P., Prévost, M., Dorner, S., 2016. Modelling the impacts of global change on concentrations of Escherichia coli in an urban river. Advances in Water Resources In Press.

Jamieson, R., Gordon, R., Joy, D., Lee, H., 2004. Assessing microbial pollution of rural surface waters: A review of current watershed scale modeling approaches. Agricultural Water Management 70(1) 1-17.

Jiang, L., O'Neill, B.C., 2015. Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change.

Jin, L., Whitehead, P., Sarkar, S., Sinha, R., Futter, M., Butterfield, D., Caesar, J., Crossman, J., 2015. Assessing the impacts of climate change and socioeconomic changes on flow and phosphorus flux in the Ganga river system. Environmental Science: Processes & Impacts 17(6) 1098-1110.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., Arnaud, Y., 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. Nature 488(7412) 495-498.

Kääb, A., Treichler, D., Nuth, C., Berthier, E., 2015. Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya. The Cryosphere 9(2) 557-564.

Kay, D., Wyer, M., Crowther, J., Stapleton, C., Bradford, M., McDonald, A., Greaves, J., Francis, C., Watkins, J., 2005. Predicting faecal indicator fluxes using digital land use data in the UK's sentinel Water Framework Directive catchment: The Ribble study. Water Research 39(16) 3967-3981.

Kc, S., Lutz, W., 2014. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change.

Kelly-Hope, L.A., Alonso, W.J., Thiem, V.D., Anh, D.D., DO GIA, C., Lee, H., Smith, D.L., Miller, M.A., 2007. Geographical distribution and risk factors associated with enteric diseases in Vietnam. The American journal of tropical medicine and hygiene 76(4) 706-712.

Kelman, I., Tryland, I., Robertson, L., Blankenberg, A.-G.B., Lindholm, M., Rohrlack, T., Liltved, H., 2011. Impact of rainfall on microbial contamination of surface water. International Journal of Climate Change Strategies and Management 3(4) 361-373.

Khalid, S., Rehman, S., Alam, S., Ali, F., 2013. Hydro-meteorological characteristics of Chitral River basin at the peak of the Hindukush range. Natural Science 5(9) 987-992.

Khalid;, S., Rehman;, S.U., Alam;, S., Ali., F., 2013. Hydro-meteorological characteristics of Chitral River basin at the peak of the Hindukush range. Natural Science 5(9) 987-992.

Khan, A.D., Ghoraba, S., Arnold, J., Luzio, M., 2014. Hydrological Modeling of Upper Indus Basin and Assessment of Deltaic Ecology. International Journal of Modern Engineering Research (IJMER) 4(1) 73-85.

Khan, M.S., Mohmand, Z.H., 2011. Environmental Effects of Hazardous Flood of 2010 in the province of Khyber Pakhtunkawa (KPK), Pakistan, its Causes and Management. Science International (Lahore) 23(2) 147-152.

Khan, S., Shahnaz, M., Jehan, N., Rehman, S., Shah, M.T., Din, I., 2012. Drinking water quality and human health risk in Charsadda district, Pakistan. Journal of cleaner production.

Khan;, A.D., Ghoraba;, S., Arnold;, J.G., Luzio., M.D., 2014. Hydrological Modeling of Upper Indus Basin and Assessment of Deltaic Ecology. International Journal of Modern Engineering Research (IJMER) 4(1) 73-85.

Kim, J.-W., Pachepsky, Y.A., Shelton, D.R., Coppock, C., 2010. Effect of streambed bacteria release on E. coli concentrations: Monitoring and modeling with the modified SWAT. Ecological Modelling 221(12) 1592-1604.

King, K.W., Arnold, J., Bingner, R., 1999. Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT. Transactions of the ASAE 42(4) 919-925.

Kinzelman, J., Ng, C., Jackson, E., Gradus, S., Bagley, R., 2003. Enterococci as indicators of Lake Michigan recreational water quality: comparison of two methodologies and their impacts on public health regulatory events. Applied and environmental microbiology 69(1) 92-96.

Knisel, W., 1980. A field scale model for chemical, runoff, and erosion from agricultural management systems. Conservation Service Report 26. US Department of Agriculture, Washington, DC.

Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. Environmental Science & Technology 50(7) 3315-3326.

Koirala, S.R., Gentry, R.W., Perfect, E., Schwartz, J.S., Sayler, G.S., 2008. Temporal variation and persistence of bacteria in streams. Journal of Environmental Quality 37(4) 1559-1566.

Kok, K., 2016. Multi-scale integration and synthesis of scenarios and adaptation narratives. ECONADAPT Deliverable 1.5. Wageningen University, Wageningen.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socioeconomic scenarios for climate change analysis: A new approach based on shared socioeconomic pathways. Global Environmental Change-Human and Policy Dimensions 22(4) 807-822.

Lashkaripour, G.R., Hussaini, S., 2008. Water resource management in Kabul river basin, eastern Afghanistan. The Environmentalist 28(3) 253-260.

Lee, J.-Y., Wang, B., 2014. Future change of global monsoon in the CMIP5. Climate Dynamics 42(1-2) 101-119.

Leemans, R., Cramer, W.P., 1991. The IIASA database for mean monthly values of temperature, precipitation, and cloudiness on a global terrestrial grid. INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, Laxenburg, Austria.

Leemans, R., Monserud, R., Solomon, A., 1992. A global biome model based on plant physiology and dominance, soil properties and climate. Journal of Biogeography 19 11734.

Levy, K., Woster, A.P., Goldstein, R.S., Carlton, E.J., 2016. Untangling the Impacts of Climate Change on Waterborne Diseases: A Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. Environmental Science and Technology 50(10) 4905-4922.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research: Atmospheres 99(D7) 14415-14428.

Liu, C., Hofstra, N., Leemans, R., 2015. Preparing suitable climate scenario data to assess impacts on local food safety. Food Research International 68 31-40.

Liu, W.-C., Chan, W.-T., 2015. Modeling fecal coliform contamination in a tidal Danshuei River estuarine system. Science of The Total Environment 502(0) 632-640.

Liu, Y., Zhang, C., Wang, X., 2009. Simultaneous detection of enteric bacteria from surface waters by QPCR in comparison with conventional bacterial indicators. Environmental monitoring and assessment 158(1-4) 535.

Lloyd, S.J., Kovats, R.S., Armstrong, B.G., 2007. Global diarrhoea morbidity, weather and climate. Climate Research 34(2) 119.

Lobmeyr, M., Lohmann, D., Ruhe, C., 1999. An application of a large scale conceptual hydrological model over the Elbe region. Hydrology and Earth System Sciences Discussions 3(3) 363-374.

Long, W.F., Lloyd, S., Zhang, F., Li, Q., Huang, H., Yi, C., 2016. Microbial contamination and environmental factors of drinking water source for households with children under five years old in two South China ethnic groups. Water Science and Technology: Water Supply 16(6) 1514-1518.

Lutz, A.F., Immerzeel, W., Kraaijenbrink, P., Shrestha, A.B., Bierkens, M.F., 2016a. Climate Change Impacts on the Upper Indus Hydrology: Sources, Shifts and Extremes. PLoS ONE 11(11) e0165630.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B., Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change 4(7) 587-592.

Lutz, A.F., ter Maat, H.W., Biemans, H., Shrestha, A.B., Wester, P., Immerzeel, W.W., 2016b. Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. International Journal of Climatology 36 3988-4005.

Madsen, H., Pearson, C.P., Rosbjerg, D., 1997. Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events: 2. Regional modeling. Water Resources Research 33(4) 759-769.

Maidment, D.R., 1993. Handbook of hydrology. McGraw-Hill Inc., the University of Michigan.

Mancini, J.L., 1978. Numerical estimates of coliform mortality rates under various conditions. Journal (Water Pollution Control Federation) 2477-2484.

Mara, D., Horan, N.J., 2003. Handbook of water and wastewater microbiology. Academic press, Great Britian.

Marsalek, J., Rochfort, Q., 2004. Urban wet-weather flows: sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. Journal of Toxicology and Environmental Health, Part A 67(20-22) 1765-1777.

Martinez, G., Pachepsky, Y.A., Whelan, G., Yakirevich, A.M., Guber, A., Gish, T.J., 2014. Rainfall-induced fecal indicator organisms transport from manured fields: Model sensitivity analysis. Environ Int 63 121-129.

