Anthropogenic impacts on global organic river pollution

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ANTHROPOGENIC IMPACTS ON GLOBAL ORGANIC RIVER POLLUTION

ANTHROPOGENIC IMPACTS ON GLOBAL ORGANIC RIVER POLLUTION

Proefschrift

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To my family

CONTENTS

SUMMARY

Organic pollution of rivers by wastewater discharge from human activities negatively impacts people and ecosystems. Without treatment, pollution control relies on a combination of natural degradation and dilution by natural runoff to reduce downstream effects. To implement integrated water management for organic river quality at global scale, a crucial step is to develop a spatial analysis of organic river pollution threats.

This thesis provides for the first time a quantitative picture of the global sanitation crisis through its impact on organic river pollution from the threats of (1) increasing wastewater discharge due to urbanization and intensification of livestock farming, and (2) reductions in river dilution capacity due to climate change and water extractions. Using in-stream Biochemical Oxygen Demand (BOD) as an overall indicator of organic river pollution, historical (2000) and future (2050) BOD concentrations in global river networks are calculated. Despite significant self-cleaning capacities of rivers, the number of people affected by organic pollution (BOD > 5 mg/l) is projected to increase from 1.1 billion in 2000 to 2.5 billion in 2050. With developing countries disproportionately affected, the results point to a growing need for affordable wastewater solutions.

In many regions of the world, intensive livestock farming has become a significant source of river organic pollution. As international meat trade is growing rapidly, environmental impacts of meat production consumed within one country are produced either domestically or internationally.

A second goal of this thesis is to quantify impacts of international meat trade on global river organic pollution at multiple scales (national, regional and gridded). Using BOD as an overall indicator of organic river pollution, spatially distributed organic pollution is computed in global river networks with and without meat trade, where the without-trade scenario assumes that meat imports are replaced by local production. A particular strength of this method is that it accounts for spatially distributed hydrological conditions.

The analysis reveals a reduction of livestock population and organic pollutant production at the global scale due to international meat trade. However, the actual environmental impact of trade, as quantified by in-stream BOD concentrations, is negative (i.e. an increase in polluted river segments), which illustrates the significance of accounting for self-cleaning capacities of rivers and basin hydrological characteristics when estimating actual impacts of trade on the environment. Furthermore, the results highlight the importance of accounting for spatial heterogeneity of impacts within countries. Such heterogenetities are typically neglected in existing economic methods, e.g. Environmental Kuznets Curve (EKC), that analyze the relation between environmental degradation on the one hand and economic development, including trade and technological innovation, on the other hand.

Given projected negative impacts, potential strategies for reducing BOD loads, improving wastewater treatment efficiency and improving hydrological conditions are reviewed based on examples from China, India and other regions. The discussion points to the need for financial incentives, integrated interventions across multiple sectors, and involvement of public and national governments. A case study in the Ganges river demonstrates that the model in this thesis provides a useful first-order explorative tool for prioritizing river pollution control strategies, which can form the basis for a regional-scale analysis that adds details that cannot be resolved with a global-scale model.

1

INTRODUCTION

1.1. ANTHROPOGENIC DISTURBANCE OF GLOBAL RIVER WATER QUALITY

The benefits of rivers as an essential renewable water resource, are often coupled with unquantified environmental costs [1, 2]. The detrimental effects of human activities on river systems at global scale encompass three chief components: (1) catchment disturbance, which is mainly driven by land use changes, such as extension of cropland and impervious surface; (2) water availability alteration due to agricultural and socio-economic water use and constructions of dams and reservoirs; and (3) water pollution and thermal regime alteration [2, 3]. With respect to human health and freshwater biodiversity, the most direct and detrimental effect is alteration of river water quality. In many cases, river pollution is an international problem that extends beyond a country's borders.

A broad suite of pollutants, including sediments, nutrients, organic pollutants and pesticides/herbicides, affect people and ecosystems worldwide. The links between direct or indirect negative effects of human activities and their major water quality pressures are presented in Figure 1.1.

Elevated sediment loads in the form of suspended particulates in river water are often associated with growth of metal contaminants and absorbed toxic substances, which results in limitation of usable water resources and increases treatment costs. Sources of sediment pollution include erosion of soil-derived particles from agricultural, urban land, and mining land use, which are affected by the construction of reservoirs and even

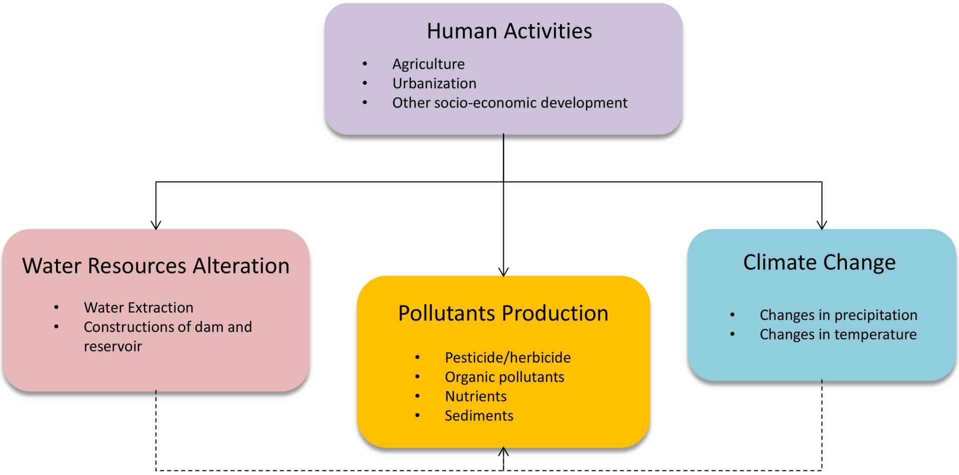


Figure 1.1: Worldwide impact of human activities on river water quality. Dash lines indicates indirect negative effects of human activities on river water quality.

climate change [4].

Nutrient pollution arising from excess application of fertilizers and inefficient management constitute a profound environmental concern at the global scale. Nutrient loads to rivers foster eutrophication (i.e. the increase of primary productivity of freshwater) and a modification of river pH balance. High levels of nutrient concentrations in drinking water pose toxic risks to humans and aquatic animals. Pesticides and herbicides used in agriculture contain xenobiotic substances, and their loading to water bodies imposes chronic toxicity on humans and other species [5].

The discharge of untreated wastewater from urban and agricultural areas, containing large amounts of organic pollutants, causes oxygen deficit in receiving water bodies, and potentially increases concentrations of toxic chemicals and nutrients [2]. Organic pollution in aquatic systems forms the most common and earliest water quality deterioration in the world [3]. Due to the lack of sanitation facilities, organic pollutants combined with high faecal contamination from human and animal excreta result in hygienic problems and a variety of diseases, including diarrhoea and typhoid fevers[6]. Transmission of diseases affects human health through ingestion of water via various pathways.

Decline in river water quality has also been associated with the consequences of human disturbance of available water resources [7]. The intensive use of water resources for agricultural and socio-economic activities results in decline of river dilution capacities, so that water quality severely deteriorates, and causes strong conflicts between multiple water users [8]. Construction of dams and reservoirs disrupts downstream flows and affects ecological connectivity and water quality of rivers [9].

Last but not least, there is evidence that climate induced changes in rainfall and air temperature lead to degradation of river water quality. Potential changes in precipitation could affect river discharge, and further influence the mobility and dilution of contaminants [10]. Increased stream temperature due to atmospheric warming has an influence on chemical reaction kinetics and bacteriological processes of various water quality parameters, such as biological oxygen demand (BOD), nitrogen concentration level, growth rates and numbers of phytoplankton, coliform bacteria and other temperature-dependent micro-organisms [11].

1.2. GLOBAL RIVER WATER QUALITY ASSESSMENTS

The Global Environment Monitoring System for freshwater (GEMS/Water) established by the United Nations provides crucial monitoring records on river water quality worldwide. The program relies heavily on data delivered by countries and constitutes more than 100 parameters from organic pollutants to major ions for about 3000 stations [12]. Developed countries dominate the number of water quality measurement stations. Since the end of the last century, a few developing countries started building national water quality monitoring networks, for example, the National Programme of Monitoring of India National Aquatic Resources (MINARS) and the Environmental Management System (EMS) in China, and have received profound improvement in water quality monitoring [13, 14]. Nonetheless, most developing countries, especially the least developed ones, have inadequate spatial and temporal coverage [1]. In parallel, research data on water quality in several major rivers are also available, but these studies are generally derived from isolated data instead of continuous observations [3].

Thus, large information gaps regarding water quality assessment still exist. Discrepancies in the number of stations, the type of water quality parameters, the frequency of data submission and the accuracy of measurement in targeted countries limit authoritativeness and reliability of available data. The success of evaluating anthropogenic impacts on global river water quality relies on sufficient data through time and space. Models and detailed spatial analyses are therefore needed to fill the gap [2]. Modelling of global-scale river water quantity and modelling water quality over small regional domains both have been studied a lot, while global-scale models of water quality are still in their infancy, especially for in-stream water quality modelling [15, 16]. The reasons for this have to do with the more complicated system geometries, kinetics and time variation for water quality modelling at large scales [17].

1.3. ECONOMIC DEVELOPMENT AND ENVIRONMENTAL QUALITY

The relationship between environmental and economic development has sparked a sizeable literature and has led to a theory for the relation between environmental pollution and income level called the Environmental Kuznets Curve (EKC). This hypothesis states that environmental quality deteriorates faster than income at initial stages of economic development and subsequently improves at higher income levels [18].

Economic development affects environmental pressures via three paths: scale effects, technological effects and composition effects [19]. First, a scale effect indicates more natural resources as input are used for production, resulting in more by-products in the form of wastes or emissions that deteriorate environmental quality. Second, as nations become wealthy and environmental awareness grows, more investments are applied to cleaner technology and environmental improvement, which constitutes a technological effect. Finally, economic structure in rich nations tends to change from polluting to environmentally friendly activities through a composition effect. International trade may further move polluting production processes from one country to another, resulting in virtual trade of pollution between countries. Therefore, environmental pollution in rich nations is expected to keep increasing with economic growth in the absence of virtual trade of pollution and wastewater control as shown in Figure 1.2. Market mechanism shifts, environmental regulation enforcement and political change can affect environmental pressures [20]. Due to the lack of data for many countries, most of the empirical studies used cross-sectional panel data to study the relation between eco-

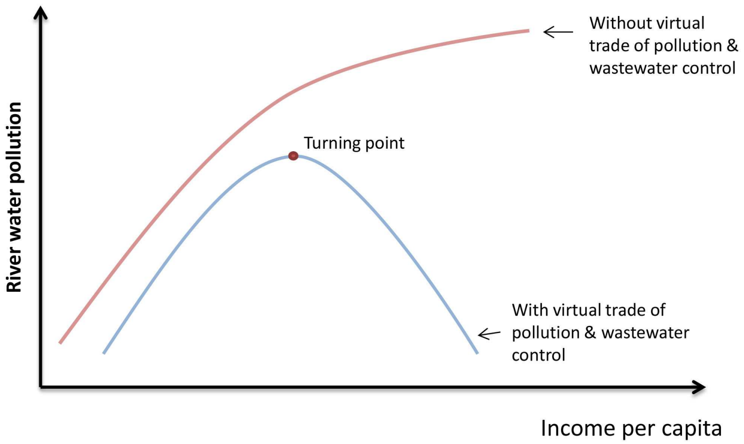


Figure 1.2: Hypothesized relations between country-level river water pollution and per capita income according to Environmental Kuznets Curve theory.

nomic development and environmental pollution. EKC uses income level as an overall measure of economic development. Indicators of environmental quality such as air and water pollutants, clean water supply and urban sanitation have been used as dependent variables in panel regressions to test the existence of an EKC [21]. The theory only applies well to some substances of air pollution [19].

1.4. ENVIRONMENTAL IMPACTS OF INTERNATIONAL TRADE IN LIVESTOCK PRODUCTS

An important example of virtual trade in (organic) pollution relates to livestock farming and meat trade. Livestock production is undergoing rapid intensification to satisfy growing global demands. This intensification manifests itself in multiple ways by impacting the environment and expanding across the world via increasing international trade. Trade in livestock products, especially meat, has grown rapidly due to a population explosion and increases in income. The quantity of international meat trade has increased by 75% from 2000 to 2013 [22]. The expansion of meat trade is likely to continue over the next decades.

Trade allows consumers to access products from a distance and live far removed from the potentially negative environmental impacts of their production. Overall environmental impacts due to international trade result from the relative impacts between exporters and importers. If the environmental impact is lower in the exporting countries than that in importing countries, the trade relationship is considered environmentally beneficial [23]. The comparison is more complex in large countries, due to the spatial heterogeneity of environmental inputs and production processes.

Increases in livestock production are coupled to a rise in animal feed trade, which results in changes in water, agricultural land and fertilizer use. By comparing water efficiency between trade partners (i.e. the differences of water volume consumed for producing livestock commodities by exporter and importer), global water savings are obtained by trading livestock products [24], and the savings significantly increased from 1986 to 2007 [25]. Similar to studies on global water savings, the concept of land use efficiency (i.e. the crop yield per land area) has been applied to evaluate land values embedded in international trade. For example, global land savings have occurred due to trade of soy-based feed (including soybean and maize) [26].

Another complication of trade in livestock products is emission of greenhouse gases from agricultural activities and transportation. Unlike for water and land, greenhouse gas emissions during transportation are important and must be accounted for when calculating impacts of trade. Potential contributions of the trade in livestock products to climate change require further research [23].

1.5. PREVIOUS GLOBAL-SCALE ASSESSMENTS OF ANTHROPOGENIC EFFECTS ON RIVER WATER QUALITY

To date, only a limited number of pollutants (nutrients; BOD; total dissolved solids) have been modelled at global or large scale and then mainly focused on pathways and loadings into rivers [16, 27]. For instance, the Global Nutrient Export from Watersheds model (NEWS) calculates annual average nutrient yield at river mouths as a function of natural and anthropogenic landscape properties in the basins [28]. In this model, in-stream pollutant concentrations are calculated via simplified biochemical reactions. For example, average monthly in-stream BOD concentrations on the European continent were calculated via a non-linear formulation with a temperature dependent decay rate [15].

Modelling climate-related impacts on fresh-water quality have received increasing interest in the last few years [10, 29]. The diversity of climate change models challenges scientific understanding of the physical processes that drive climate and hinders political decision making [30]. Nonetheless, climate model scenarios can support building illustrative projections of climate-induced changes in fresh-water quality and have instigated research on potential changes in surface water quality at multiple scale [27, 31–33].

With the development of global environment assessment and modelling, especially in the field of high-resolution spatial analyses, scientists are able to evaluate the links between environmental pollution and economic development. An EKC was found using measured metal and organic matter data as river quality indicators in Western Europe [3]. Water quality in Western Europe deteriorated rapidly from 1950 onwards due to industrial development, population growth and lack of appropriate wastewater treatment, but has subsequently improved by financial investment and technological innovation of wastewater treatment since 1970. Another study on global river biodiversity and water security, based on high-resolution spatial analysis, also concluded that rich nations could reduce their high levels of negative impacts through environmental regulations [2].