Matsuda, F., Ishimura, S., Wagatsuma, Y., Higashi, T., Hayashi, T., Faruque, A., Sack, D., Nishibuchi, M., 2008. Prediction of epidemic cholera due to Vibrio cholerae O1 in children younger than 10 years using climate data in Bangladesh. Epidemiology and Infection 136(01) 73-79.

Meals, D.W., Braun, D.C., 2006. Demonstration of Methods to Reduce Runoff from Dairy Manure Application Sites. Journal of Environmental Quality 35(4) 1088-1100.

Medema, G., Bahar, M., Schets, F., 1997. Survival of Cryptosporidium parvum, Escherichia coli, faecal enterococci and Clostridium perfringens in river water: influence of temperature and autochthonous microorganisms. Water Science and Technology 35(11) 249-252.

Medema, G., Schijven, J., 2001. Modelling the sewage discharge and dispersion of Cryptosporidium and Giardia in surface water. Water Research 35(18) 4307-4316.

Medema, G., Teunis, P., Blokker, M., Davison, A., Charles, P., Loret, J.F., Wilson, J., 2009a. Risk Assessment of Cryptosporidium in Drinking-water (World Health Organization): World Health Organization Geneva.

Medema, G., Teunis, P., Blokker, M., Deere, D., Davison, A., Charles, P., Loret, J., 2009b. Risk assessment of Cryptosporidium in drinking water. World Health Organization 143.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., 2007. Global climate projections. Climate change 3495 747-845.

Millson, M., Bokhout, M., Carlson, J., Spielberg, L., Aldis, R., Borczyk, A., Lior, H., 1990. An outbreak of Campylobacter jejuni gastroenteritis linked to meltwater contamination of a municipal well. Canadian journal of public health= Revue canadienne de sante publique 82(1) 27-31.

Molden, D.J., Shrestha, A.B., Nepal, S., Immerzeel, W.W., 2016. Downstream Implications of Climate Change in the Himalayas, Water Security, Climate Change and Sustainable Development. Springer, pp. 65-82.

Monteith, J., 1965. Evaporation and environment, Symp. Soc. Exp. Biol.

Montgomery, M.A., Elimelech, M., 2007. Water and sanitation in developing countries: including health in the equation. Environ. Sci. Technol 41(1) 17-24.

Moore, J., Smyth, J., Baker, E., Miner, J., Moffitt, D., 1989. Modeling bacteria movement in livestock manure systems. Transactions of the ASAE 32(3) 1049-1053.

Moors, E., Singh, T., Siderius, C., Balakrishnan, S., Mishra, A., 2014. Climate change and waterborne diarrhoea in northern India: Impacts and adaptation strategies. Science of the Total Environment 468-469 S139-S151.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T. ASABE. 50(3) 885-900.

Morris, M.D., 1991. Factorial sampling plans for preliminary computational experiments. Technometrics 33(2) 161-174.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., 2010. The next generation of scenarios for climate change research and assessment. Nature 463(7282) 747-756.

Mukhopadhyay, B., Khan, A., 2014. A quantitative assessment of the genetic sources of the hydrologic flow regimes in Upper Indus Basin and its significance in a changing climate. Journal of Hydrology 509 549-572.

Nabeela, Azizullah, Bibi, Uzma, Murad, Shakir, Ullah, Qasim, Hader, 2014. Microbial contamination of drinking water in Pakistan—a review. Environmental Science and Pollution Research.

Nachtergaele, F., van Velthuizen, H., Verelst, L., Wiberg, D., 2012. Harmonized World Soil Database, Version 1.2, FAO, IIASA, ISRIC, ISSCAS, JRC.

Narsimlu, Ashvin, K.G., Chahar, Singh, 2015. SWAT Model Calibration and Uncertainty Analysis for Streamflow Prediction in the Kunwari

River Basin, India, Using Sequential Uncertainty Fitting. Environmental Processes 2 79-95.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. Journal of Hydrology 10(3) 282-290.

National Water Policy Pakistan, 2012. National Water Policy, Pakistan (http://waterinfo.net.pk/sites/default/files/knowledge/National%20Water%20Policy%20(Draft).PDF)

Neitsch, S., Arnold, J., Kiniry, J.e.a., Srinivasan, R., Williams, J., 2002. Soil and water assessment tool user's manual version 2000, GSWRL report. Texas Water Resource Institute: Texas, USA.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute: Texas, USA.

Nichols, G., Lane, C., Asgari, N., Verlander, N.Q., Charlett, A., 2009. Rainfall and outbreaks of drinking water related disease and in England and Wales. Journal of Water and Health 7(1) 1-8.

Nisar, A., Rashid, M., Vaes, A.G., 2003. Fertilizers and their use in Pakistan, Extension Bulletin. National Fertilizer Development Centre, Planning and Development Division, Government of Pakistan.: Pakistan, p. 268.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122(3) 387-400.

Odonkor, S.T., Ampofo, J.K., 2013. Escherichia coli as an indicator of bacteriological quality of water: an overview. Microbiology research 4(1) 2.

Ouattara, N.K., de Brauwere, A., Billen, G., Servais, P., 2013. Modelling faecal contamination in the Scheldt drainage network. Journal of marine systems 128 77-88.

Parajuli, P.B., 2007. SWAT bacteria sub-model evaluation and application. ProQuest Information and Learning Company, United States.

Parajuli, P.B., Mankin, K.R., Barnes, P.L., 2009. Source specific fecal bacteria modeling using soil and water assessment tool model. Bioresour Technol 100(2) 953-963.

Paredes-Paredes, M., Okhuysen, P.C., Flores, J., Mohamed, J.A., Padda, R.S., Gonzalez-Estrada, A., Haley, C.A., Carlin, L.G., Nair, P., DuPont, H.L., 2011. Seasonality of diarrheagenic Escherichia coli pathotypes in the US students acquiring diarrhea in Mexico. Journal of travel medicine 18(2) 121-125.

Park, D., Markus, M., 2014. Analysis of a changing hydrologic flood regime using the Variable Infiltration Capacity model. Journal of Hydrology 515 267-280.

Parmar, D., Sharma, V., 2002. Studies on long-term application of fertilizers and manure on yield of maize-wheat rotation and soil properties under rainfed conditions in Western-Himalayas. Journal of the Indian Society of Soil Science 50(3) 311-312.

Patil, S.B., Deshmukh, D., Dixit, J., Damle, A., 2011. Epidemiological investigation of an outbreak of acute diarrheal disease: A shoe leather epidemiology. Journal of global infectious diseases 3(4) 361.

Payment, P., Plante, R., Cejka, P., 2001. Removal of indicator bacteria, human enteric viruses, Giardia cysts, and Cryptosporidium oocysts at a large wastewater primary treatment facility. Canadian Journal of Microbiology 47(3) 188-193.

Pechlivanidis, I., Jackson, B., McIntyre, N., Wheater, H., 2011. Catchment scale hydrological modelling: a review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. Global NEST Journal 13(3) 193-214.

Philipsborn, R., Ahmed, S.M., Brosi, B.J., Levy, K., 2016. Climatic Drivers of Diarrheagenic Escherichia coli Incidence: A Systematic Review and Meta-analysis. Journal of Infectious Diseases 214(1) 6-15.

Pierson, S., Cabrera, M., Evanylo, G., Schroeder, P., Radcliffe, D., Kuykendall, H., Benson, V., Williams, J., Hoveland, C., McCann, M., 2001. Phosphorus losses from grasslands fertilized with broiler litter. Journal of Environmental Quality 30(5) 1790-1795.

Priestley, C., Taylor, R., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly weather review 100(2) 81-92.

Prüss-Üstün, A., Bos, R., Gore, F., Bartram, J., 2008. Safer water, better health: costs, benefits and sustainability of interventions to protect and promote health. World Health Organization.

Rajbhandari, R., Shrestha, A., Kulkarni, A., Patwardhan, S., Bajracharya, S., 2015. Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). Climate Dynamics 44(1-2) 339-357.

Rankinen, K., Butterfield, D., Sànchez, M.F., Grizzetti, B., Whitehead, P., Pitkänen, T., Uusi-Kämppä, J., Leckie, H., 2016. The INCA-Pathogens model: An application to the Loimijoki River basin in Finland. Science of The Total Environment 572 1611-1621.

Rankl, M., Kienholz, C., Braun, M., 2014. Glacier changes in the Karakoram region mapped by multimission satellite imagery. The Cryosphere 8(3) 977-989.

Räty, O., Räisänen, J., Ylhäisi, J.S., 2014. Evaluation of delta change and bias correction methods for future daily precipitation: intermodel cross-validation using ENSEMBLES simulations. Climate Dynamics 42(9-10) 2287-2303.

Reddy, K., Khaleel, R., Overcash, M., 1981. Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes. Journal of Environmental Quality 10(3) 255-266.

Reder, K., Flörke, M., Alcamo, J., 2015. Modeling historical fecal coliform loadings to large European rivers and resulting in-stream concentrations. Environmental Modelling & Software 63(0) 251-263.

Refsgaard, J.C., 1997. Parameterisation, calibration and validation of distributed hydrological models. Journal of Hydrology 198(1) 69-97.

Refshaard, J., Storm, B., Singh, V., 1995. MIKE SHE. Computer models of watershed hydrology. 809-846.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Climatic Change 109(1) 33.

Ridley, J., Wiltshire, A., Mathison, C., 2013. More frequent occurrence of westerly disturbances in Karakoram up to 2100. Science of The Total Environment 468 S31-S35.

Robles-Morua, A., Vivoni, E.R., Mayer, A.S., 2012. Distributed hydrologic modeling in northwest Mexico reveals the links between runoff mechanisms and evapotranspiration. Journal of Hydrometeorology 13(3) 785-807.

Rose, J.B., 2015. Water, Sanitation and the Millennium Development Goals: A Report Card on Global Progress http://www.waterandhealth.org/water-sanitation-millennium-development-goals-report-card-global-progress/ (Accessed 24 April 2017).

Rose, J.B., Epstein, P.R., Lipp, E.K., Sherman, B.H., Bernard, S.M., Patz, J.A., 2001a. Climate variability and change in the United States: potential impacts on water-and foodborne diseases caused by microbiologic agents. Environmental Health Perspectives 109(Suppl 2) 211.

Rose, J.B., Epstein, P.R., Lipp, E.K., Sherman, B.H., Bernard, S.M., Patz, J.A., 2001b. Climate variability and change in the United States: potential impacts on water-and foodborne diseases caused by microbiologic agents. Environmental Health Perspectives 109(Suppl 2) 211-220.

Sadeghi, A.M., Arnold, J.G., 2002. A SWAT/microbial sub-model for predicting pathogen loadings in surface and groundwater at watershed and basin scales, Total Maximum Daily Load (TMDL): Environmental Regulations, Proceedings of 2002 Conference. American Society of Agricultural and Biological Engineers, pp. 56-63.

Saeed, T.U., Attaullah, H., 2014. Impact of extreme floods on groundwater quality (in Pakistan). British Journal of Environment and Climate Change 4(1) 133.

Saleh, A., Du, B., 2004. Evaluation of SWAT and HSPF within BASINS program for the upper North Bosque River watershed in central Texas. Transactions of the ASAE 47(4) 1039-1049.

Sanders, E.C., Yuan, Y., Pitchford, A., 2013. Fecal coliform and E. coli concentrations in effluent-dominated streams of the Upper Santa Cruz watershed. Water 5(1) 243-261.

Santhi, C., Arnold, J., Williams, J., Hauck, L., Dugas, W., 2001a. Application of a watershed model to evaluate management effects on point and nonpoint source pollution. Transactions of the ASAE 44(6) 1559-1570.

Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R., Hauck, L.M., 2001b. Validation of the swat model on a large rwer basin with point and nonpoint sources. JAWRA Journal of the American Water Resources Association 37(5) 1169-1188.

Sarıkaya, M.A., Bishop, M.P., Shroder, J.F., Ali, G., 2013. Remote-sensing assessment of glacier fluctuations in the Hindu Raj, Pakistan. International journal of remote sensing 34(11) 3968-3985.

Sarikaya, M.A., Bishop, M.P., Shroder, J.F., Olsenholler, J.A., 2012. Space-based observations of Eastern Hindu Kush glaciers between 1976 and 2007, Afghanistan and Pakistan. Remote sensing letters 3(1) 77-84.

Savoskul, O.S., Smakhtin, V., 2013. Glacier systems and seasonal snow cover in six major Asian river basins: hydrological role under changing climate. IWMI.

Savoskul, O.S., Smakhtin, V., Vladimir, V., 2013. Glacier systems and seasonal snow cover in six major Asian river basins: water storage properties under changing climate. IWMI.

Sayama, T., Ozawa, G., Kawakami, T., Nabesaka, S., Fukami, K., 2012. Rainfall–runoff–inundation analysis of the 2010 Pakistan flood in the Kabul River basin. Hydrological Sciences Journal 57(2) 298-312.

Schilling, K.E., Zhang, Y.-K., Hill, D.R., Jones, C.S., Wolter, C.F., 2009a. Temporal variations of Escherichia coli concentrations in a large Midwestern river. Journal of Hydrology 365(1–2) 79-85.

Schilling, K.E., Zhang, Y.-K., Hill, D.R., Jones, C.S., Wolter, C.F., 2009b. Temporal variations of Escherichia coli concentrations in a large Midwestern river. Journal of Hydrology 365(1) 79-85.

Schwarzenbach, R.P., Escher, B.I., Fenner, K., Hofstetter, T.B., Johnson, C.A., Von Gunten, U., Wehrli, B., 2006. The challenge of micropollutants in aquatic systems. Science 313(5790) 1072-1077.

Seas, C., Alarcon, M., Aragon, J.C., Beneit, S., Quiñonez, M., Guerra, H., Gotuzzo, E., 2000. Surveillance of bacterial pathogens associated with acute diarrhea in Lima, Peru. International journal of infectious diseases 4(2) 96-99.

Seidu, R., Stenström, T.A., Löfman, O., 2013. A comparative cohort study of the effect of rainfall and temperature on diarrhoeal disease in faecal sludge and non-faecal sludge applying communities, Northern Ghana. Journal of Water and Climate Change 4(2) 90-102.

Semenza, J.C., Menne, B., 2009. Climate change and infectious diseases in Europe. The Lancet infectious diseases 9(6) 365-375.

Senhorst, H., Zwolsman, J.J., 2005. Climate change and effects on water quality: a first impression. Water Science and Technology 51(5) 53-59.

Servais, P., Garcia-Armisen, T., George, I., Billen, G., 2007. Fecal bacteria in the rivers of the Seine drainage network (France): sources, fate and modelling. Science of The Total Environment 375(1) 152-167.

Service, U.S.S.C., 1972. SCS national engineering handbook, section 4: hydrology. The Service, University of Minnesota, USA.

Shaikh;, A.S., Rahman;, H.u., Ehsan, S., 2010. Climate Change Impact on River Flows in Chitral Watershed. Pakistan Journal of Engineering and Applied Sciences 7 12-23.

Shirmohammadi, A., Chaubey, I., Harmel, R., Bosch, D., Muñoz-Carpena, R., Dharmasri, C., Sexton, A., Arabi, M., Wolfe, M., Frankenberger, J., 2006. Uncertainty in TMDL models. Transactions of the ASAE 49(4) 1033-1049.

Shrestha, S., Kazama, F., 2007. Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. Environmental Modelling & Software 22(4) 464-475.

Sokolova, E., Aśtröm, J., Pettersson, T.J.R., Bergstedt, O., Hermansson, M., 2012. Estimation of pathogen concentrations in a drinking water source using hydrodynamic modelling and microbial source tracking. Journal of Water and Health 10(3) 358-370.

Sokolova, E., Pettersson, T.J.R., Bergstedt, O., Hermansson, M., 2013. Hydrodynamic modelling of the microbial water quality in a drinking water source as input for risk reduction management. Journal of Hydrology 497(0) 15-23.

Speelmon, E.C., Checkley, W., Gilman, R.H., Patz, J., Calderon, M., Manga, S., 2000. Cholera incidence and El Nino–related higher ambient temperature. Jama 283(23) 3072-3074.

Sperber, K.R., Annamalai, H., Kang, I.-S., Kitoh, A., Moise, A., Turner, A., Wang, B., Zhou, T., 2013. The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Climate Dynamics 41(9-10) 2711-2744.

Srinivasan, R., Ramanarayanan, T.S., Arnold, J.G., Bednarz, S.T., 1998. Large area hydrologic modeling and assessment part II: model application. JAWRA Journal of the American Water Resources Association 34(1) 91-101.

Sterk, A., Schijven, J., de Roda Husman, A.M., de Nijs, T., 2016. Effect of climate change on runoff of Campylobacter and Cryptosporidium from land to surface water. Water Research 95 90-102.

Strokal, M., Kroeze, C., 2013. Nitrogen and phosphorus inputs to the Black Sea in 1970–2050. Regional Environmental Change 13(1) 179-192.