At the global scale, trade of feed crops has contributed to elevated water pollution of nitrogen and input of phosphorous from agricultural activities [34, 35]. However, application efficiencies of nutrients between trade partners in these studies were not compared. In addition to the stage of feed production, pollution from the stages of production of live animals and processing into final products cannot be neglected. A previous global model tracking land, nitrogen and water inputs for these three stages emphasized the urgent need for improving environmental input efficiencies [36]. Again, the conclusion from this study is not clear regarding the overall environmental impacts. Furthermore, these country-level assessments did not include consideration of spatial heterogeneity, which leads to loss of spatially detailed information on natural resource scarcity and ecosystem vulnerability.

1.6. OBJECTIVES OF THESIS

As previously mentioned, anthropogenic activities and ongoing climate change pose huge challenges for global sustainability of river ecosystems. The global sanitation crisis is approaching like a relentless steam roller [37]. Where are the hot spots and what type of measure will be most effective? These important questions form the focus of this thesis. Fist, assessment of worldwide river ecosystem health requires understanding of global-scale river water quality patterns and their trends. Second, river self-cleaning capacities, which play an important role in downstream impacts and are affected by climate change and human disruptions of natural river flows, were neglected in previous global-scale studies. Third, impact of international trade in livestock products on global water pollution is still an important gap. Last but not least, due to uneven socio-economic conditions, the roles of different socio-economic drivers such as urbanization, wastewater treatment and trade on global water quality need to be evaluated.

To meet these challenges and to seek suitable solutions for future water management, this thesis develops a global-scale model for assessing river organic pollution, which is a significant component of aquatic health. Thus, the overall objective of the thesis is to quantify global anthropogenic impacts on organic river pollution accounting for the following factors:

(1) Increasing wastewater discharge due to urbanization and intensification of livestock farming.

(2) Changes in river dilution capacity due to climate change and water extractions.

(3) Environmental externalities due to growing international trade in livestock products.

(4) Effects of international trade and wastewater treatment investments as a function of economic development.

It is worth noting that organic river pollution is not a complete indicator of river health, but aims to provide a sufficient understanding of essential effects of multiple factors and a generic framework for estimating other substances of river water pollution.

1.7. OUTLINE OF THE THESIS

The thesis is organized as follows:

Chapter 2 contains information on (1) modelling strategy and model equations for computing global river organic pollution, (2) all spatially distributed model inputs, (3) a comparison of model results to observed historical organic pollution, and (4) a reflection on model reliability in light of the most important assumptions made in the model.

Chapter 3 presents a quantitative assessment of urbanization, intensive livestock farming and global climate change impacts on organic pollution of rivers, based on simulated BOD concentrations for historical (2000) and future (2050) conditions under various scenarios. In this chapter, the effects of wastewater treatment in different economic groups are also discussed.

Chapter 4 presents a new method to quantify the impacts of international trade in livestock products on organic river pollution. Taking meat trade as an example, the method accounts for self-cleaning capacities of rivers, spatial heterogeneity of hydrological characteristics and socio-economic conditions, as opposed to country-level assessments used in previous studies. Subsequently, the impacts of international meat trade on global river organic pollution at multiple scales (national, regional and gridded) are evaluated, and results are compared to previous studies (including EKC studies) on environmental impacts of global trade.

Chapter 5 discusses the portfolio of available policies to curb projected increases in organic river pollution due to urbanization, intensive livestock farming and climate change, and to reduce impacts of international trade. Taking the Ganges river as an example, several alternative policies are quantitatively evaluated and compared using the global-scale model from chapter 2.

Chapter 6 synthesizes the essential contributions of the thesis, and proposes recommendations for further research on global river water quality and management.

2

A GLOBAL MODEL TRACKING HISTORICAL AND FUTURE RIVER BOD CONCENTRATIONS

Based on: Yingrong Wen, Gerrit Schoups, and Nick van de Giesen. Organic pollution of rivers: combined threats of urbanization, livestock farming and global climate change, *Scientific Reports*, 7:43289, feb 2017.

2.1. INTRODUCTION

The previous chapter briefly discussed the importance and the challenges of modelling impacts of human activities and climate change on global organic river pollution. Organic pollution of rivers by wastewater discharge from human activities (cities, farming, industry) affects humans and ecosystems worldwide through the global sanitation crisis. First, untreated urban sewage contains pathogens that cause a variety of diseases, including diarrhoea [6], globally the leading cause of illness and death. As of 2015, up to 2.4 billion people, primarily in sub-Saharan Africa and southern Asia, lack access to proper sanitation [37]. Second, accumulation of organic pollutants in rivers stimulates microbial growth, leading to oxygen depletion and disturbance of the entire river ecosystem [38].

The level of organic pollution in a river, commonly expressed by the Biochemical Oxygen Demand (BOD) [2], is the result of two counteracting mechanisms: pollutant loading and natural cleaning (Fig. 2.1). Wastewater discharge from cities and intensive livestock farms constitute the main organic pollutant loads into rivers [3, 39]. With rapid urban population growth expected in the next decades, both sources of organic pollution will increase [40]. Although pollution is introduced at wastewater discharge points along the river, impacts extend to downstream populations and ecosystems, as pollutants are transported through the river network [41]. The extent of downstream impacts depends on self-cleaning capacities of rivers via dilution by natural runoff and natural degradation by micro-organisms. Changes in river discharge due to climate change affect river dilution capacities, increasing the risk of river pollution in areas that experience reductions in climate wetness [42, 43]. Increases in water extractions to support a growing global population may further decrease river dilution capacities.

Quantitative assessments of human and climate effects on increasing in-stream BOD have been carried out at catchment and continental scales [15]. However, climate-related organic river pollution requires a global perspective to articulate the geographic linkage of urbanization, intensive livestock farming, and freshwater variability. Global-scale studies of river BOD so far have ignored wastewater from livestock farming and self-cleaning capacities of rivers by natural degradation [44, 45], as well as future climate-related changes in river dilution capacity [2]. Here, historical and future in-stream BOD concentrations are calculated for the first time in global river networks, accounting for BOD loading from urban areas and intensive livestock farming, wastewater treatment, downstream transport, dilution and natural degradation.

In this chapter, first, more details on the conceptual and mathematical underpinnings of the model are provided. Detailed information on all spatially distributed model inputs is described in Section 3 and Appendix. Comparison of computed BOD concentrations to observations from global, continental, and national river BOD datasets in Section 4 provides confidence in the presented results. Assumptions and possible extensions of this model in light of available data are discussed in Section 5.

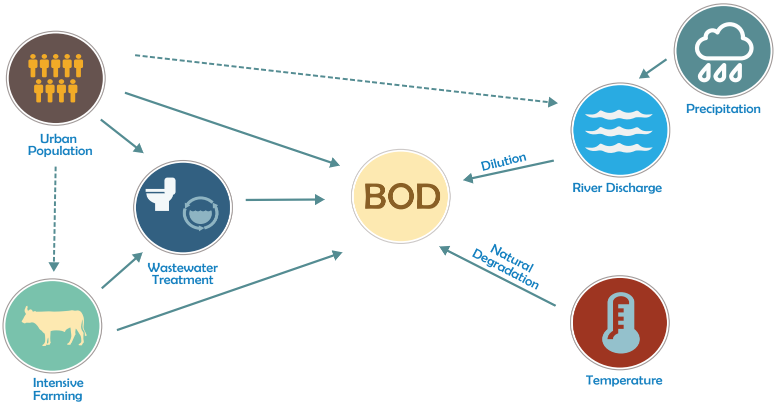


Figure 2.1: Variables and processes affecting organic pollution of rivers, expressed as in-stream Biochemical Oxygen Demand (BOD).

2.2. MODELLING STRATEGY AND EQUATIONS

Figure 2.2 shows a conceptual diagram of this approach for computing in-stream BOD concentrations as a function of urban organic pollution production, wastewater treatment, intensive livestock farming, upstream-downstream transport, dilution, and natural degradation. The approach follows Voss et al. [15], who applied a similar model to European river networks. Vörösmarty et al. [2] also included BOD in their global analysis but did not account for natural degradation, neither did they look at future changes. The calculation is implemented on a 0.5-degree grid, and thus only major rivers are taken into account, with urban regions and intensive farming areas that are within 5 km of a major stream included as point sources.

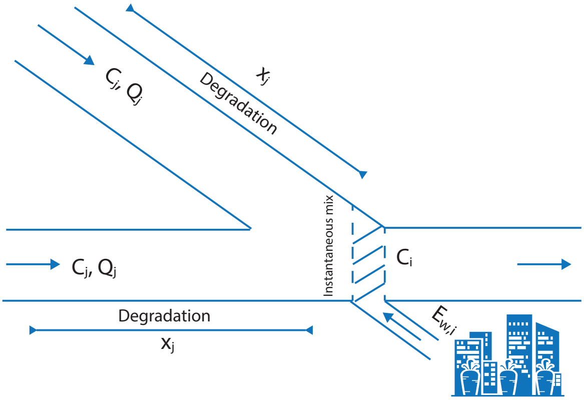


Figure 2.2: Conceptual diagram of computing in-stream BOD concentrations.

Estimating in-stream BOD concentrations along discretized river networks is based on a local mass balance that relates downstream concentration in a river segment or grid cell to concentrations in upstream segments: C_i is BOD concentration in segment i (mg/l) after mixing, Q_i is discharge in segment i (l/day), x_j is length of river segment j (m), $E_{w,i}$ is local BOD load from urban wastewater and intensive livestock farming into segment i (mg/day), calculated as:

$$E_{w,i} = P_i E_{hum}(1 - \sum_{t=1}^{3} f_{i,t} w_{i,t}) + \sum_{a}^{4} P_{a,i} E_a (1 - 0.85 p_i) \tag{2.1}$$

where P_i is urban population in grid cell i, E_{hum} is country-average BOD production from urban population (mg/person/day), $f_{i,t}$ is the fraction of urban domestic wastewater collected for treatment type t with treatment efficiency $w_{i,t}$, $P_{a,i}$ is the population of livestock type a raised in intensive farming system in grid cell i (a = chicken, pig, water buffalo and cattle), E_a is average BOD production from livestock type a (mg/stock/day), p_i is the proportion of livestock farming wastewater collected for treatment. There were no data available for intensive livestock farming treatment levels, all livestock farming treatment levels are assumed as secondary, i.e. 85% treatment efficiency [46]. This approach differs from previous work where BOD loads were based on estimated nitrogen (N) emissions and BOD:N ratios [2].

Assuming stream and wastewater discharge are at steady state, and instantaneous full mixing of all flows, the total BOD load $L_{BOD,i}$ into downstream segment i can be calculated as:

$$L_{BOD,i} = \sum C_j Q_j e^{-k(T)t_j} + E_{w,j} \tag{2.2}$$

where the sum is over all upstream river segments draining into grid cell i. The instantaneous mixing concentration of BOD is:

$$C_i = \frac{L_{BOD,i}}{Q_i} \tag{2.3}$$

The travel time for BOD in each upstream segment is calculated as:

$$t_j = \frac{x_j}{v_j} \tag{2.4}$$

where v_j is average flow velocity in river segment j (m/day).

The first-order degradation rate coefficient k is temperature T dependent according to [47]:

$$k(T) = k(20)\theta^{(T-20)} \tag{2.5}$$

where typical values for θ range from 1.02 to 1.15, with a value of 1.047 used in many models [15, 48]. The reported range for laboratory-measured k values is from 0.3 to 0.5 day^{-1} at a temperature of 20°C which is considered representative of field conditions [17, 49]. A value of 0.35 day^{-1} was used in this model, somewhat higher (more conservative) than the value of 0.23 day^{-1} used in a previous study [15].

Calculations for the year 2050 are based on mean projected urban population, intensive livestock farming and discharge, derived from an ensemble of two IPCC emission scenarios (A2 - fast growth, and B1 - slow growth), three coupled atmosphere-ocean General Circulation Models (GCMs), and one Global Hydrological Model (GHM), i.e. WaterGAP [50]. Projections suggest that air temperature will increase by about 1°C in 2050, relative to the 1986-2005 period [51]. A sensitivity analysis showed that an increase in air temperature of 2°C would lead to an increase in annual average river temperature of 1.3°C [52]. A worldwide projected increase of average first-order decay rates due to global warming is up to 10% [11], a small change, suggesting that the direct temperature effect of climate change on river BOD concentrations is small, especially compared to effects of changes in river discharge.

2.3. MODEL INPUTS

2.3.1. MODEL INPUTS FOR HISTORICAL CALCULATIONS (YEAR 2000)

Data input into the model equations can be divided into model inputs for historical calculations (year 2000) and for changes in the future (year 2050). Table 2.1 gives an overview of all data sources and methods related to estimating model inputs.

Table 2.1: Overview of sources and methods for estimating model inputs.

Parameter	Symbol	Values	Sources
Upstream/downstream river segments	j/i	By grid cell	[53]
River discharge	Q_i	By grid cell	[54]
River length	X_j	By grid cell	[53]
River flow velocity	v_j	By grid cell	[55]
First-order rate coefficient for natural degradation	k	0.35 day^{-1}	[47]
Human BOD production	E_{hum}	By country	[56]
Urban population	P_i	By grid cell	[57, 58]
Livestock animal population raised in intensive farming system	P_a	By grid cell	[59]
Livestock animal BOD production	E_a	By livestock type	[60]
Domestic wastewater treatment fraction	$f_{i,t}$	By city or country	[27, 61]
Domestic wastwater treatment efficiency	$w_{i,t}$	By country	[62]
Intensive livestock farming treatment fraction	p_i	By region	[63]

Table 2.2: Urban BOD generation data for selected countries and regions [56].

Country/region	BOD (g/cap/day)
South Africa	40±10
Zimbabwe	40±10
Japan	55±10
China	35±10
Africa, Asia, Latin America, Caribbean	35±10
Russia	50±10
Europe	60±10
United States	65±10
Canada	60±10
Australia and New Zealand	65±10

The river network was derived from a global drainage direction map (DDM 30) [53]. DDM30 is a raster map which describes the drainage directions of surface water with a spatial resolution of 0.5 degree. The river length was calculated from DDM 30. Average gridded discharge (from year 1991 to 2000) values were calculated by WaterGAP taken from WATCH 21st century model output [54]. River discharge takes human impacts like dams and water withdrawals and use into account. In the calculation, only the potential active river networks where runoff exceeds 3 mm/yr was considered [64]. The average river discharge in year 2000 is shown in Figure A.1. The average river flow velocity was calculated following Schulze et al., 2005 [55], which used a simple function of discharge. All calculations are performed on the 0.5-degree grid.

Urban daily per capita BOD loadings depend on diet, metabolism, body weight, food preparation habits, bathing, cleaning and laundering. Table 2.2 lists average BOD loadings for domestic wastewater in selected countries and regions. The full list of country-specific BOD generation data is available from the US EPA [56]. For countries where BOD generation data is not known, average continent-based data was used. The global distribution of urban population in the year 2000 is shown in Figure A.2.

BOD pollution from livestock farming varies due to differences in animal type, diet, age, usage, productivity and management [60]. In this model, mean BOD values was used based on livestock manure production and characterization (Table 2.3). Tropical livestock units (TLU) are used to provide an equivalent estimate of livestock biomass. One TLU is equivalent to 250 kg, where one bovine is equivalent to 1 TLU.

Table 2.3: Livestock BOD generation data and animal mass equivalent coefficients [65].