Tahir, A.A., Chevallier, P., Arnaud, Y., Neppel, L., Ahmad, B., 2011. Modeling snowmelt-runoff under climate scenarios in the Hunza River basin, Karakoram Range, Northern Pakistan. Journal of Hydrology 409(1) 104-117.

Tang, J., McDonald, S., Peng, X., Samadder, S.R., Murphy, T.M., Holden, N.M., 2011. Modelling Cryptosporidium oocysts transport in small ungauged agricultural catchments. Water Research 45(12) 3665-3680.

Tariq, M.A.U.R., van de Giesen, N., 2012. Floods and flood management in Pakistan. Physics and Chemistry of the Earth, Parts A/B/C 47–48 11-20.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93(4) 485-498.

Teklehaimanot, G.Z., Coetzee, M.A., Momba, M.N., 2014. Faecal pollution loads in the wastewater effluents and receiving water bodies: a potential threat to the health of Sedibeng and Soshanguve communities, South Africa. Environmental Science and Pollution Research 21(16) 9589-9603.

Terink, W., Lutz, A., Simons, G., Immerzeel, W., Droogers, P., 2015. SPHY v2. 0: Spatial Processes in HYdrology. Geoscientific Model Development 8(7) 2009-2034.

Thampi, S.G., Raneesh, K.Y., Surya, T., 2010a. Influence of scale on SWAT model calibration for streamflow in a river basin in the humid tropics. Water Resources Management 24(15) 4567-4578.

Thampi, S.G., Raneesh, K.Y., Surya, T.V., 2010b. Influence of Scale on SWAT Model Calibration for Streamflow in a River Basin in the Humid Tropics. Water Resources Management 24(15) 4567-4578.

Thomas, K.M., Charron, D.F., Waltner-Toews, D., Schuster, C., Maarouf, A.R., Holt, J.D., 2006. A role of high impact weather events in waterborne disease outbreaks in Canada, 1975–2001. International Journal of Environmental Health Research 16(03) 167-180.

Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M.A., Clarke, L.E., 2011. RCP4. 5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 109(1-2) 77-94.

Thurston-Enriquez, J., Gilley, J., Eghball, B., 2005a. Microbial quality of runoff following land application of cattle manure and swine slurry. J Water Health 3 157-171.

Thurston-Enriquez, J.A., Gilley, J.E., Eghball, B., 2005b. Microbial quality of runoff following land application of cattle manure and swine slurry. Journal of Water and Health 3(2) 157-171.

Tian, Y.Q., Gong, P., Radke, J.D., Scarborough, J., 2002. Spatial and temporal modeling of microbial contaminants on grazing farmlands. Journal of Environmental Quality 31(3) 860-869.

Tiefenthaler, L.L., Stein, E.D., Lyon, G.S., 2009. Fecal indicator bacteria (FIB) levels during dry weather from Southern California reference streams. Environmental monitoring and assessment 155(1) 477-492.

Trærup, S.L., Ortiz, R.A., Markandya, A., 2011. The costs of climate change: A study of cholera in Tanzania. International Journal of Environmental Research and Public Health 8(12) 4386-4405.

Tunnermeier, T., Houben, G., 2005. Hydrogeology of the Kabul Basin Part: 1, Geology, aquifer characteristics, climate and hydrography: BRG, pp. 1-52.

UN, 2015. Levels and Trends in Child Mortality - Child Mortality Estimates (http://www.childmortality.org/files_v20/download/igme%20report%202015%20child%20mortality%20final.pdf) Accessed 07 May 2017

UNEP, 2016. A Snapshot of the World's Water Quality: Towards a global assessment. United Nations Environmental Program, Nairobi, Kenya.

UNICEF, WHO, 2012. Progress on Drinking Water and Sanitation: Geneva.

USACE, 2016. User Manual HEC-SSP Software Package 2.1. Hydrological Engineering Center: Army Mil USA.

USDA, 1986. Urban hydrology for small watersheds. Tech Release 55 2-6.

USEPA, 2001. Protocol for Developing Pathogen TMDLs. EPA 841-R-00-002. Washington, DC: Office of Water

Van Griensven, A., Francos, A., Bauwens, W., 2002. Sensitivity analysis and auto-calibration of an integral dynamic model for river water quality. Water Science and Technology 45(9) 325-332.

van Lieverloo, J.H.M., Blokker, E., Medema, G., 2007. Quantitative microbial risk assessment of distributed drinking water using faecal indicator incidence and concentrations. Journal of Water & Health 5.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., 2011a. The representative concentration pathways: an overview. Climatic Change 109 5-31.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011b. The representative concentration pathways: an overview. Climatic Change 109(1-2) 5-31.

Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for Climate Change Research: scenario matrix architecture. Climatic Change 122(3) 373-386.

Vermeulen, L.C., de Kraker, J., Hofstra, N., Kroeze, C., Medema, G., 2015a. Modelling the impact of sanitation, population growth and urbanization on human emissions of cryptosporidium to surface waters—A case study for Bangladesh and India. Environmental Research Letters 10(9) 094017.

Vermeulen, L.C., Hofstra, N., 2013. Influence of climate variables on the concentration of Escherichia coli in the Rhine, Meuse, and Drentse Aa during 1985–2010. Regional Environmental Change 14(1) 307-319.

Vermeulen, L.C., Hofstra, N., 2014. Influence of climate variables on the concentration of Escherichia coli in the Rhine, Meuse, and Drentse Aa during 1985–2010. Regional Environmental Change 14(1) 307-319.

Vermeulen, L.C., Hofstra, N., Kroeze, C., Medema, G., 2015b. Advancing waterborne pathogen modelling: lessons from global nutrient export models. Current Opinion in Environmental Sustainability 14 109-120.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., 2010. Global threats to human water security and river biodiversity. Nature 467(7315) 555-561.

Walker, C.L.F., Rudan, I., Liu, L., Nair, H., Theodoratou, E., Bhutta, Z.A., O'Brien, K.L., Campbell, H., Black, R.E., 2013. Global burden of childhood pneumonia and diarrhoea. The Lancet 381(9875) 1405-1416.

Walters, S.P., Thebo, A.L., Boehm, A.B., 2011. Impact of urbanization and agriculture on the occurrence of bacterial pathogens and stx genes in coastal waterbodies of central California. Water Research 45(4) 1752-1762.

Wang, G., Doyle, M.P., 1998. Survival of enterohemorrhagic Escherichia coli O157: H7 in water. Journal of Food Protection® 61(6) 662-667.

Wang, S.Y., Davies, R.E., Huang, W.R., Gillies, R.R., 2011. Pakistan's two-stage monsoon and links with the recent climate change. Journal of Geophysical Research: Atmospheres 116(D16).

Warner, N.R., Levy, J., Harpp, K., Farruggia, F., 2008. Drinking water quality in Nepal’s Kathmandu Valley: a survey and assessment of selected controlling site characteristics. Hydrogeology Journal 16(2) 321-334.

WATSAN, 2014. Water and Sanitation at Khyber Pukhtunkhwa http://www.urbanpolicyunit.gkp.pk/water-and-sanitation/ (Assessed 24 March 2017).

Whitehead, P., Sarkar, S., Jin, L., Futter, M., Caesar, J., Barbour, E., Butterfield, D., Sinha, R., Nicholls, R., Hutton, C., 2015. Dynamic modeling of the Ganga river system: impacts of future climate and socioeconomic change on flows and nitrogen fluxes in India and Bangladesh. Environmental Science: Processes & Impacts 17(6) 1082-1097.

Whitehead, P., Wilby, R., Battarbee, R., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrological Sciences Journal 54(1) 101-123.

Whitman, R.L., Nevers, M.B., 2008. Summer E. coli patterns and responses along 23 Chicago beaches. Environmental Science & Technology 42(24) 9217-9224.

WHO, 1985. GUIDELINES FOR DRINKING-WATER QUALITY: Geneva.

WHO, 2007. The world health report 2007-a safer future: global public health security in the 21st century. World Health Organization, Geneva.

WHO, 2008a. Guidelines for Drinking-water Quality, third edition, incorporating first and second addenda. World Health Organization, Geneva.

WHO, 2008b. World Health Organization and United Nations children's fund joint monitoring programme for water supply and sanitation (JMP). Progress on drinking water and sanitation: special focus on sanitation. WHO.

WHO, 2009. Global health risks: mortality and burden of disease attributable to selected major risks. World Health Organization.

WHO, 2013. Diarrhoeal disease http://www.who.int/mediacentre/factsheets/fs330/en/ (Accessed 24 April 2017).

WHO, 2016. Drinking-water http://www.who.int/mediacentre/factsheets/fs391/en/ (Accessed 23 April 2017).

Widmer, K., Van Ha, N.T., Vinitnantharat, S., Sthiannopkao, S., Wangsaatmaja, S., Prasetiati, M.A.N., Thanh, N.C., Thepnoo, K., Sutadian, A.D., Thao, H.T.T., 2013. Prevalence of Escherichia coli in surface waters of

Southeast Asian cities. World Journal of Microbiology and Biotechnology 29(11) 2115-2124.

Wilby, R.L., Wigley, T., 1997. Downscaling general circulation model output: a review of methods and limitations. Progress in Physical Geography 21(4) 530-548.

Wilcox, B.P., Rawls, W., Brakensiek, D., Wight, J.R., 1990. Predicting runoff from rangeland catchments: a comparison of two models. Water Resources Research 26(10) 2401-2410.

Williams, J., Izaurralde, R., Steglich, E., 2008. Agricultural policy/environmental extender model. Theoretical Documentation, Version 604 2008-2017.

Wiltshire, A., 2014. Climate change implications for the glaciers of the Hindu Kush, Karakoram and Himalayan region. The Cryosphere 8(3) 941-958.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climatic Change 62(1-3) 189-216.

Wu, J., Long, S., Das, D., Dorner, S., 2011a. Are microbial indicators and pathogens correlated. A statistical analysis of 40 265-278.

Wu, J., Long, S., Das, D., Dorner, S., 2011b. Are microbial indicators and pathogens correlated? A statistical analysis of 40 years of research. Journal of Water and Health 9(2) 265-278.

Wu, J., Rees, P., Storrer, S., Alderisio, K., Dorner, S., 2009. Fate and Transport Modeling of Potential Pathogens: The Contribution From Sediments1. JAWRA Journal of the American Water Resources Association 45(1) 35-44.

Wunderlin, D.A., María Del Pilar, D., María Valeria, A., Fabiana, P.S., Cecilia, H.A., María De Los Ángeles, B., 2001. Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A Case Study: Suquía River basin (Córdoba-Argentina). Water Res 35(12) 2881-2894.

Yu, W., Yang, Y.-C., Savitsky, A., Alford, D., Brown, C., 2013. The Indus basin of Pakistan: The impacts of climate risks on water and agriculture. World Bank Publications.

Zhang, L., Seagren, E.A., Davis, A.P., Karns, J.S., 2012. Effects of Temperature on Bacterial Transport and Destruction in Bioretention Media: Field and Laboratory Evaluations. Water Environment Research 84(6) 485-496.

Zhang, Y., Bi, P., Hiller, J.E., 2008. Weather and the transmission of bacillary dysentery in Jinan, northern China: a time-series analysis. Public health reports 61-66.

Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., 2016. Consumptive water footprint and virtual water trade scenarios for China—With a focus on crop production, consumption and trade. Environment International 94 211-223.

APPENDICES

APPENDIX 1 ADDITIONAL INFORMATION FOR CHAPTER 3

Total cumulative estimated economic losses of all the floods that have been already reported in the Kabul river basin. Figure S1 presents all the losses in terms of direct losses, human loss, no of villages that were damaged or destroyed due to these floods in the past 80 years. Similarly, in Table S1 the direct damages due to floods in lower part of the Kabul basin are reported specifically in 2010 flood which was most devastating in the history.

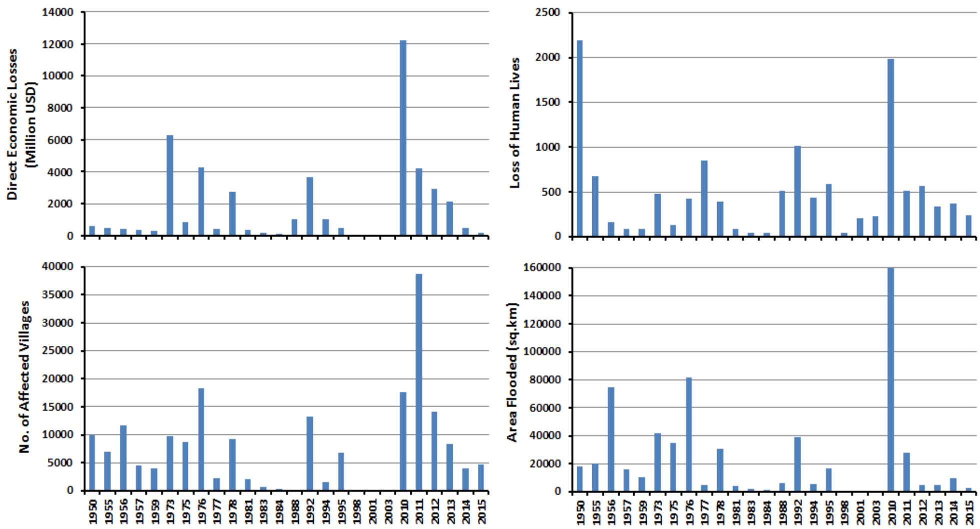

Figure S1: Flood damages during 1950-2015 in the overall Indus Basin, Pakistan (FFC, 2016)

Table S1: District-wise flood damages in 2010 in the lower Kabul basin in Pakistan (Khan and Mohmand, 2011).

Districts	Number of Affected Villages	Number of Human Deaths	Number of Injured People	Total Population Displaced	Loss of Crops (ha)
Peshawar	16	46	68	37373	37555
Charsadda	34	66	115	145810	16480
Nowshera	27	167	10	350336	No data
Mardan	43	8	40	11403	285
Swabi	11	7	4	742	40
Swat	42	95	207	101220	13950
Total	**173**	**389**	**444**	**646884**	**68310**

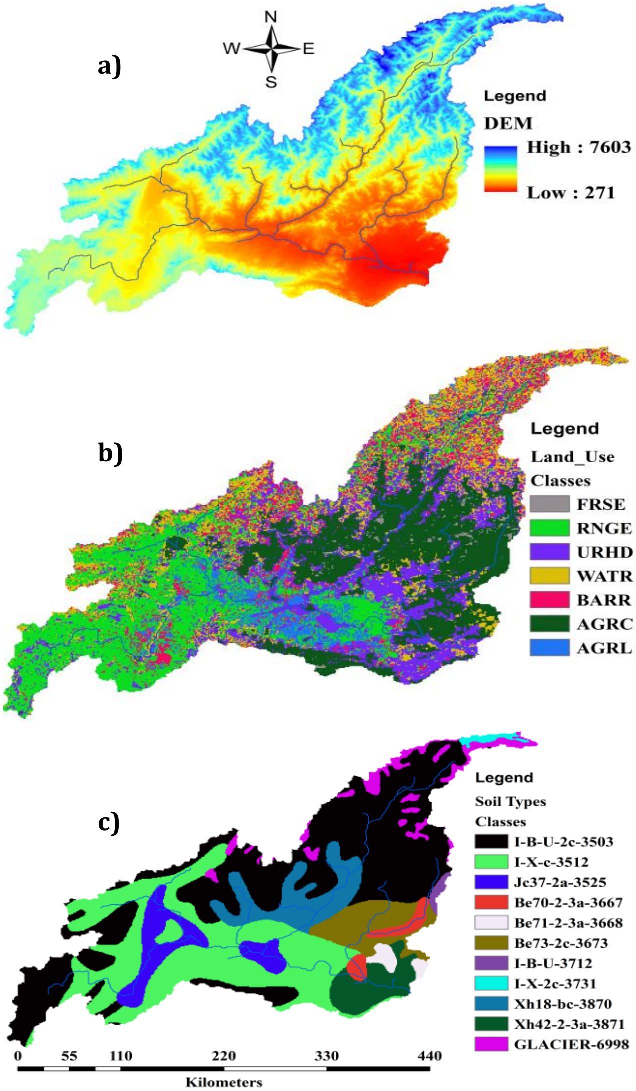

Figure S2: (a)Digital Elevation Model (resolution 90m) ranges from 271m to 7603m (b) land-use classes, where FRSE = Forest, RNGE = Range Land / Pasture land, URHD= Urban area, WATR= Water bodies, BARR= Barren land, AGRC= Agricultural land close grown crops, and AGRL= General Agricultural land, all the land-use classes were taken from (Arnold et al., 2009) (c) soil types classification of the Kabul basin.