	BOD (kg/1000 kg live animal mass/day)	Average animal mass equivalent coefficients	BOD (g/stock/day)
Buffalo& Cattle	1.6	1	400
Pig	3.1	0.3	233
Chicken	3.3	0.01	8.3

Table 2.4: Threshold density of intensive buffalo and cattle farming in different regions [65].

Region	Threshold density (TLU/km^2)
Central and South America	29
East Asia	15
South Asia	61
Southeast Asia	13
Sub-Sahara Africa	8
West Asia & North Africa	10
Others	25

Maps of global distribution of intensive cattle/buffalo production systems were built based on threshold densities in different regions (Table 2.4). For poultry and pig, such existing maps with a spatial resolution of 0.05 degree were directly used for calculating production. Global distributions of intensive livestock animal production systems in year 2000 are shown in Figure A.3 and Figure A.4.

2.3.2. WASTEWATER TREATMENT

Country-average data of domestic wastewater treatment systems for most countries was used, and treatment fractions were derived from percentages of population connected to different treatment types and percentages of population living in urban areas in the year 2000 (see Figure A.5). For India, China and Brazil, downscaled data of wastewater treatment was used. The overall values for BOD removal fractions were estimated as a weighted fraction of no treatment (zero efficiency), primary treatment (25% efficiency), secondary treatment (85% efficiency) and higher treatment (99% efficiency) [62].

Cities in India were divided into four classes based on population size. Wastewater treatment data for metropolitan cities, Class I cities and Class II cities was taken from a research report on the status of water supply, sanitation and solid waste management in urban areas in India [66]. For less populated cities (Table A.1), country-average values were used.

Wastewater treatment in eastern China and in urban areas is more developed than in western China and township areas, respectively [67]. The eastern part includes the following provinces and cities: Anhui, Beijing, Chongqing, Fujian, Guangdong, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Shandong, Shanghai, Tianjin and Zhejiang. The urban and township areas were derived from global urban settlement points in the year 2000 [68]. Urban wastewater treatment data in China is shown in Table A.2.

Brazilian cities were also divided into five classes based on population size (Table A.3), where 10% of treated wastewater receives primary treatment and 68% receives secondary treatment [61].

Intensive livestock farming is considered a manufacturing activity [63, 69], thus the fraction of manufacturing wastewater treatment data was applied to intensive livestock farming activities (see Fig. A.6).

2.3.3. MODEL INPUTS FOR CHANGES IN THE FUTURE

The average change of river discharge from three GCMS (CNCM3, ECHAM and IPSL) under scenarios A2 and B1 was calculated (Fig. 2.3). Runoff is notably projected to become less in southern Europe, western Africa, northeast of South America and southern Asia. River discharge is projected to increase in high latitudes, wet tropics, eastern part of the United States and southeast Asia. These changes generally agree with projections from the IPCC [70].

Estimates and projections of the total national population of each country or area were calculated based on the proportion of the population living in urban areas, which is uniformed within the countries [57]. The urban population in grid cells was derived from global urban settlement points in 2000 [68].

Assuming exponential growth, urban population in 2050 is calculated by country-based urban growth rates for two scenarios (A2: high fertility, B1: low fertility), which were applied to gridded urban populations in the year 2000 [57, 71]. The national urban population growth rate reads as follows:

$$r_{sc} = \frac{1}{t} ln \frac{u_2 TP_{sc,2}}{u_1 TP_{sc,1}} \tag{2.6}$$

Where r_{sc} is the national urban population growth rate under scenario sc , $u_{1..2}$ is the proportion of the population living in urban areas in two different time periods,

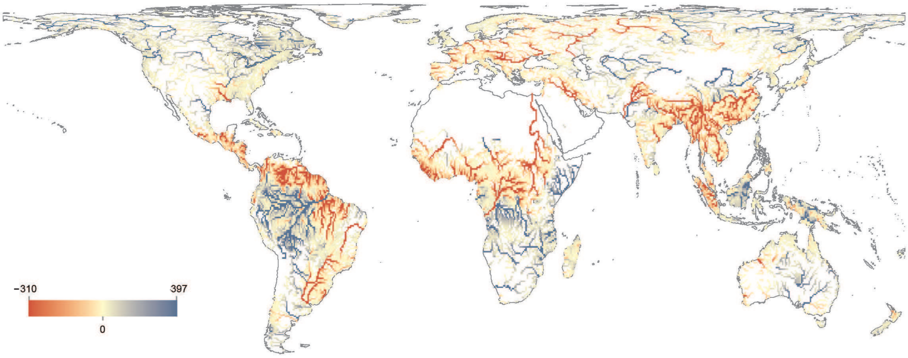


Figure 2.3: Average change of river discharge from year 2000 to 2050 (km^3/yr).

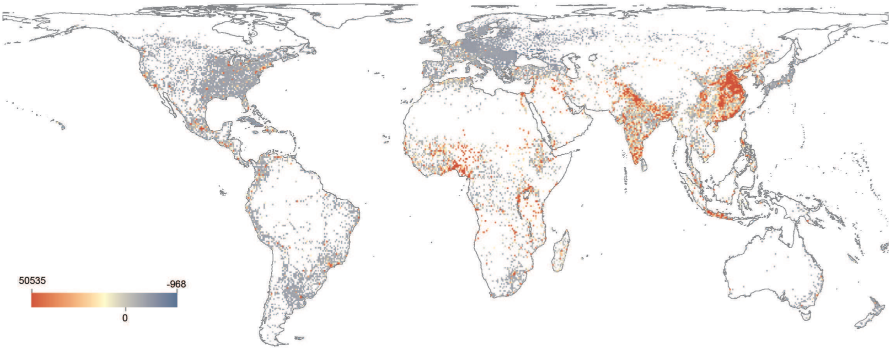


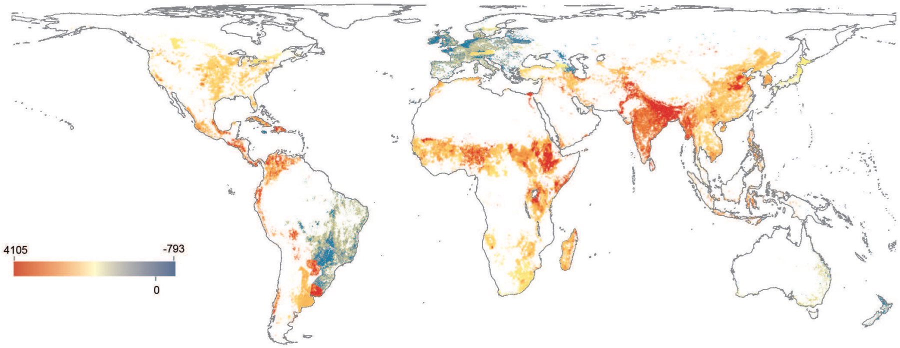
Figure 2.4: Average change of urban population from 2000 to 2050 (in thousands of people).

$TP_{sc,1..sc,2}$ is the total national population and t is the number of years between the two time periods.

Urban population under scenarios A2 and B1 were computed and the average was calculated, then the average was compared with the urban population distribution in 2000 (Fig. 2.4). The most significant increases in urban population occur in China, Africa and the Indian subcontinent. In eastern Europe, some areas are projected to experience a decrease in urban population.

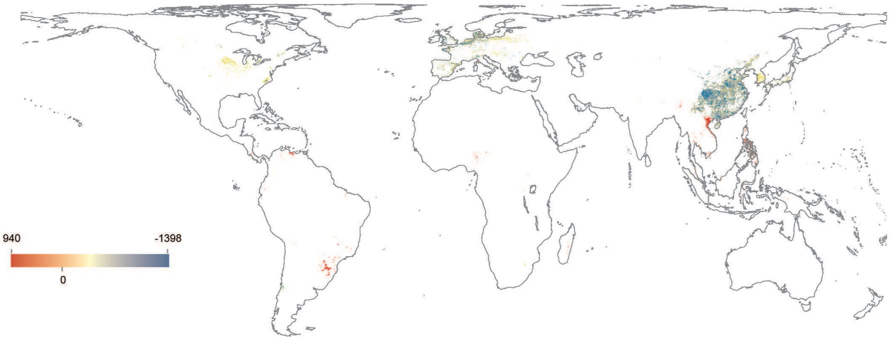
The country-based projections of livestock animal production in 2050 were taken from the output of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), developed by IFPRI [72]. In this model, livestock production is determined by the livestock's price and the prices of other competing commodities, the prices of intermediate feed inputs, and the number of animals slaughtered for meat production. The proportions of livestock raised in both intensive and extensive production systems were assumed to remain the same in the future. Changes in intensive livestock farming systems from 2000 to 2050 are shown in Figs. 2.5 and 2.6. In 2050, the most significant increases of intensive bovine productions are projected to be in India, central Africa and the Caribbean. The intensive production of chicken in China and Europe is projected to decrease, while it is projected to increase in India and Southeast Asia. The intensive production of pig is projected to increase in the United States and Brazil.

Average change of intensive buffalo production from 2000 to 2050 (stock/km^2)

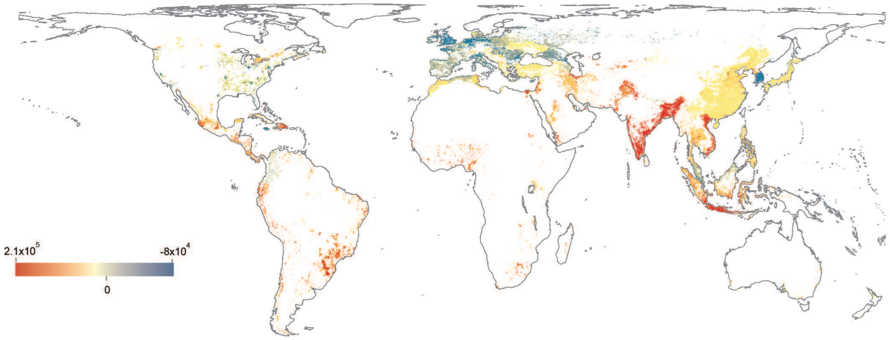


Average change of intensive cattle production from 2000 to 2050 (stock/km^2)

Figure 2.5: Average change of intensive buffalo and cattle production from 2000 to 2050 (stock/km^2).



Average change of intensive pig production from year 2000 to 2050 (stock/km^2)



Average change of intensive poultry production from year 2000 to 2050 (stock/km^2)

Figure 2.6: Average change of intensive pig and poultry production from 2000 to 2050(stock/km^2).

2.4. COMPARISON WITH OBSERVED RIVER BOD CONCENTRATIONS

Measurements of BOD concentrations were taken from the GEMS global river water quality database, the European Waterbase database, the STORET Data Warehouse of the United States, the Central Pollution Control Board of India, the Ministry of Environmental Protection of the People's Republic of China and the National Water Agency of Brazil [12, 73–76]. Measured data in China is reported in pollution classes with corresponding BOD concentration ranges shown in Table 2.5 [76, 77]. Mean values/grades of BOD concentrations were calculated at over 700 observation spots from 1991 to 2000 and compared these with the calculations in this chapter.

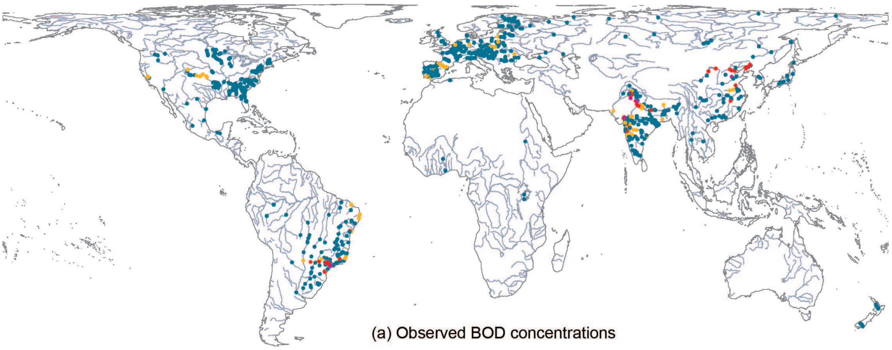
The results show that for the complete data set, the model gives satisfactory results because most calculated concentrations (94%) are in the same water quality class as observed data (Table 2.6), with an underestimation of the number of polluted sites for BOD concentrations in the range 5-10 mg/l. The results conclude that model calculations do not disagree with available data when interest is in assessing river water quality in terms of the broad BOD concentration categories of Table 2.6. In Figure 2.7, which presents the average simulated and measured BOD concentrations at observation stations, underestimation mainly occurs for rivers in Europe and India. A possible reason for these differences is the contribution of industrial BOD pollution, which is not accounted for in this model. The most important industries in terms of organic river pollution are paper and pulp, iron and steel, non-ferrous metals, miscellaneous manufacturing, industrial chemicals, beverages, food production, and rubber and petroleum production [78]. For example, the lower Ebro river in Spain receives sewage from three paper mills, which are important contributors of intensive organic pollutants [79]. Industrial activities are concentrated in big cities along the river and industrial point sources contribute more than 70% of organic matter [80], which leads to observed BOD concentrations between 5 and 10 mg/l (based on 6 locations along the Ebro river), whereas simulated BOD concentrations are less than 5 mg/l. Similarly, the polluted zone of the Krishna river in India is likely due to organic inputs from sugar industries [81, 82], which results in an underestimation of 2 polluted sites in the Maharashtra region with BOD concentrations in the range 5-10 mg/l.

Table 2.5: Classification of BOD concentrations into six classes in China [76, 77].

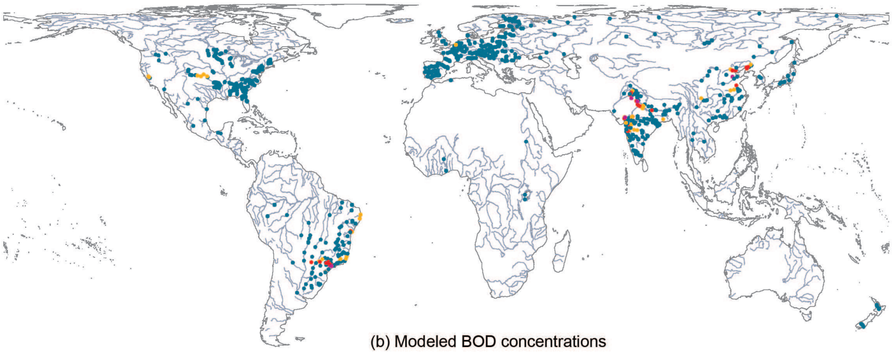
Class	I&II	III	IV	V	VI
BOD concentrations (mg/l)	≤3	3 - 4	4 -6	6 - 10	>10

Table 2.6: Comparison of calculated BOD concentrations to data from the GEMS global river water quality database, the European Waterbase database, the STORET Data Warehouse of the United States, Central Pollution Control Board of India, Ministry of Environmental Protection of the People's Republic of China and National Water Agency of Brazil presented as confusion matrix [83]. Values show the number of locations with observed and calculated concentrations in each of four categories. BOD concentrations above 5 mg/l indicate polluted water and above 10 mg/l require treatment before urban and agricultural reuse [84, 85].

		Observed BOD concentration (mg/l)			
		0-5	5-10	10-30	>30
Calculated BOD concentration (mg/l)	0-5	654	33	5	0
	5-10	1	31	3	0
	10-30	0	0	28	0
	>30	0	0	0	8



(a) Observed BOD concentrations



(b) Modeled BOD concentrations

Figure 2.7: Monitoring stations with average observed and simulated BOD concentration in year 2000.

2.5. ASSUMPTIONS AND POSSIBLE EXTENSIONS OF THE MODEL

Here, the rationale behind several model assumptions, and possible model extensions in light of available data are discussed. A first group of assumptions relates to sources of organic river pollution that are not explicitly included in the model:

- industrial sources: a previous continental-scale study in Europe [46] concluded that organic loads from domestic and livestock farming sources are each at least ten times greater than contributions from industrial activities. As such, organic pollution from industry is considered a secondary driver and not included in the model. However, locally, industrial pollution may still be an important factor: areas where the model underestimates observed concentrations due to potential industrial activities are identified and discussed in the previous section. In the absence of globally extensive datasets, efforts to add industrial sources to the model should focus on these areas first.

- agricultural non-point sources: by their very nature, non-point sources, such as extensive livestock farming and manure applied to agricultural fields, contribute much lower BOD values than effluents from intensive livestock farming, albeit over larger areas. Previous work [45] in extensive livestock areas suggests that in-stream BOD levels exceed the range of natural water only during raining periods. The model is limited to long-term average conditions (steady-state) and ignores such seasonal or shorter-term effects on organic pollution.

- rural domestic sources: following other global river pollution studies [15, 27, 28], Organic pollutants from rural areas were assumed that do not enter rivers due to either collection of human waste in latrines and septic tanks, or retention and degradation in soil.

- wastewater interception and diversion: local effects of urban pollution interception and diversion (e.g. to the ocean as in the San Francisco Bay Area) [86, 87] are not included but could be added where available.

A second group of assumptions relates to parameterization of pollution and degradation processes:

- BOD degradation rates: as mentioned earlier, a constant rate coefficient k of 0.35 day^{-1} is used. This value is similar to laboratory measured values and to a value of 0.23 day^{-1} used in another large-scale modelling study [15]. Previous work [17, 49] has considered these values representative of rivers with discharge larger than 22.7 m^3/s [47] (i.e. most of the rivers in this study). While k values may change spatially with river hydraulic conditions, these effects are currently not included in the model. A possible model extension is to include these effects via settling and bed effects equations in shallow streams [17]. It is worth to note that the direct effect of river flow velocity on degradation *is* included (Eq.2.4). In addition, neither secondary effects of organic pollution such as eutrophication nor light degradation in in-stream reservoirs are included in the calculation in this chapter [2], as it depends on daily or seasonal variation and oxidizable nitrogen compounds in polluted waters [88, 89].

- <u>wastewater treatment fractions and efficiencies</u>: assumed spatial distributions of treatment fractions reflect available data (by city or country for domestic sources, and by region for livestock farming; see section 3.2 and Table 2.1). Similarly, domestic treatment efficiencies are only available by country. In the absence of systematic data on treatment efficiency in intensive livestock farming, a uniform efficiency of 85% (secondary level) was assumed based on the following considerations:(i) other studies [63, 69] considered intensive livestock farming a manufacturing activity subject to secondary or tertiary treatment, at least in European countries [46], (ii) in Asia, effluents from large livestock farms are either diluted and reused for irrigation, or processed through (an)aerobic treatment plants such as lagoons, resulting in organic removal rates that approach secondary treatment levels [90, 91], and (iii) a sensitivity analysis reveals that computed BOD concentrations are relatively insensitive to the assumed efficiency in Africa and South America because of the low fractions of livestock farming wastewater treatment in these regions (from 6% to 20%, Fig. 2.7).

Finally, as with other climate change studies, the projections are subject to uncertainties in future population (e.g. grid-scale projected changes in urban population assume uniform exponential growth rates across each country [58]) and river discharge as simulated by a limited number of scenarios and generally imperfect global climate-hydrological models [30]. Projected river discharge applied in this model generally agrees with forecasting from IPCC (see Fig. 2.3). In addition, one aim of this study is to estimate consequences of river pollution in the absence of additional investments in wastewater treatment. Thus, the projected results rely on the assumption that wastewater treatment remains at current levels.

2.6. CONCLUSION

This chapter presented a global-scale model of in-stream BOD concentrations with details on methodology and inputs. The model constitutes for the first time. A spatially global assessment of in-stream BOD concentrations due to combined threats of urbanization, livestock farming and climate change, and takes the first account for natural degradation mechanism into global-scale analysis. The model is also used for the projection of future organic river pollution with multiple scenarios. Since the comparison is performed in categories, the use of the modelling approach aims to point out potential hotspots of changes in water quality under varied scenarios.

Favourable comparison of the resulting model predictions to data confirms the robustness of the approach of this chapter, although the model was built on some assumptions. The main assumptions concern organic emissions from industries, extensive agricultural activities and rural areas, and interception and diversion of wastewater. Local information on individual catchments, such as industrial activities in Spain and India, has illustrated that it can improve understanding of differences between calculations and observations within the model. Thus, if the focus of water management is on individual basins, it is necessary to use more detailed local information.

Any model must consider the trade-off between model complexity and data availability [92]. As such, a global model of organic river pollution cannot be expected to include all details and processes. Instead, the modelling strategy was to focus on the main drivers, including population growth, intensification of livestock farming and climate change, affecting spatial patterns of organic pollution in global river networks.

3

HISTORICAL AND FUTURE PATTERNS OF ORGANIC RIVER POLLUTION

Based on: Yingrong Wen, Gerrit Schoups, and Nick van de Giesen. Organic pollution of rivers: combined threats of urbanization, livestock farming and global climate change, *Scientific Reports*, 7:43289, feb 2017.

3.1. INTRODUCTION

Using a global spatially distributed framework, a suite of major threats was combined to assess their cumulative impacts on river water quality. Scenarios allow us to quantify the pressure of livestock and human population growth and the contributions of climate change to the levels of organic river pollution in the future. The previous chapter demonstrated the modelling approach, important assumptions and detailed model inputs. Comparison of computed in-stream BOD concentrations to observed datasets provided confidence in the model.

Degrees of organic river pollution are unique to each river resulting from the distinctive hydrological conditions and accumulated stresses along flow paths. In this chapter, the results of the global-scale analysis of historical (year 2000) and future (year 2050) in-stream BOD concentrations are presented, accounting for the threats, separately and combined, of urbanization, intensive livestock farming and climate change.

Taking two representative upstream-downstream transects as examples, this chapter will first highlight the diversity of factors that contribute to levels of organic pollution in river systems. Subsequently, calculated global patterns of organic river pollution resulting from distinct patterns of different factors for the year 2000 is presented. Section 3.3 shows global patterns of simulated BOD concentrations for different scenarios with three GCM models for the year 2050. Given the fact that organic pollution exposes people to direct health risks, the impacts of multiple threats are evaluated by counting changes in population sizes that affected by organic pollution at both catchment and global scales in the year 2050.

3.2. HISTORICAL PATTERNS OF ORGANIC RIVER POLLUTION

3.2.1. UPSTREAM-DOWNSTREAM PATTERNS OF IN-STREAM BOD CONCENTRATIONS

Figure 3.1 illustrates, for the Rhine and Yamuna-Ganges river basins, upstream-downstream BOD concentration profiles that result from the basin-specific interplay of river pollution processes, i.e. pollutant loading at urban settlements and livestock farms, downstream transport, and concentration decrease due to wastewater treatment, natural degradation and dilution by natural runoff.

Without natural degradation and wastewater treatment (purple profiles), BOD concentrations gradually increase along the densely populated Rhine, whereas for the Yamuna-Ganges river a rapid increase near the cities of Delhi and Agra is followed by dilution with freshwater from several large tributaries. Pollutant loading from livestock farming adds significant pollution in both basins, as shown that red profiles lie everywhere above the profiles only with human produced pollutants.

When natural degradation is taken into account (yellow profiles), BOD concentra-

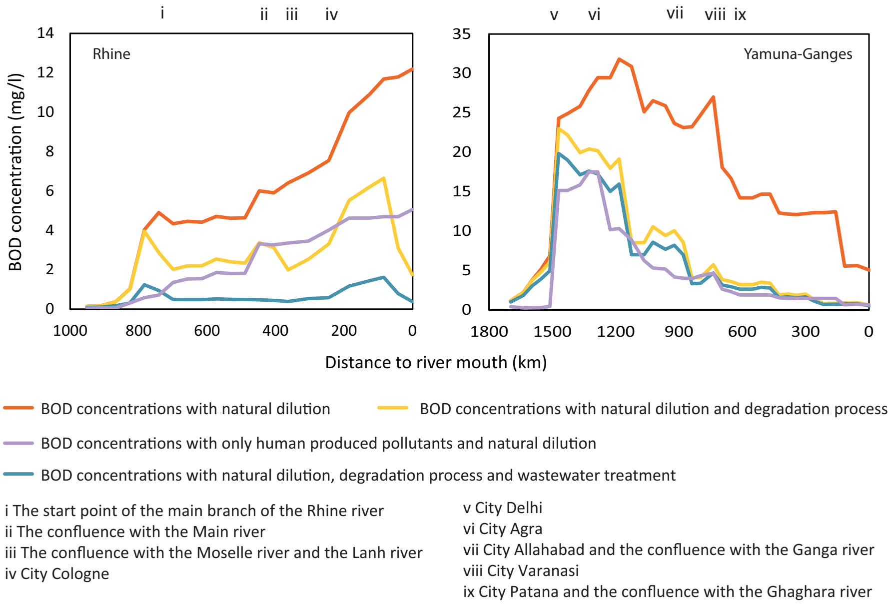
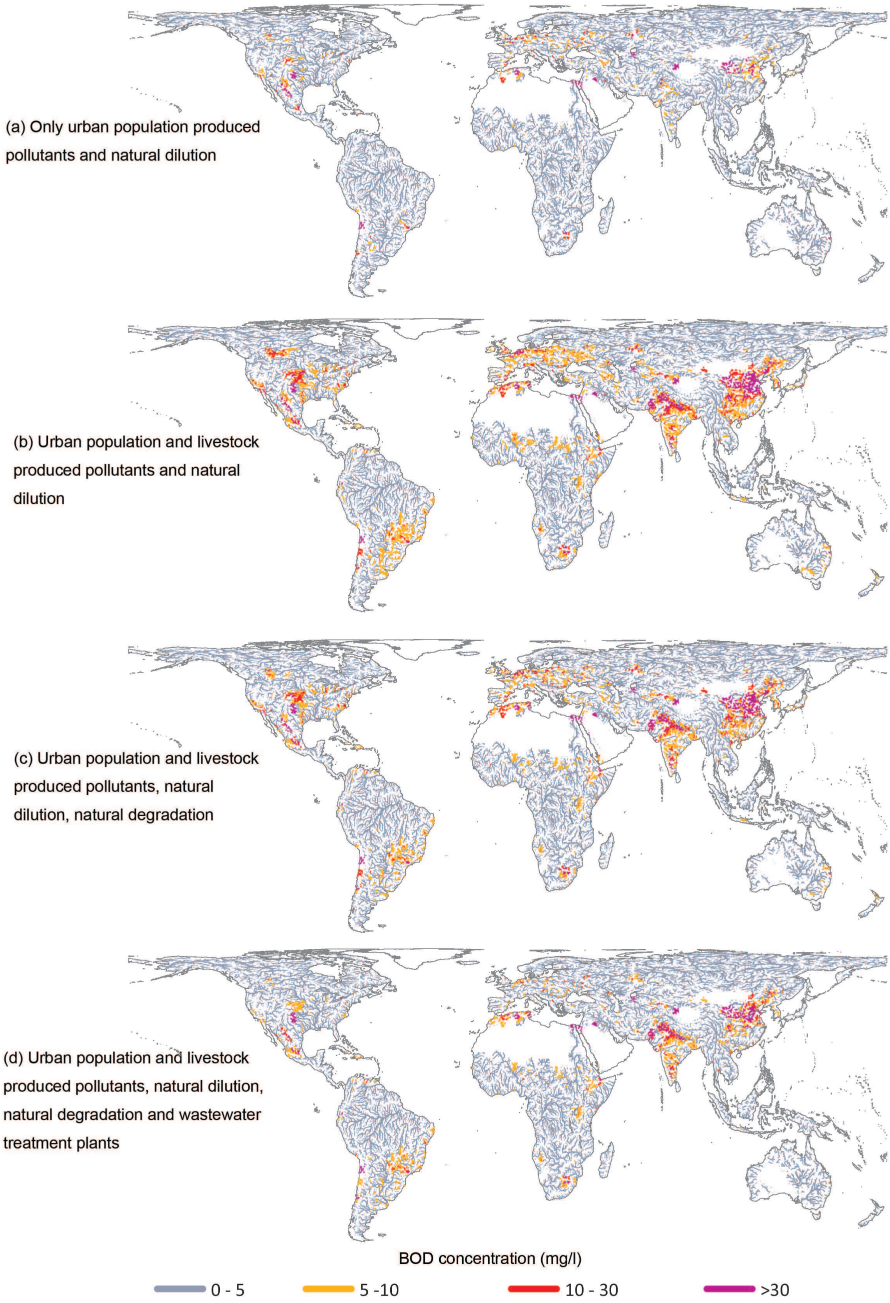


Figure 3.1: Calculated in-stream BOD concentration profiles from headwater to river mouth for the year 2000 along the main stem of the Rhine and Yamuna-Ganges rivers.

tions decrease significantly in both rivers, reducing the downstream effects of pollutant loadings, and illustrating the self-cleaning capacity of natural rivers [44]. Wastewater treatment (blue profiles) further reduces BOD concentrations, especially in the Rhine, but also near Delhi and Agra, which have higher rates of wastewater treatment than smaller cities further downstream [39].

3.2.2. SIMULATED BOD CONCENTRATIONS SEPARATED BY CONTRIBUTING FACTORS IN 2000

Figure 3.2(a) shows river organic pollution directly affected by pollutants produced by urban residents and natural dilution in year 2000. Rivers in mid-eastern China, Northwest Indian sub-continent, Europe, western United States, Morocco, as well as smaller regions in Japan, Korea, Mexico, Caribbean and South America exhibit the most serious pollution. Booming populations in these regions are coupled with expansion of urbanized areas and accelerated development. In the post-war period, economic development has increased migration rates to Third World cities, resulting in increased aquatic pollutant emissions [93]. Many of these regions are approaching severe pollution levels due to uncontrolled growth and water use [94].



(a) Only urban population produced pollutants and natural dilution

(b) Urban population and livestock produced pollutants and natural dilution

(c) Urban population and livestock produced pollutants, natural dilution, natural degradation

(d) Urban population and livestock produced pollutants, natural dilution, natural degradation and wastewater treatment plants

Figure 3.2: Simulated BOD concentrations in 2000 separated by contributing factors.