Table-S2: Parameters selected and final calibrated values for SWAT-Model.

Parameter_ Name	**Min_value**	**Max_value**	**Final_ value**
Snow peak temperature ^{0}C lag factor (*TIMP*)	0.8736	1.0000	0.462
Snowmelt base temperature ^{0}C (*SMTMP*)	-1.896	5.0000	4.616
Snowfall temperature ^{0}C (*SFTMP*)	0.2772	2.8087	1.841
Curve number (CN_2)	73.084	78.5429	75.1572
Average slop steepness (*HRU_SLP*)	0.7265	1.7533	1.144
"n" value for overland flow (*OV_N*)	-0.0682	0.4341	0.219
Average slop length in meters (*SLSUBBSN*)	1.0473	3.0849	1.057
Base-flow alpha factor days(*ALPHA_BF*)	0.3441	0.6601	0.455
Groundwater delay (*GW_DELAY*)	37.1930	47.7085	41.933
Soil available water capacity (*SOL_AWC*)	0.0894	0.2897	0.179
Evaporation compensation coefficient (*ESCO*)	0.6033	1.0619	0.776
Surface runoff lag coefficient (*SURLAG*)	5.1419	18.7473	13.501
Saturated hydraulic conductivity (*SOL_K*)	1.04199	3.3747	1.377
Threshold depth of water in the shallow aquifer for return flow (*GWQMIN*)	1.9528	4.0842	2.789

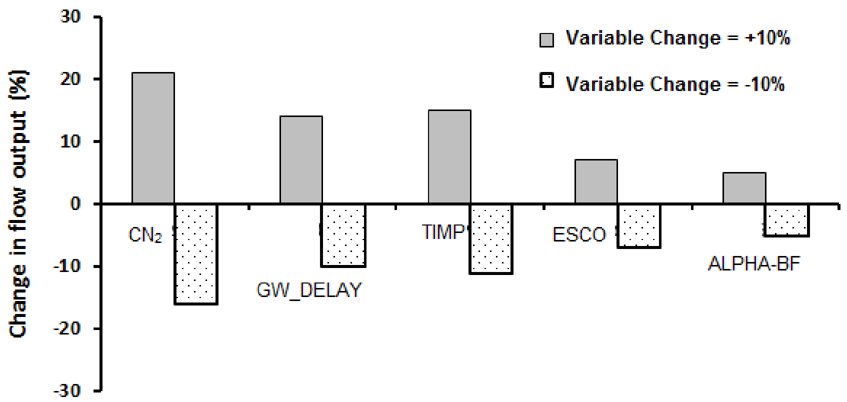

Figure S3: Sensitivity analysis for flow simulation, where CN_2 is the curve number, GW_DELAY is the groundwater delay, TIMP is the snow peak temperature, ESCO is the evaporation compensation coefficient and ALPHA-BF is the base-flow alpha factor day.

Table-S3: Flow (m^3/s) for the 5, 25, 50, 100, 500 and 1000 year return periods for RCP 4.5 and RCP 8.5 for all selected GCMs and observed annual maximum flow for the contemporary period (1981-2015), near (2031-2050) and far (2081-2100) future.

	Time Period per RCP	5 yrs.	25 yrs.	50 yrs.	100 yrs.
Observed	**1981-2015**	4500	5700	7300	8200
INM-CM4		4300	5165	6880	7733
IPSL-CM5A	**RCP4.5 2031-2050**	5829	6565	8580	9644
EC-EARTH		6384	7172	9840	11060
MIROC5		9626	10250	11698	13148
INM-CM4		4320	5093	7194	8086
IPSL-CM5A	**RCP8.5 2031-2050**	5520	6295	9094	10222
EC-EARTH		7063	8088	11024	12391
MIROC5		11360	12335	12814	14403
INM-CM4		4205	5262	7258	8158
IPSL-CM5A	**RCP4.5 2081-2100**	6181	6962	8781	9870
EC-EARTH		7870	9079	10932	12288
MIROC5		11929	13215	13455	15123
INM-CM4		4510	5100	7042	7915
IPSL-CM5A	**RCP8.5 2081-2100**	5872	6614	8342	9376
EC-EARTH		7366	8305	10205	11471
MIROC5		11030	12500	13122	14749

APPENDIX 2 ADDITIONAL INFORMATION FOR CHAPTER 4

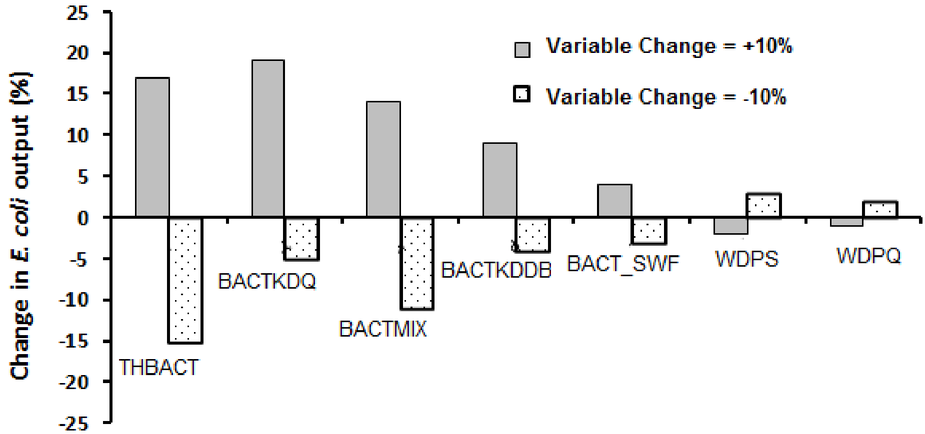

Figure S4: Sensitivity analysis results for the *E. coli* simulations, where THBACT is the temperature adjustment factor; BACTKDQ is the bacteria partition coefficient in surface runoff; BACTMIX is the bacterial percolation coefficient; BACTKDDB is the bacterial partition coefficient in manure; BACT_SWF is the fraction of manure applied to land; WDPS is the die-off factor for persistent bacteria adsorbed to soil particles; and WDPQ is the die-off factor for persistent bacteria in soil solution.

SUMMARY

Clean water is indispensable for the sustenance of life and maintenance of health. However, water quality is threatened by changes in socioeconomic developments (population growth, urbanisation, livestock increase and sanitation) and climate (surface air temperature and precipitation patterns). Major water quality contaminants include microorganisms, such as fecal coliforms, Escherichia Coli (*E.coli*) and pathogens. Microbial contamination poses serious health risks in developing countries like Pakistan, where people do not have access to clean water due to lack of waste water treatment and thorough manure management. Therefore, to reduce the present and future health risk, it is important to understand the impacts of socioeconomic development and climate-change on microbial fate and transport in surface water resources in the Kabul River Basin in Pakistan.

The objective of this study is quantifying the impact of socioeconomic development and climate change on *E.coli* concentrations in the Pakistani Kabul River. To reach the objective, I sampled *E.coli* concentrations at several locations in Kabul River, applied statistical and process based modelling, developed future global change scenarios and analysed the impact of these scenarios on *E.coli* concentrations. I focus on *E.coli* rather than pathogens, because sampling of pathogens and its chemical analysis are expensive. Kabul River Basin is a tributary of the Indus river and is located in the Hindukush-Karakoram-Himalayas (HKH) and suffers from floods every year. The population suffers from a high risk of waterborne diseases. The water is contaminated by direct sewage inputs from large cities, like Peshawar, direct manure inputs from animal sheds along the river and indirect manure inputs from the land.

Kabul River Basin is subjected to hazardous levels of microbiological pollution. The concentration of micro-organisms is influenced by hydro-climatic variables, such as water and surface air temperature, precipitation and discharge. However, the net effect of these variables remains thus far unclear. High concentrations of *E.coli* were found in the main stream and its tributaries (Chapter 2). Samples were collected along the Kabul river and drinking water samples from the city of Nowshera (April 2013 to July 2015) and all surface water samples violate the bathing water criteria and all drinking water samples violate the drinking water criteria. The correlation between hydro-climatic variables and *E.coli* concentration was analysed. Water temperature and surface air temperature were positively correlated, most likely because high temperatures coincide with high precipitation and discharge. Precipitation and river discharge data were also

positively correlated with *E.coli* concentrations. This shows that precipitation, which increases the surface runoff, transports *E.coli* and other waterborne pathogens to the river nearby (correlation with precipitation) and further upstream (correlation with discharge). A regression model was also applied that explained 61% of the *E.coli* variability in surface water and 55% of *E.coli* variability in drinking water resources, even when other factors, such as location and land-use variables are ignored (Chapter 2).

To better understand the hydrology in the basin, the current and future flows of Kabul river were modelled using the Soil and Water Assessment Tool (SWAT), which serves as a basis for the process-based *E.coli* model. Flash floods occur every year in the basin as a result of increased discharge due to snow and glacier melt together with monsoon precipitation. The Kabul River Basin is one of the most vulnerable regional basin to climate change. The hydrological model was calibrated and validated for the full Kabul River Basin and performed well (NSE equals 0.77 and 0.72 respectively). Flood frequency and expected return period were analysed for a contemporary period (1981-2000) and two future periods (i.e. 2031-2050 and 2081-2100) using the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios based on four bias-corrected downscaled climate models (Chapter 3). The flood frequency analysis shows that the present day's one-in-a-fifty year event could occur between once in every 3 year (EC-EARTH and MIROC climate-models) and once in every 24 years (IPSL climate-model). This study presents climate-change impact assessment in the Kabul River Basin. The selected approach is in general well accepted in the scientific community and the results can be useful in flood management in the region. Outcomes of this study can be helpful for regions that have similar hydro-climatological conditions.

To better understand the fate and transport of bacteria from land to water resources and to assess source contribution, the SWAT model was calibrated and validated for *E.coli*. Our study is the first bacterial modelling study for the Kabul River Basin (Chapter 4). The simulated concentrations have slightly lower variability than the observed concentrations. The model performance could be improved further by using more input *E.coli* data, but the current model results agree well enough with our measured *E.coli* concentrations (NSE equals 0.69 and 0.66 for calibration and validation respectively). Based on the pathogen source estimations, point (direct) sources are identified to be the most important microbial pollution sources. Pollution from upstream areas is also important, while non-point (diffuse) sources play a role mostly during the periods with high discharge. Our study underlines the importance of wastewater treatment and manure management both in and upstream of the study area. Studies like ours were lacking in developing countries like Pakistan and can be used for scenario analyses in the region (Chapter 4). The model can be useful in microbial water quality assessments in other watersheds and for pathogenic microorganisms, such as *Cryptosporidium* and *Rotavirus*.

The calibrated and validated SWAT bacterial model (Chapter 4) was used to assess *E.coli* concentrations in a comprehensive scenario analysis (Chapter 5). We developed two future scenarios based on state-of-the-art approaches, using the Shared Socioeconomic Pathways (SSPs), RCPs and own assumptions in line with the SSP storylines. We took the modelled *E.coli* concentrations from Chapter 4 as baseline scenarios and defines two future scenarios as Scenario_1 (sustainability scenario) and Scenario_2 (uncontrolled scenario). These scenarios represent different socioeconomic development and climate change. The two scenarios were developed by combining SSP1, a sustainable, equitable and environmentally focussed world with RCP4.5 (limed climate change) in Scenario_1, and SSP3 (a divided world, with no interest in the environment) with RCP8.5 (strong climate change) in Scenario_2. Currently, no wastewater treatment plant exists in the basin, because the 2010 floods destroyed the available plants. We assumed excellent and poor wastewater and manure treatment for 2050s and 2100s for Scenario_1 and Scenario_2 respectively, in line with the storylines. Scenario_2 resulted in higher *E.coli* concentrations compared to the baseline scenarios due to high population growth, poor wastewater and manure treatment and land-use changes. However, microbial water quality was found to improve under Scenario_1. This was achieved by implementing improved and technologically advanced wastewater treatment and manure management. Future concentrations were found to be between 0.6% and 7% of the baseline concentrations depending on the treatment technology used (Chapter 5). This study highlights the need for substantial improvements in wastewater and manure treatment systems in the Kabul River Basin to assure future *E.coli* concentrations in water sources will be within the limits of WHO and US-EPA regulations for drinking and bathing water quality. The primary treatment facility that is currently installed is a good start, but insufficient to strongly reduce concentrations. Hence major investments are required to install technologically advanced wastewater treatment and manure treatment plants to cut-down the current contamination level of Kabul river.

My PhD thesis provides a base for devising optimal coping strategies that are essential for the sustainability of hydrological resources under socioeconomic developments and climate-change impacts. The results of our research are helpful to further assess alternative water quality management options. The outcomes of this study also increase the knowledge in the field of microbial fate and transport in water resources in a developing country like Pakistan, where such studies are lacking. A limited number of previous studies on global change impacts on microbial contamination of surface water in other areas of the world focused only on the climate-change impacts on microbial water quality. This is the first study to evaluate the influence of combined socioeconomic and climate-change impacts on *E.coli* concentrations in the Kabul River Basin. The developed SWAT model and scenario analysis can be used for other contaminants, such as nutrients, pesticides and heavy metals. Our study can be a first step to improve water quality of the Kabul River Basin by providing tools for water managers and health specialists to improve the water quality and reduce the risks related to the use of contaminated water resources. This study will be useful not only in this region, but also for other regions of the world with similar microbial water contamination issues.

ACKNOWLEDGEMENTS

Born in a large family, I realised the importance of limited resources at a very early age in my life. I got primary education in a school where we used to sit on the ground under the open sky, before moving to the newly-built government school. My great father Muhammad Shoaib Khan always inspired me to seek knowledge and attend classes. I can't forget his motivational words: "I want to see you successful in your class, else I will make you a car mechanic". My dear father, I dedicate this thesis to your vision, affection and sincerity. I hope that this study conveys the importance of climate-change impacts on flooding and waterborne issues in Pakistan. My elder brother, Dr. Muhammad Javed Iqbal, inspired me and became my role model after my father passed away. He stimulated me to obtain a PhD. I have greatly benefitted from my second brother's, Muhammad Nadeem Iqbal, pleasant company and optimistic attitude. I also thank my two sisters: one took me to the kindergarten and the other taught me academic skills before starting university life. Praises to Almighty ALLAH to give me strength to complete my PhD

During the course of my PhD study, several people helped me professionally and personally. I will try to acknowledge them all.

I cannot but thank my promoter and esteemed mentor, Professor Dr. Rik Leemans for accepting me as a PhD student. I still remember when I met him for the first time at the Lumen building and immediately felt his warmth and friendliness. I have always admired you for your immense experience, knowledge, enthusiasm and vision about the science that matters. My heartfelt thanks for your kind supervision, scholastic guidance, critical remarks on my drafts, patience to overcome bureaucratic hurdles, a very good sense of humour, and personal support. Working with you was a great honour and pleasure. This shaped not only this PhD project but also the course of my future career. I am deeply indebted to you for all thorough discussions, the valuable guidance to develop my research proposal, recurring reviews of my draft research articles, suggesting relevant literature and for the tour to the Keukenhof with its impressive tulips.

I express my gratitude and appreciation to Dr. Nynke Hofstra, my daily supervisor, for the countless discussions, skilful guidance, constructive suggestions for improving my writing skills and, above all, your patience. I feel a scarcity of words to express my emotions of this appreciation for your countless hours of support during day-to-day assistance, without which the successful completion of this thesis would have been impossible. You are such a comprehensive person and I feel lucky to have had you on my side during this whole period. I have benefitted from your professional skills in microbial analysis, scholastic suggestions and your perseverance. Your inspiring ideas, verbatim corrections of manuscripts, and in particular your advice “be specific”’ helped me to focus. I value your scientific and personal support over the past five years. You taught me how to construct scientific ideas and stressed the importance of an endless process of checking and re-checking numbers, equations, figures and references. I will never forget your dynamic supervision and moral support and my nick name (Crazy-man). I really enjoyed my PhD time under your supervision.

I thank Dr. Erik Querner for your help in understanding the SWAT model and being a co-author of the hydrology paper. I also thank Professor Dr. Gertjan Medema who advised me in an irreplaceable manner to understand microbial analysis.

I am dedicated to my best friend in Pakistan, Dr. Nauman Ahmad, who works at the Department of Agricultural Chemistry, University of Agriculture in Peshawar. I am highly indebted to you to encourage me to apply for an overseas scholarship. I appreciate your unstinted help since 2011. You made the completion of my thesis possible. I am looking forward to see you in Pakistan soon. I also sincerely thank Dr. Afia Zia (University of Agriculture, Peshawar) for useful discussions and valuable suggestions. Dr. Zafar Mahmood Khattak and Dr. Audil Rasheed helped in designing the experiments and collecting and analysing the data. I appreciate their untiring support and have always enjoyed our conversations about water pollution and everything else.