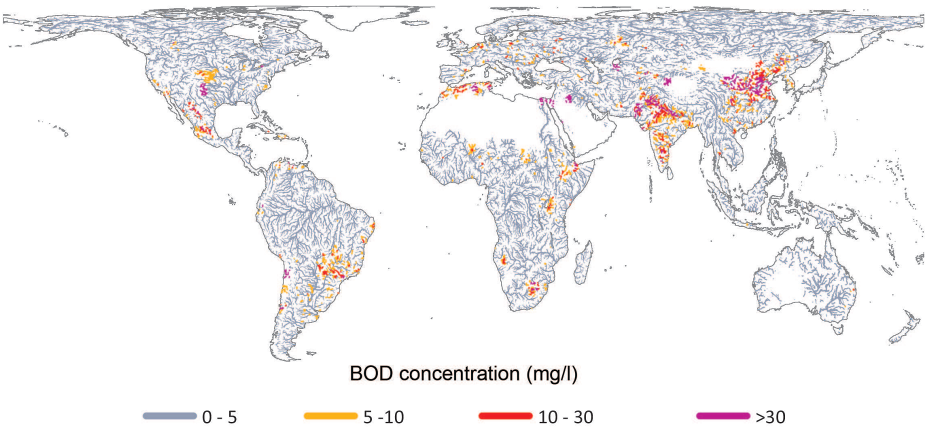


Figure 3.3: Global patterns of computed river BOD concentrations in the years 2000.

Figure 3.2(b) shows global BOD concentrations with pollutants from urban and intensive livestock framing in the year 2000. The impact is overwhelming when compared to Figure 3.2(a). China, Korea, Japan, the Indian sub-continent, Europe, the United States, Mexico, South America and smaller parts in Africa and Australia show significant deterioration of river water quality. These regions are representative for either big consumers or large exporters of livestock products associated with high development of intensive farming.

The effect of decreasing river organic pollution is prominent in parts of Brazil, Nigeria, eastern Europe and southeast China, when natural degradation is also taken into account as shown in Figure 3.2(c). For river systems in Europe, the United States, Japan, Australia and southeast China, organic pollutions are largely controlled as shown in Figure 3.2(d). Because these regions gradually invested more in sewage collection and wastewater treatment, and enforced strict environmental regulations. While rivers in the Indian sub-continent, mid-eastern China, Africa, Mexico, Caribbean and South America still exhibit severe pollution due to a lack of appropriate treatment plants.

3.2.3. GLOBAL PATTERNS OF IN-STREAM BOD CONCENTRATIONS IN 2000

Figure 3.3 shows global patterns of computed BOD concentration for the year 2000 resulting from corresponding spatial patterns in river discharge (Fig. A.1), urban population (Fig. A.2), intensive livestock farming (Fig. A.3 and A.4), wastewater treatment (Fig. A.5 and A.6), and natural degradation. Rivers that flow through humid, sparsely populated areas (high latitude and wet tropical regions) show low or no pollution (BOD <5 mg/l), while several regions with dense human activities and limited dilution power (dry

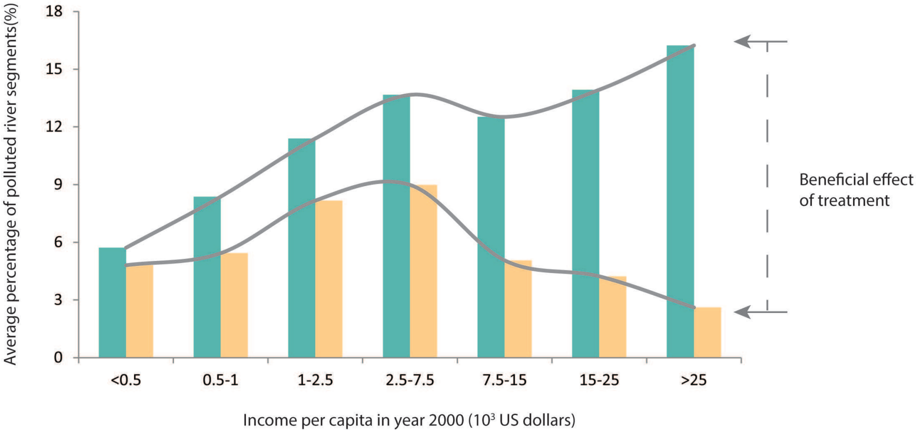


Figure 3.4: Environmental Kuznets curves for the relation between computed country-wide organic river pollution (with and without wastewater treatment) and per capita income in the year 2000.

climates) demonstrate remarkable deterioration of water quality.

As shown in section 3.2.2, the impacts of intensive livestock farming are significantly more widespread than those of urban population (about 5 times more polluted grid cells; Fig. 3.2). Sizeable portions (about 23% of polluted grid cells) of these organic pollutants are naturally degraded. Further reductions in BOD concentrations by wastewater treatment are successful in removing river pollution in large parts of Europe (69%) and North America (68%), while in other regions (Indian sub-continent, mid-eastern China, South Korea, Brazil, Mexico, as well as smaller regions in Africa, south-eastern Asia) wastewater treatment remains insufficient to keep BOD concentrations below 5 mg/l (Fig. 3.3).

These results largely agree with the notion of an environmental Kuznets curve [19], as shown in Fig. 3.4. Relatively low levels of pollution occur in both poor and rich nations due to, respectively, absence and control of pollution sources. Relatively high levels of pollution are found in rapidly developing nations characterized by urbanizing populations and expanding economies that have not yet implemented comprehensive control and treatment of pollution sources [93, 94]. There is however also large heterogeneity within countries. For example, China is one of the fastest growing economies in the world but its urban population and economic development are concentrated in the eastern part of the country. Likewise, organic river pollution is also concentrated in the east (Fig. 3.3), despite a higher rate of 55% wastewater treatment in eastern China compared to 20 % in western China [95]. While urban areas possess financial and technical resources for pollution control, control measures typically lag behind population increase.

3.3. FUTURE PATTERNS OF ORGANIC RIVER POLLUTION

3.3.1. SIMULATED BOD CONCENTRATIONS FOR DIFFERENT SCENARIOS WITH THREE GCM MODELS

By 2050 the world's urban population is projected to increase by 2.5 billion people, with most of this growth taking place in poor countries, particularly in Asia and Africa [57, 73]. Using historical river discharge and intensive livestock production, Figure 3.5(a) shows that population growth is projected to exacerbate river pollution in parts of India, China, Africa, Mexico, Caribbean and South America. Urban population in most of these regions are also projected to grow due to high-fertility rates [96], referring to the global map of urban population change from 2000 to 2050 in Figure 2.4. Urban population in Europe, Japan and South Korea are not expected to change much in the coming decades, a few cities will even experience population decline [57]. However, several mega cities (e.g. Paris, Birmingham, Tokyo and Seoul) with continuously rising populations are projected to experience high environmental pressures.

The accumulated changes of intensive livestock farming deteriorate river water quality in small parts of central Africa, mid-northern India, Caribbean and South America, as shown in Figure 3.5(b), in comparison with Figure 3.5(a). These regions are projected to experience increases of intensive livestock farming as shown on the global map of intensive livestock farming change from year 2000 to year 2050 in Figure 2.5 and 2.6.

Finally, Figure 3.5(c) illustrates the combined effects of changes in urban population, intensive livestock farming and river discharge. Rivers in eastern China, southern India, central Africa, Brazil, Mexico and Caribbean are projected to face the double threat of reduced river discharge and increased pollutants loadings.

Figures 3.7 to 3.9 present simulated BOD concentrations using three different GCM models (CNCM, ECHAM and IPSL) in 2050. River organic pollution calculated by IPSL is the severest. Almost every major river in India is projected to be polluted. South America and central Africa will also face significant organic river pollution.

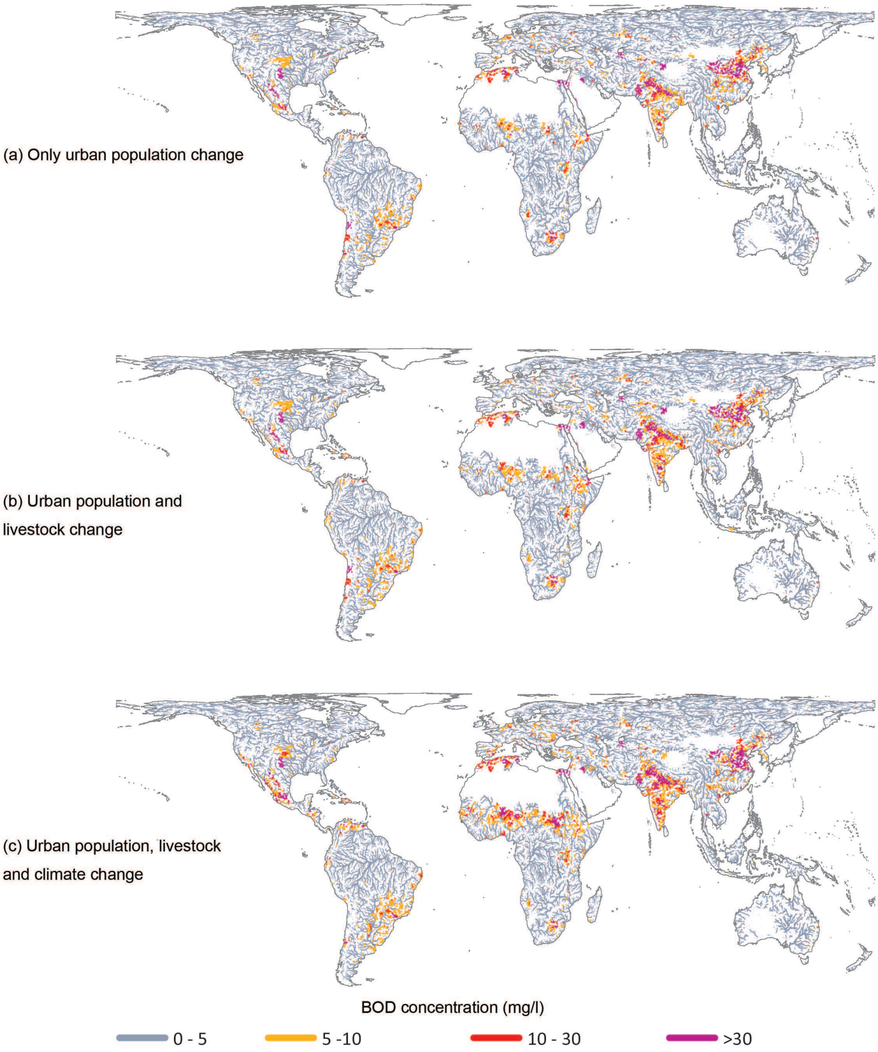


Figure 3.5: Simulated BOD concentrations in 2050 separated by contributing factors.

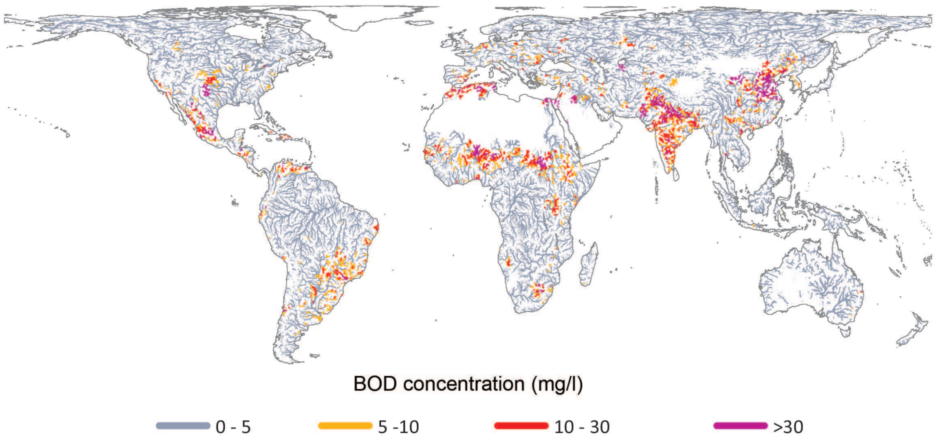


Figure 3.6: Global patterns of computed river BOD concentrations in the years 2050.

3.3.2. GLOBAL PATTERNS OF IN-STREAM BOD CONCENTRATIONS IN 2050

Figure 3.6 shows computed BOD concentrations for the year 2050 resulting from projected changes in urban population (Fig. 2.4), intensive livestock farming (Fig. 2.5 and 2.6), and river discharge (Fig. 2.3), the latter due to climate change and changes in water extractions to support a growing global population. A sensitivity analysis suggests that the effect of temperature change on natural degradation is secondary (see in section 2.2) and it is not included. In all scenarios, wastewater treatment rates are kept constant at their current levels. As such, computed results give an indication of pollution impacts in the absence of additional investments beyond current treatment capacity to curb the global sanitation crisis.

Figure 3.6 shows that by 2050 the biggest deterioration is projected to occur in India, sub-Saharan Africa and Mexico, with many smaller regions all over the world also facing substantial challenges. Urbanization is the main factor in Africa, India, China, and parts of South America ([57, 97]; Fig. 2.4, Fig. 3.1(a)). Intensification of livestock farming is mainly a factor in India, Africa and South America (Fig. 3.1(b)), while intensive livestock farming in Europe and China is expected to stay constant or decline in the coming decades, thereby reducing impacts on river basins in these regions. Finally, regions with a significant decrease in discharge, such as most parts of Europe, West Africa, western and southern Asia, and Latin America excluding the Amazon, experience a decrease in dilution capacity, which translates into increased pollution levels in several river basins (Fig. 3.1(c): Ganges, Yangtze, Indus, Parana, Nile, Danube, Niger). Other basins (Yellow & Huai, Mississippi) benefit from an increased dilution capacity due to a projected increase in mean discharge (Fig. 2.3). However, increased discharge may also have negative effects not accounted for in this analysis. For example, cities may experience pollution surges as increases in urban overload the capacity of sewer systems and wastewater treatment plants [98].

3.3.3. AFFECTED POPULATION AT CATCHMENT AND GLOBAL SCALES

Table 3.1 summarizes the number of people living near polluted rivers for major river basins around the world, with Asian basins (Ganges, Yangtze, Yellow & Huai, Indus) topping the list. Note that about half of the affected people live in smaller basins scattered throughout the world. The numbers in Table 1 also reveal the main pollution sources in each basin, i.e. urban (Yellow & Huai), livestock (Ganges), or a combination of both (Yangtze). Natural degradation and wastewater treatment are most successful in reducing pollution impacts in the Rhine, Mississippi, and Danube basins.

Except for the Rhine, all basins listed in Table 3.1 are projected to experience increasing impacts in 2050 compared to 2000, with the largest increases in Ganges, Indus, Nile, and Niger. Reasons for these increases differ by basin. Urban population growth for the Yellow and Huai, Yangtze, and Mississippi, decreases in river discharge for the Danube basin, and a combination of all three factors for the Ganges, Indus, Parana, Nile, and Niger basins.

Globally, a total of 2.5 billion people (26% of global population) will be affected by living near polluted rivers (BOD $>$ 5 mg/l) in the year 2050, up from 1.1 billion people (19%) in the year 2000. Basins listed in Table 3.1 account for about half of affected people. This is a conservative estimate because several factors not accounted for in this analysis (industrial pollution, eutrophication, seasonal discharge cycles and smaller streams with limited dilution capacity) would further increase these numbers [2, 3].

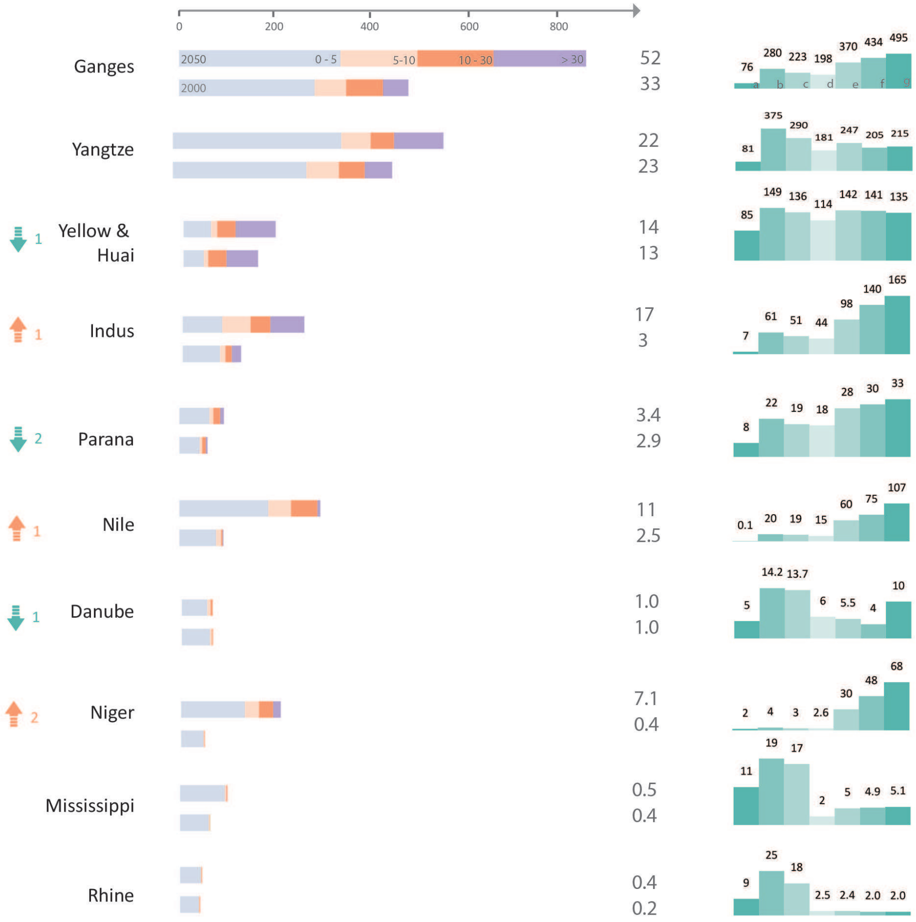
3.4. CONCLUSION

Combined with upstream-downstream transects, global patterns of in-stream BOD concentrations that were simulated with separated contributing factors and scenarios, characterize each river system arising from complex influences of hydrological conditions and human activities. Thus, distinctive patterns of changes in organic river pollution serve to reflect the primary factors of changing levels of organic river pollution and to indicate areas at risk.

Projected global patterns of in-stream BOD concentrations illustrate that on-going and near-future global-scale changes in urbanization, intensive livestock farming and river discharge over the next decades will negatively affect and exacerbate river water pollution problems. With the conservative estimation, there will be more than twice as many people as in year 2000 affected by living near polluted rivers, and large increases will occur in developing regions in year 2050. The results point to a growing need for affordable sewage control solutions.

To obtain a more complete picture of surface water quality, it will be necessary to consider interactions with temporal variability of flows (seasonality, extreme conditions), economic development, hydrological patterns and societal responses to water pollution. In light of the findings in this chapter, an approach integrating urbanization, livestock farming and climate change is an essential part of such an analysis.

Table 3.1: Number of people (in millions) living along polluted rivers in 10 major river basins. Basins are listed from more to less polluted in the year 2000, with green and red arrows to the left indicating their change in ranking in the year 2050.



	River Basin	**Color bars: population in different BOD concentration ranges (10^6); Numbers: fractions of global population affected by organic river pollution in year 2000 and 2050 (‰)**	**Population affected by organic river pollution for different scenarios (10^6)**						
			a	b	c	d	e	f	g
	Ganges	52 33	76	280	223	198	370	434	495
	Yangtze	22 23	81	375	290	181	247	205	215
↓ 1	Yellow & Huai	14 13	85	149	136	114	142	141	135
↑ 1	Indus	17 3	7	61	51	44	98	140	165
↓ 2	Parana	3.4 2.9	8	22	19	18	28	30	33
↑ 1	Nile	11 2.5	0.1	20	19	15	60	75	107
↓ 1	Danube	1.0 1.0	5	14.2	13.7	6	5.5	4	10
↑ 2	Niger	7.1 0.4	2	4	3	2.6	30	48	68
	Mississippi	0.5 0.4	11	19	17	2	5	4.9	5.1
	Rhine	0.4 0.2	9	25	18	2.5	2.4	2.0	2.0

a-d : scenarios in year 2000; e-g: scenarios in year 2050;
a: Only urban population BOD loading and natural dilution;
b: Urban population and livestock BOD loadings and natural dilution;
c: Urban population and livestock BOD loadings, natural dilution and degradation;
d: Urban population and livestock BOD loadings, natural dilution and degradation and wastewater treatment plants;
e: Only urban population change;
f: Urban population and intensive livestock production change;
g: Urban population, livestock production and river discharge.

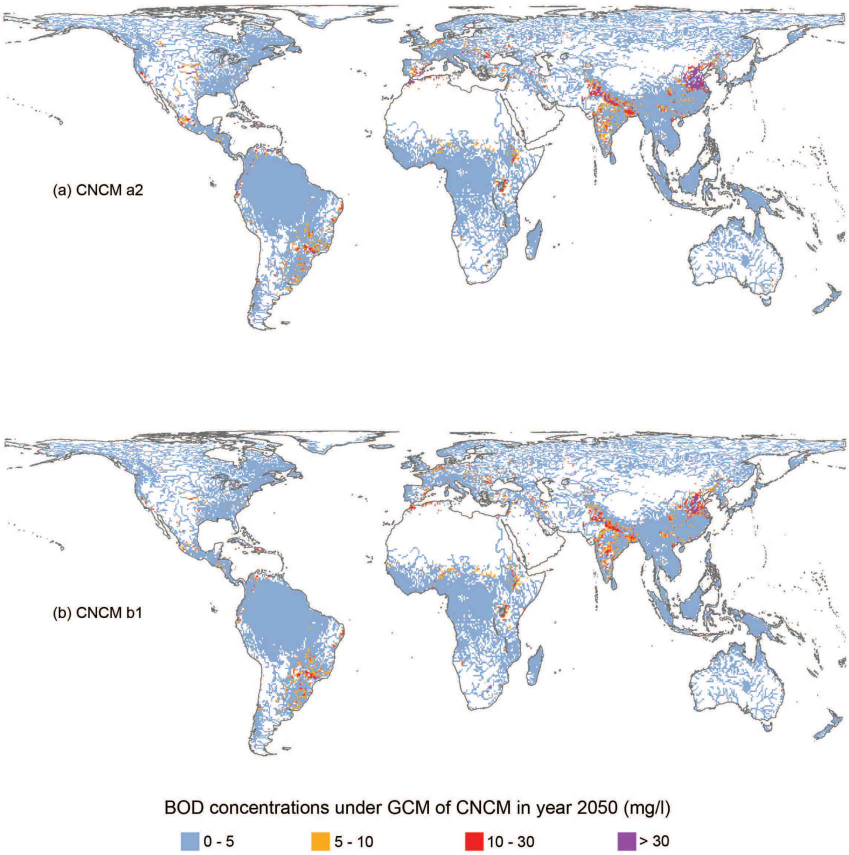


Figure 3.7: Simulated BOD concentrations using GCM of CNCM.

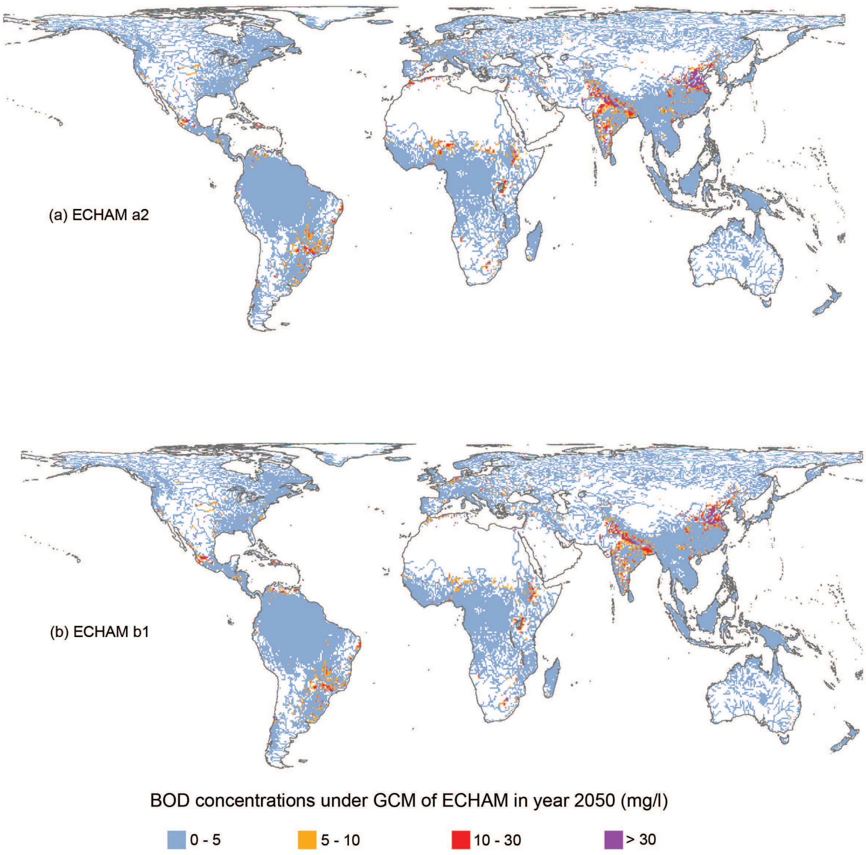


Figure 3.8: Simulated BOD concentrations using GCM of ECHAM.

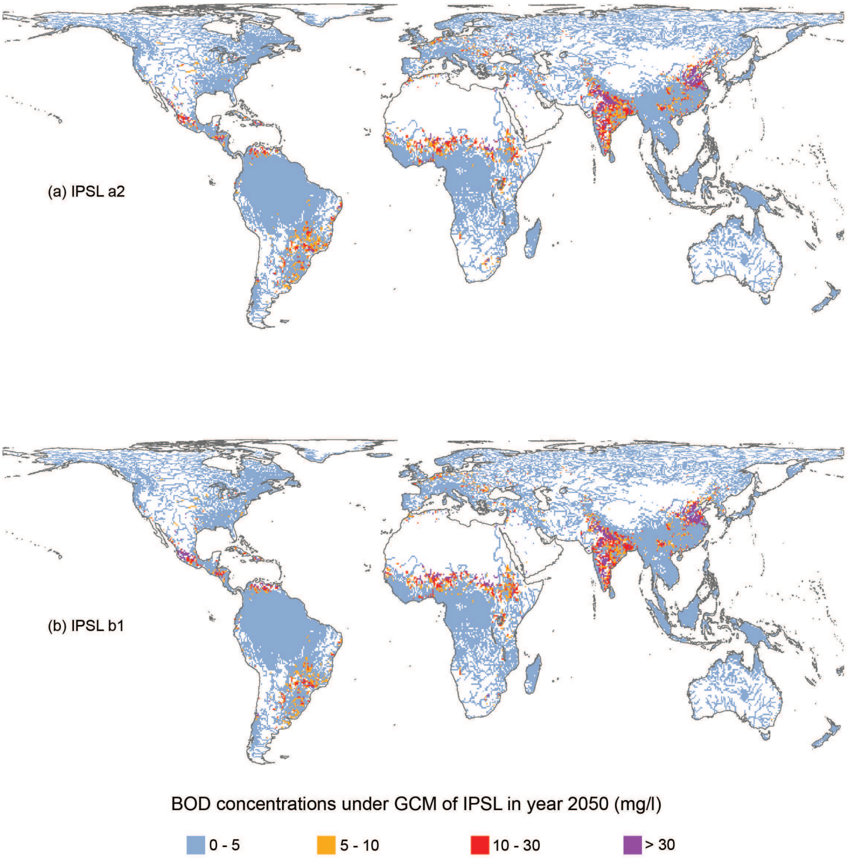


Figure 3.9: Simulated BOD concentrations using GCM of IPSL.

4

GLOBAL IMPACTS OF MEAT TRADE ON IN-STREAM ORGANIC RIVER POLLUTION

Based on: Yingrong Wen, Gerrit Schoups, and Nick van de Giesen. Global impacts of meat trade on in-stream organic river pollution: importance of spatially distributed hydrological conditions, *Environmental Research Letters*, accepted, Oct. 2017.

4.1. INTRODUCTION

Livestock is a key provider of food, income, employment and nutrients to human well-being [99]. Already common in developed countries, livestock farming intensification is rapidly growing throughout developing nations [100]. Besides improving productivity and efficiency, intensification creates additional positive impacts, such as increasing profitability and investment in livestock farms and developing regulations for livestock systems [101]. However, negative impacts on the environment cannot be overlooked, as intensive livestock farming is a major source of global river organic pollution[3, 102]. Discharge of intensive farm effluents rich in organic pollutants contributes to river biodiversity reduction and disruption of aquatic ecosystems through oxygen depletion [2, 45]. These polluted effluents also contain pathogens that threaten human health by causing a variety of diseases, including diarrhea [6].

Production of meat products has increased globally in the past half century [22], a trend likely to continue due to a projected doubling of both meat demand and meat trade in the coming decades, mostly in the developing world, as a result of population growth, urbanization and increased income [40, 103]. As trade of livestock products plays an increasingly significant role in global food supply, it is crucial to better understand and quantify environmental impacts of meat trade and, specifically, effects on organic pollution of rivers. The overall impact of trade on the environment is considered beneficial if moving production to exporting countries generates less pollution than domestic production [23]. Due to spatial heterogeneity of farming practices, natural resource availability and climate, environmental impacts and costs occur over a range of scales (from national, to regional, to local). Such complexity should ideally be accounted for in any impact analysis.

Impacts of trade in livestock products on alteration of global nitrogen and phosphorus cycles are of increasing importance [34, 104], and have been the subject of several studies. O'Bannon et al 2014 [35] quantified leaching and runoff of nitrogen-fertilizers applied to animal feed crops using the concept of 'grey water footprint'(GWF), which is defined as the volume of water needed to dilute river pollutants to comply with existing water quality standards [105]. However, the study did not account for waste produced by livestock, nor did it estimate whether pollution is avoided by trade. Other studies have provided country-level estimates of the effect of international trade in meat products on nitrogen cycling in several major trade countries using the MEAT model, which is a partial equilibrium model that traces nitrogen inputs to different stages of meat production and nitrogen-use efficiency [36, 106]. These studies concluded that current trade contributes to concentrated nitrogen pollution impacts in meat exporting countries, but did not assess the net environmental benefit of trade.