My appreciation also goes to the Environmental Systems Analysis (ESA) Group: Karen, Arnold, Sophie, Lars, Wim, Dolf, André, Bas, Lenny, Rob, Wichertje, Mathilde and Gerbert. I am thankful to the ESA staff for their nice gestures, cheerful company and social gatherings to make my life in Wageningen inspiring and enjoyable. My pleasant roommates, Duku Confidence, Majedul Islam and Dian Afriyanti, created a comforting environment. Mathilde, I thank you for all your administrative and other support. I thank my fellow PhD students for their company and guidance (e.g. ArcGIS aid, modelling discussions etc.): Lucie, Lena, Aritta, Alexey, Eka, Sarahi, Halima, Jillian, Leonardo, Saritha, Maddy, Gabriela and Julia. I very much enjoyed our social activities, such as lunch followed by a Cappuccino at Orion. You will all stay in my heart as my ‘Science Family’ where I felt at home academically. Thanks for your company I hope our roads will cross again in the future.

Dr. Asif Khan welcomed me not only at IIASA but also helped me to understand hydrology. I have nice memories from our visits to Bratislava (Slovakia) and Budapest (Hungary). You contributed to achieving my goal.

I thank Hesham Gibriel for his support and time we spent together during late night useless discussions. You always motivated me and made me happy. My Dutch Pakistani friends, Rajan Pirzada, Nabeel Baig, Nadeem Abbasi, Kamran Bhai, Asad Bhai, Abdul Basit, Zahid Rasheed, Ehtesham and Qamar kept me sane and connected. I value your friendships.

I particularly thank the one and only Zakir Hussain Dahri for his nice and cheerful company during my PhD endeavour. I appreciate that you shared in my struggle, arranged many dinner parties, accompanied me for lunch, the trips we made together, your nice jokes and fights on petty issues, and the countless cups of tea that we shared since 2012. I wish you success in finalizing your PhD and look forward to receive a copy of your thesis. I also remember Ahmad Zakria's cheerful company and all the silly things that we did together, including cleaning my filthy room. I also appreciated Usman's dinners (ROSH) and endless encouragements. In summary, sincere thanks to all my friends for everything you did for me.

No words could adequately express my feelings for my friend Nasir Bilal Mirza, who is just alike my elder brother. You always reduced my stress and trouble, and always helped me. I really enjoyed our European tour (Austria, Luxemburg, Germany, and Belgium). I thank my friend Bilal Bhai for everything and above all for bearing me. I appreciate my friends Shahzeb particularly for cooking *biryani* and *chicken tikka* over the weekends, Usman Kyani for his cheerful company and cracking nice jokes, and Khurram Butt for his numerous *unproductive* but hilarious discussions. My PhD was a great chance to make new friends.

I feel privileged to mention indebtedness towards my dearest friends in Pakistan, Masood Iqbal Awan, Azizullah and Waqar Baig. Their encouragement and continuous moral support paved the way for me. I wish to record my sincere appreciation towards my family, especially Atif Nisar, Umer Farooq, Anis Ahmad and Adnan Bashir for their endless support and warm wishes.

I am highly thankful to my wife Afshan Shahid. Without her support, I would have been unable to reach this goal. I was away from home for over four years, while she took care of everything back home. She is brave: hats off to you. Whenever I was down and depressed my princes and daughter Fatima and son Abdullah would always talk to me about their school life, class mates, games and send jokes with funny faces. This brought life and motivation back to me. They send me their drawings that are posted in my room.

Thank you for supporting me in every step of my PhD . You all share in the success of achieving this PhD

I have sweet memories of my Father Muhammad Shoaib Khan, whom I don't want to write as *Late*. Aba Gee, I won't hear you saying this again *Much tathi?* (Are you angry?) Especially when Pakistan was not playing well at cricket. But I am sure you must be proud over my achievement. I miss you and I wish you could see me......

Last but not least, I want to thank my affectionate mother and aunty Phupo, from whom I learned how to be content and happy with limited resources. Words do not come out easy for me to mention the feelings of obligation towards my mother and Phupo for their love, care and patience. Especially this enabled me to acquire this long desired academic degree.

ABOUT THE AUTHOR

Shahid was born on 10th November 1979 in Rawalpindi town, Pakistan. Shahid was keen to explore about nature at an early age. His favourite childhood books were about natural landscapes and how different coloured things are prepared. He undergraduate education at the University of Agriculture in Peshawar, Pakistan where he graduated with a First Class Honours in BSc Agricultural Chemistry. He would go on to first work in the same University as a Teaching Assistant for one and half years, supervising practical sessions in Chemistry for undergraduates, before enrolling in the MSc Agricultural Chemistry and Environmental Sciences programme. Shahid has experience in pharma industry and worked there for quite some time. In 2010, Pakistan faces sever flood of the history and Shahid was working in flood relief program that changes his mind from Agricultural sciences to Water Quality issues. The MSc programme after opening his eyes to this exciting field, however, could not sate Shahid's appetite. He wanted more. Hence, he decided to change courses opting for a more specialised and technical programme in water quality and environmental modelling. After completing this study Shahid got the opportunity to work with NGO in water sector. After two years of work at that institute Shahid joined Edwardes College as lecturer where he teaches to BSc students regarding water quality and basic of Environmental Sciences. In this respect, he was awarded a Netherlands Fellowship Award (Nuffic-NFP). This programme was an eye-opener for him. Shahid joined the Environmental Systems Analysis Group of Wageningen University and Research, as a PhD researcher. His PhD research focussed on Quantifying the impact of socioeconomic development and climate change on Escherichia Coli in the Pakistani Kabul River Basin. His PhD research was not the part of any project, he worked hard and got some exciting finding which he spread in the scientific community via conferences presentation, workshop presentations and lectures. During his PhD research, he also supported educational activities and gave lecture to MSc students on modelling in support of environmental systems analysis back at Pakistan top ranked universities and research institutes. Shahid is now looking forward to the next challenge in his life and career.

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

For specialised PhD training

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Muhammad Shahid Iqbal

born on 10 November 1979 in Rawalpindi, Pakistan

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Wageningen, 30 August 2017

the Chairman of the SENSE board

Prof. dr. Huub Rijnaarts

the SENSE Director of Education

Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

K O N I N K L I J K E N E D E R L A N D S E
A K A D E M I E V A N W E T E N S C H A P P E N

The SENSE Research School declares that **Mr Muhammad Shahid Iqbal** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 37 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2012)
- Research in context activity: 'Taking initiative and organizing expert and stakeholder workshop on 'SWAT: Soil and Water Assessment Tool' - Peshawar, Pakistan' (2015)

Other PhD and Advanced MSc Courses

- Information literacy PhD including EndNote introduction, Wageningen University (2012)
- Introduction to environmental systems analysis, Wageningen University (2012)
- Project and time management, Wageningen University (2012)
- Scientific publishing, Wageningen University (2012)
- Basic GIS tools and its application, The University of Agriculture, Pakistan (2013)
- Techniques for writing and presenting a scientific paper, Wageningen University (2014)
- The art of modelling, Wageningen University (2015)

External training at a foreign research institute

- Techniques used for water quality assessment in Microbiology lab (e.g. LFU, Micro-lab etc.), Nuclear Institute for Food and Agriculture (NIFA), Pakistan (2013)

Management and Didactic Skills Training

- Teaching to intermediate and BSc students at Edwardes College Peshawar, Pakistan in the courses 'Water quality assessment', 'Basics of environmental sciences' and 'Organic chemistry' (2011-2015)

Oral Presentation

- *Quantifying the impact of flooding in Kabul River Basin.* Workshop Disaster Management at Comstech, the Ministerial Standing Committee on Scientific and Technological Cooperation of the OIC, 22-25 October 2014, Islamabad, Pakistan
- *The Relationship Between Hydro-Climatic Variables & E. coli Concentrations in Surface & Drinking Water of Kabul River Basin, Pakistan.* 18th International Symposium on Health-Related Water Microbiology - WaterMicro2015, 13-18 September 2015, Lisbon, Portugal

SENSE Coordinator PhD Education

Dr. ing. Monique Gulickx

The research described in this thesis was financially supported by NUFFIC under the Netherlands Fellowship Program (NFP) providing a PhD scholarship for Muhammad Shahid Iqbal and financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Photo on the cover page : Sasin Tipchai
Cover design : Gildeprint, www.gildprint.nl
Printed by : Gildeprint, www.gildprint.nl