Footprint studies have highlighted that pollution associated with exporting agricultural trade often occurs in developing countries [35, 105, 107]. However, empirical work by economists on the role of trade in improving environmental quality has found that trade has an overall positive impact on environment, because trade liberalization improves efficiency of natural resource use and lowers peak levels of environmental degradation in developing economies [108, 109]. Economists introduced the Environmental Kuznets Curve (EKC) theory, which states that environmental quality deteriorates faster than income at initial stages of economic development and subsequently improves at higher income levels [19]. Income level is used as an overall indicator for all changes, including trade, technological innovation, regulations etc., that accompany economic development [110]. Improvement of environmental quality can be achieved by either (i) importing goods whose production creates pollution (e.g. meat), or (ii) strengthening environmental regulations and investing in local pollution control (e.g. treatment plants). On the other hand, trade may lead to increased pollution in exporting countries. The impact of trade liberalization on environment also depends on available water and land resources in a country [111]. Understanding effects, such as trade and technological innovation, on the environment under different economic conditions is essential to build better environmental policies and to mitigate and turn around negative impacts.

Important shortcomings of previous studies, using either footprint (GWF) or economic-based approaches, are the lack of consideration for within-country spatial heterogeneity of pollution impacts, and reliance on pollutant production or pollutant loadings rather than concentrations in streams. Indeed, in-stream concentrations are arguably more direct indicators of pollution since they include effects of dilution by natural runoff and degradation by micro-organisms. These effects are significant for evaluating the real risk humans would face due to changes in trade and climate.

In this chapter, a new method for quantifying impacts of international meat trade on river organic pollution is developed and introduced by computing spatially distributed organic pollution in global river networks with and without meat trade, where the without-trade scenario assumes that meat imports are replaced by local production. Based on the model introduced in Chapter 2, the resulting changes in BOD emissions are quantified neglecting any subsequent effects of trade restriction, such as changes in efficiency of meat production and wastewater treatment. Global gridded data on hydrology and country based meat trade data are combined to estimate impacts on global patterns of BOD loadings into rivers and in-stream BOD concentrations along rivers. Finally, environmental impacts of the with- and without-trade scenarios are compared using EKC theory.

The novelty of this chapter is threefold: (i) it evaluates trade impacts in terms of freshwater dissolved pollutant (BOD) concentrations, as opposed to GWF or pollutant release into the environment, which are incomplete and indirect measures of freshwater pollution, (ii) it considers spatial heterogeneity of land and water resources, as opposed to country-level assessments reported in the economics and EKC literature, and (iii) it focuses on organic river pollution, as opposed to nitrogen and phosphorous emissions from fertilizer and pesticide use that have been the focus of GWF studies.

4.2. METHOD

4.2.1. COUNTRY-LEVEL BOD PRODUCTION FROM INTENSIVE LIVESTOCK FARMING

The analysis focuses on intensive livestock farming and meat trade of pig, chicken and cattle (incl. buffalo), which together make up almost 93% of total global meat production, with more than half of pig and poultry meat coming from intensive (industrialized) farming systems [112, 113]. Given this focus, BOD production in extensive farming systems is not taken into account, i.e., low density animal farms, BOD production from animal feed crop farming, and BOD production during meat processing. Previous studies on pollution from livestock farming areas suggest that BOD pollution from extensive systems only becomes important under high rainfall conditions. During dry periods, BOD from extensive systems is diffused in the soil and does not end up in streams [45]. Seasonal or short-term effects from extensive systems are thereby of less interest in this research, which considers a steady state, temporally average, situation. In the absence of spatial datasets, BOD production during meat processing is ignored.

Since trade data are available by country, the effect of trade on changes in livestock population and BOD production in intensive farming systems is calculated at country-level. When there is no meat trade, local meat consumption in a country will need to be completely satisfied by local meat production. Hence, in such a scenario, and assuming consumption is constant, a net importer (exporter) will see a corresponding increase (decrease) in local animal and meat production. This leads to the following relation for each animal type (pig, chicken, cattle), country and year:

$$P_{no-trade} = max\left(0, P_{trade} + \frac{Q_{im} - Q_{ex}}{Y}\right) \tag{4.1}$$

Here, P_{trade} and $P_{no-trade}$ are the number of livestock animals (in units of head) slaughtered for meat in intensive farming systems with and without trade, respectively. Q_{im} and Q_{ex} are quantities (ton) of meat imported resp. exported, and Y is meat yield per slaughtered animal (ton/head). This relation assumes that traded meat originates from intensive farming systems, a reasonable assumption since intensification of a single commodity typically leads to better market access [114]. An exception occurs for large net exporters (negative Q_{im} - Q_{ex}) with a significant portion of export originating from extensive farming systems (small P_{trade}), as is e.g. the case for beef in Argentina [22]. In such situations, the $max()$ operator in the equation ensures that the computed number of livestock animals in intensive farms without trade is zero rather than negative.

Next, livestock numbers are multiplied by BOD production rates (ton BOD/head/day) to obtain annual country-level BOD production (ton) from livestock farming. BOD production rates vary by animal type, age, diet, and other factors.

Table 4.1: Data provided by FAO for estimating model inputs [22, 114].

Parameter	Symbol/value	Units
Livestock animal population raised in intensive farming systems	P_{trade}	Head
Yield of meat production quantity and slaughtered animals[1]	Y	Ton/head
Quantity of meat production	Q_{pr}	Ton
Quantity of imported meat[1]	Q_{im}	Ton
Quantity of exported meat[1]	Q_{ex}	Ton
BOD production rate of buffalo & cattle	4×10^{-4}	Ton BOD/head/day
BOD production rate of pig	2.3×10^{-4}	Ton BOD/head/day
BOD production rate of chicken	8.3×10^{-6}	Ton BOD/head/day

[1] Data in trade and yield of pig and chicken meat is defined as meat with bone in, with FAOSTAT item code 1035 and 1058; cattle and buffalo meat include meat with and without bone, with combined item code 2731.

Here, average values are used based on livestock manure production and characterization, while global data on P_{trade}, Q_{im}, Q_{ex}, and Y for the year 2000 were obtained from FAO (Table 4.1). Tropical livestock units (TLU) are used for livestock biomass; one TLU is equivalent to 250kg, where one cattle or buffalo is equivalent to 1 TLU, a pig is equivalent to 0.3 and a chick is equivalent to 0.01 [114].

4.2.2. GRIDDED BOD LOADING IN RIVER NETWORKS

Estimation of BOD loading in river networks is based on the spatial distribution of river networks, intensive livestock systems and wastewater treatment. Gridded river networks were derived from a global drainage direction map (DDM 30) with a spatial resolution of 0.5 degree [53]. In this calculation, rivers as grid cells with runoff exceeding 3 mm/yr were identified[64].

Gridded data of livestock numbers in intensive farming systems were obtained from FAO. For chicken and pig, these were available at a spatial resolution of 3' [114]. For cattle/buffalo production systems, gridded data of total livestock numbers were converted to corresponding maps of intensive livestock numbers by using threshold animal densities which varied by region [114]. Only intensive farming areas that are within a distance of 5 km of a major river were included in the calculation.

The above data are for the current existing situation with trade. To obtain the corresponding gridded numbers for the no-trade scenario, country-level computed values of $P_{no-trade}$ (see previous section) were taken and downscaled to individual grid cells using the same spatial distribution as for the current situation.

As with the country-level analysis in the previous section, the gridded livestock numbers, for both scenarios - trade/no trade, were multiplied by BOD production rates to obtain gridded BOD loading into global river networks. Since part of these effluents are treated before being discharged, the final numbers were multiplied by wastewater treatment fractions which varied by region [63].

4.2.3. GRIDDED BOD CONCENTRATIONS IN RIVER NETWORKS

As a final step, in-stream BOD concentrations along river networks at a spatial resolution of 0.5 degree were calculated as a function of the accumulation of BOD loading, from both urban and intensive livestock areas, wastewater treatment, transportation, dilution and natural degradation. Before loading into streams, urban domestic wastewater receives country-scaled or downscaled treatment with variable levels and efficiencies.

Estimation of in-stream BOD concentrations is based on a local mass balance that relates upstream and downstream river segments [15, 102]. Assuming stream and wastewater discharge are at steady-state, the instantaneous mixing of all upstream flows in one river segment drains into the downstream segment with simultaneous first-order natural degradation. Comparison of calculated BOD concentrations with observations from various river BOD datasets confirmed the validity of this model [102].

Resulting in-stream BOD concentrations were computed for the trade and no-trade scenarios using the respective BOD loading data, as described in the previous section, and with all other model inputs identical, thus allowing quantification of river water quality impacts due to international meat trade. The relatively coarse spatial resolution of the calculations (0.5 degree grid) was locally refined to a 5’ grid for Singapore and Hong Kong due to their small land area yet large population and meat demand [115–120].

4.3. RESULTS

4.3.1. GLOBAL IMPACT OF MEAT TRADE ON BOD PRODUCTION

Figure 4.1 highlights countries where BOD production increases or decreases due to the hypothetical restriction of meat trade. Net importing regions, including Russia, Japan and Saudi Arabia, would experience net increases in BOD production to meet their domestic demands. This includes countries with relatively small land areas compared to their meat demand, such as Singapore and Hong Kong. For large exporters, such as the USA, Brazil, The Netherlands and Belgium, the opposite applies. The large decrease in BOD production in the USA due to chicken farming, mostly for export, especially stands out. For countries with both significant imports and exports, like China and Germany, the impacts are mixed. In China, although domestic livestock production is large, additional imports are needed to meet its large demand for pig and chicken meat.

Tracing the flows of BOD production rates associated with trade, Figure 4.2 shows changes in BOD production for several bilateral trade relationships. For example, local meat demand in The Netherlands can be completely met by extensive livestock farms, which means that, in the absence of trade, current intensive BOD production in the country would disappear and instead would move to the main importers of Dutch meat, i.e. Germany (31%), United Kingdom (13%) and Italy (11%). Both Brazil and USA have large domestic BOD production rates, yet even larger exports (Brazil: 10% to Hong Kong, 9.5% to Japan; USA: 25% to Russia, 9% to Mexico). Russia imports large amounts of meat, corresponding to virtual BOD imports at a rate of 4684 ton/day, compared to domestic BOD production equal to about one third of this value.

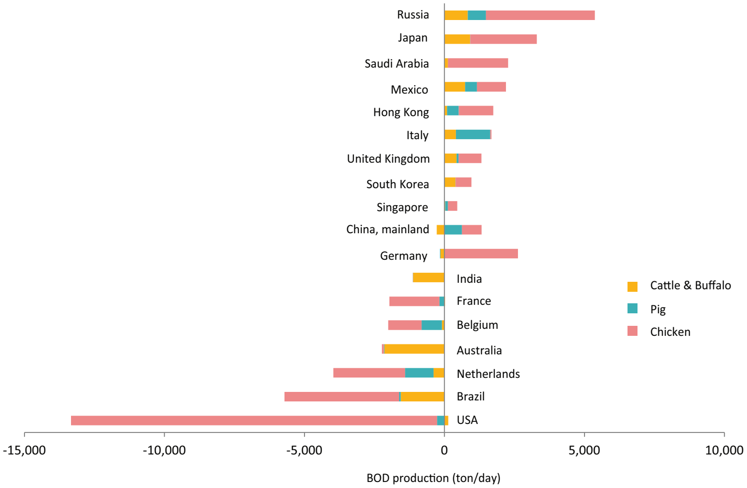


Figure 4.1: Country-based changes in BOD production from intensive livestock farming if all meat consumption were produced locally (no trade). Net importers (exporters) experience an increase (decrease) in BOD production.

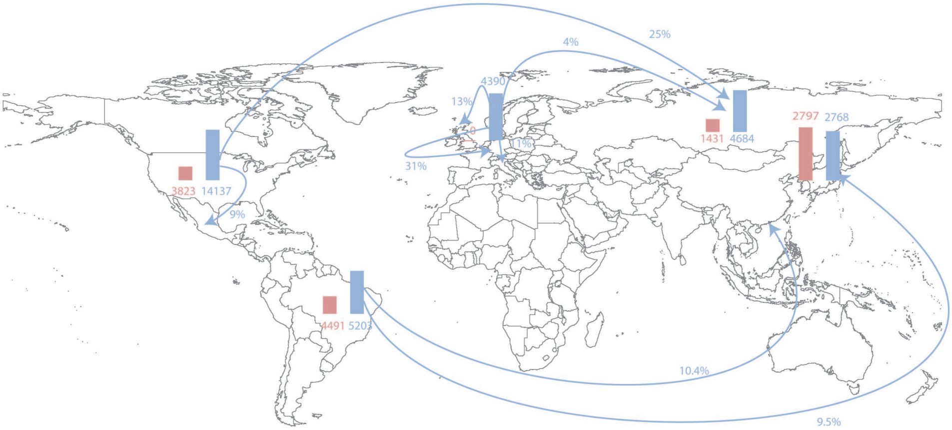


Figure 4.2: BOD production rates (in ton/day) associated with intensive livestock farming in selected countries. Red bars indicate local BOD production rates for meeting domestic meat consumption, while blue bars show virtual BOD production rates associated with meat trade, as indicated by blue arrows (with percentages showing shares of total exports going to different countries).

4.3.2. GLOBAL IMPACT OF MEAT TRADE ON BOD LOADING TO RIVER NETWORKS

Figure 4.3 presents changes in BOD loading from intensive livestock farming into rivers between the trade and no-trade scenarios. These maps highlight the spatial heterogeneity of potential impacts on river systems, resulting from spatial patterns of intensive livestock farming systems (Figs. A.3 and A.4) superimposed on changes in intensive livestock populations when trade is removed. BOD loading typically increases in net importing countries with high proportions of intensive farming, for example Russia, South Korea, Japan and Mexico, resulting in significant growth of livestock populations along major rivers. Major meat exporting countries like Brazil, Argentina, India, Belgium, The Netherlands and Australia show the opposite trend, suggesting potential benefits on river health by terminating meat trade. Changes in the USA, Germany and China are mixed due to their dual roles as both importers and exporters of meat, combined with the uneven distribution of intensive livestock farms in these countries. For the USA, increases in BOD loading dominate in middle and western parts of the nation, home to intensive cattle farms (Figs. A.3 and A.4)[22], which increase their meat and BOD production in the absence of trade, since the USA is a large importer of cattle meat with 16% of global cattle meat trade. As a large exporter of chicken and pig meat, mid-eastern parts of the USA experience a decrease of organic pollution threats in the absence of trade.

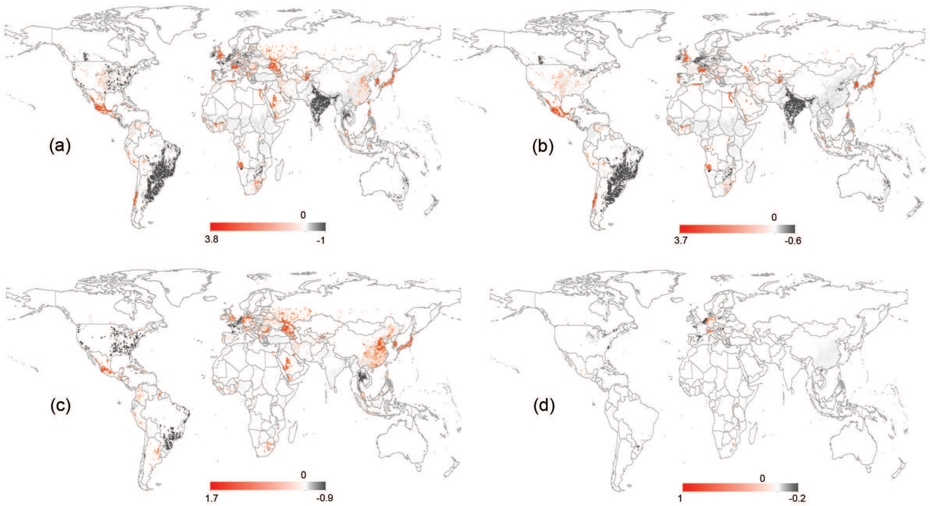


Figure 4.3: Changes in BOD loading to global river networks from intensive livestock farming systems (ton×108/day/grid cell) if all meat consumption were produced locally (no trade). a: accounting for all intensive livestock farming systems; b: intensive cattle and buffalo farms only; c: intensive chicken farms only; d: intensive pig farms only.

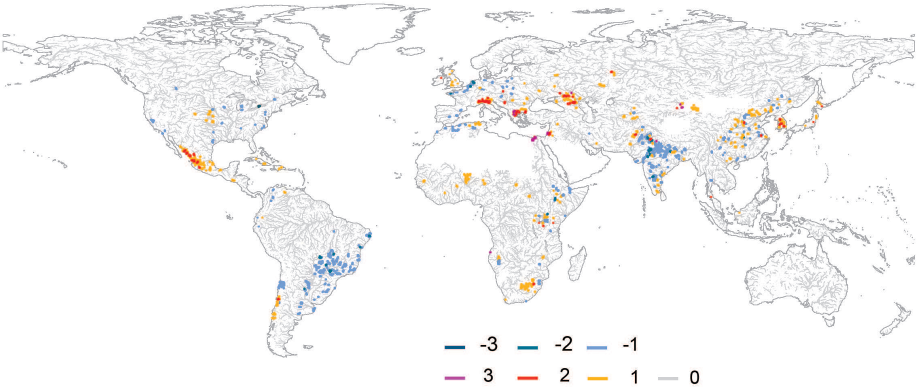


Figure 4.4: Changes in organic river pollution in the absence of meat trade, i.e. when all animals are raised locally in the country where they are consumed. Positive (negative) numbers indicate an increase (decrease) in BOD pollution level on the following categorical scale: BOD < 5 mg/l, 5 < BOD < 10, 10 < BOD < 30, BOD > 30 mg/l. For example, a value of +2 (-2) means pollution levels worsened (improved) by two categories.

4.3.3. GLOBAL IMPACT OF MEAT TRADE ON BOD CONCENTRATIONS TO RIVER NETWORKS

In this section, the actual impact on river BOD concentrations due to trade-induced changes in BOD loading is evaluated. The calculation accounts for upstream-downstream effects as pollutants are transported through the river network with spatially varying degrees of dilution by natural runoff and natural degradation by micro-organisms [102]. Figure 4.4 shows spatial patterns of computed changes in river BOD concentrations when trade is removed and all livestock farming is for local consumption. These changes are largely congruent with corresponding changes in BOD loading from intensive farms (Figure 4.3). Regions with a large increase in BOD loading, e.g. United Kingdom, Italy, Mexico, South Korea and Japan, exhibit remarkable deterioration of water quality, while regions with a decrease in BOD loading, e.g. India, the Netherlands, Brazil and Belgium, experience improvement of river water quality. However, increases in BOD loading do not always translate into more pollution, as is evident for rivers in eastern Australia, New Zealand and the Philippines, where river cleaning capacities, consisting of dilution and natural degradation, are sufficiently high to assimilate increased loading without a significant effect on river BOD concentrations.

Figure 4.5 further highlights the poor correlation (R^2 = 0.019) between local BOD loading and river BOD concentrations, clearly showing the importance of quantifying actual pollution levels as opposed to local pollution loading, by taking into account the intricate spatial patterns of pollutant loading, upstream-downstream transport, dilution and natural degradation along river networks.

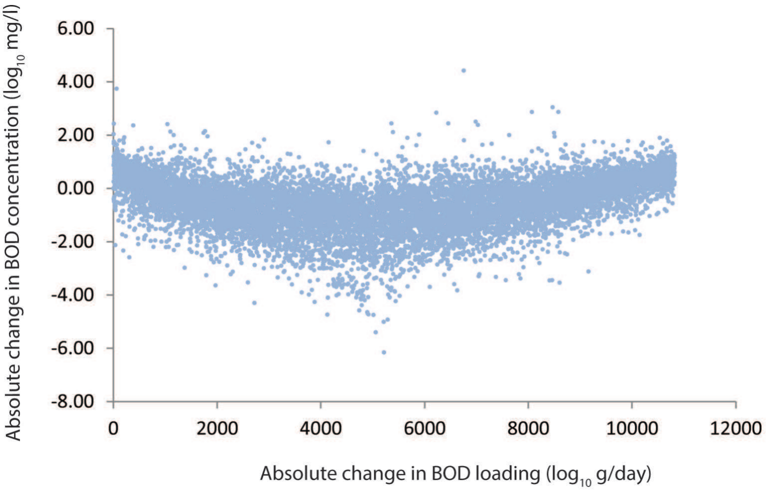


Figure 4.5: Lack of relation between simulated grid-scale change in BOD loading and corresponding simulated change in BOD concentration at the same location. It emphasizes that BOD loading can not be used as a proxy for BOD concentration.

While results in Fig. 4.4 clearly reveal large spatial variation of trade impacts between and within countries, it is also instructive to look at overall global effects of trade. Table 4.2 summarizes various measures at the global scale. First of all, even though total meat consumption is constant between the two scenarios, international meat trade leads to a lower total livestock population and consequently lower total global BOD production, because, on average, yield of meat production (variable Y in Eq. 4.1) in exporting countries is higher than in importing countries [22]. Indeed, intensification of livestock farming is not only characterized by high animal population density, but also greater input of protein-rich and high-energy animal feeds [22]. Non-ruminants, pigs and chicken, have an advantage of making use of feed concentrates to improve livestock growth rates and yields of meat production. The better feed conversion for ruminants, cattle and buffalo, is limited to developed countries with low grain-meat price ratios [100]. Chicken meat exporters like USA and Brazil also produce protein-rich animal feeds, such as cereal and soybean, which results in higher yields of meat production (20% in Brazil and 29% in USA) than their trade partner Russia. Eventually, meat yields may adjust to the new no-trade situation [121], but these subsequent effects are not considered here.

Table 4.2 further shows that actual total BOD loading into major rivers, in both scenarios, is less than half of total BOD production due to wastewater treatment and exclusion of BOD generated far from rivers, with slightly less overall BOD loading due to trade, although the difference with the no-trade scenario is smaller than for BOD production. Interestingly, the effect of trade on actual river pollution and number of affected people is exactly the opposite. Although the differences are relatively small, trade overall results in more pollution relative to no-trade. This again underscores the importance of considering actual impacts rather than changes in pressures.

Table 4.2: Global impacts of meat trade on BOD production, loading to major rivers, polluted river segments and affected human population.

	Trade	No-trade	Change(%)
Intensive cattle & buffalo population (× 10^7head)	4.3	5.1	18
Intensive pig population (× 10^8head)	5.1	5.2	0.4
Intensive chicken population (× 10^{10}head)	1.2	1.3	5.5
Total BOD production from intensive livestock farms (× 10^5 ton/day)	2.4	2.5	3.9
Total BOD loading into major rivers from intensive livestock farms (× 10^5 ton/day)	1.09	1.11	2.5
Polluted river length (km)[1]	115928	110166	-2.3
Population affected by organic pollution (billion)[2]	1.14	1.09	-3.9

[1] sum of all river segments with BOD > 5 mg/l;
[2] sum of all people living in grid cells with polluted river segments.

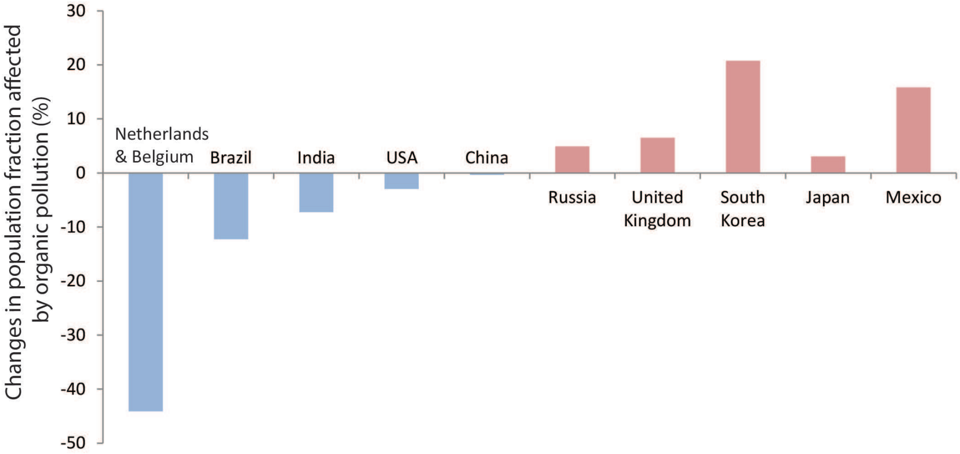


Figure 4.6: Changes in population fractions affected by river organic pollution in major meat trading nations.

Figure 4.6 presents a further breakdown of these results for major meat trading countries. In line with the numbers reported in Fig. 4.1, population fractions affected by polluted rivers increase (decrease) for meat importing (exporting) countries when trade is removed. However, the results in Fig. 4.6 are also affected by spatial distributions of water resources, livestock farms, and urban centres. In the early stages of industrialized contexts, large-scale intensive farms emerge close to cities driven by a series of factors such as expanding labour demands, quicker access to urban demand centres, and availability of food conservation [100]. This proximity of intensive farms to cities in meat exporting regions with insufficient technology, such as southern Brazil and the Ganges river basin in India as shown in Figure 4.4, contributes greatly to river organic pollution and affected populations. When the corresponding livestock animals are raised in importing countries with less population, such as Russia, higher technology, such as Japan, or less intensive farms along rivers, such as Iran, it leads to a reduction of negative impacts [22].

4.3.4. LINKS BETWEEN ECONOMIC DEVELOPMENT AND RIVER POLLUTION

Figure 4.7a presents the computed relation between country-wide average organic river pollution in terms of fraction of polluted river segments and level of economic development in terms of per capita income for the trade and no-trade scenarios. River organic pollution levels with trade (blue line in Figure 4.7a) follow an inverted-U shape with respect to economic growth (income), in line with the hypothesis of the Environmental Kuznets Curve (EKC). The corresponding curves without trade (green line) and without wastewater treatment (red line) are also shown in Figure 4.7a for comparison. Hence, EKC records the combined effects of international trade and technological investment

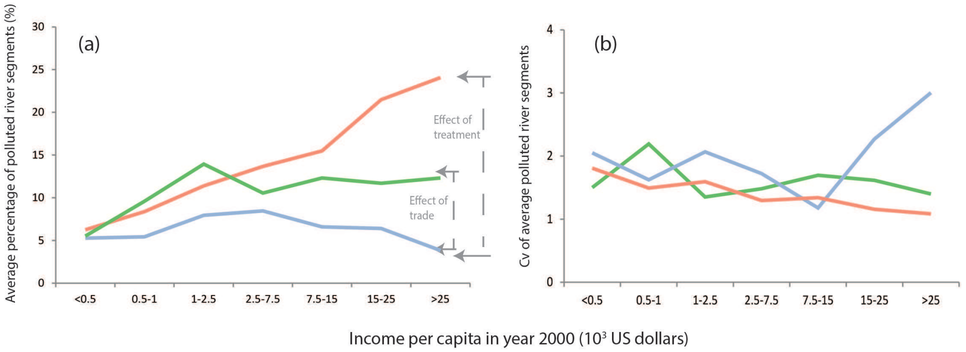


Figure 4.7: Left: Country-wide percentage of polluted river segments (blue: regards trade and wastewater treatment; green: regards treatment only; red: regards trade only) as a function of per capita income in the year 2000 for countries grouped into World Bank income categories [122]; Right: Coefficient of variation of environmental impact within each income category; countries within each category are listed in Supplementary Table A.4.

in wastewater treatment for reducing environmental impacts.

For poor nations, differences between the effects of international meat trade and wastewater treatment are relative small due to low consumption of meat and pollutant loading. Technological investment in wastewater treatment increases as economies grow, hence wastewater treatment has a bigger effect on the EKC than trade in rich countries. Global meat trade also improves environmental impacts in some rich nations via externalization of organic pollution to other economies. However, high standards of food safety and quality in rich nations result in large portions of meat trade between developed countries. For instance, approximately 94% of pig meat imported into the United Kingdom is from Western and Northern Europe [22].

Two important remarks apply to the EKC analysis however. First, despite the fact there are overall fewer polluted river segments in the absence of trade (Table 4.2), the no-trade curve in Fig. 4.7a lies everywhere above the curve with trade. This contradictory result is due to averaging pollution impacts over large and small countries within each income category. Specifically, regions with very limited land and natural resources, such as Singapore and Hong Kong, are unlikely to produce meat efficiently and largely rely on imports [106]. Given limited water resources, growing livestock locally for expanding meat demands in these small polluted countries has a relatively large influence when averaging over countries in each income category. Second, as shown in Fig. 4.7b, variation of pollution impacts within each income category is large, reducing the significance of trade and wastewater treatment effects depicted in Fig. 4.7a.

4.4. DISCUSSION & CONCLUSIONS

This chapter presented a new method for quantifying impacts of international meat trade on river organic pollution based on the global-scale model on in-stream BOD concentrations. This method allows comparison of trade impacts at multiple scales (national, regional and gridded). The approach extends for the first time environmental impacts of international trade to gridded in-stream scale, which takes combined effects of natural degradation and dilution by natural runoff into account. These effects are crucial for evaluating the direct risk humans and river systems would face.

In line with previous environmental assessments of global water and land footprints of international trade in agricultural products [26, 105], it is found that at the global scale trade is beneficial by reducing livestock populations and pollutant loads. The export of meat from a production-yield efficient region to an inefficient region saves BOD production globally. As agricultural intensification, food consumption and international trade is projected to increase globally, this effect will become more significant in the future.

However, in terms of BOD concentrations, the overall extent of downstream impacts become more severe with trade, illustrating the importance of distinguishing between potential impacts of BOD production and loading and actual environmental impacts as BOD concentrations. While pollutants discharge at distinct locations along rivers, impacts extend to downstream populations and ecosystems and depend on self-cleaning capacities of rivers, local hydrological characteristics, and upstream-downstream connections. As a result, it was shown that correlation between computed local BOD loading and in-stream BOD concentrations is poor.

Comparison of impacts by country, by income category or even globally results in loss of spatial information, underscoring the need to account for within-country spatial patterns when quantifying effects of international trade on water quality [23]. Intensive agricultural systems are generally concentrated in areas with good soil and water resources [123], and thus it is important to account for spatially detailed environmental vulnerability in trade analysis, especially in large and heterogeneous countries, such as the United States.

Averaging trade impacts by income category, as done in the EKC analysis, skews the effect of trade on pollution due to the relatively large influence of small countries in EKC analysis. It also hides large variation in pollution impacts within each income category. Still, the EKC analysis helps to distinguish the effects of different economic variables, namely trade and wastewater treatment, in different economic groups, and influences in small countries can be highlighted that are easily neglected on a map. Rich nations tolerate relatively high levels of river organic pollution threats, but mitigate the negative impacts by importing environmentally damaging products and treating symptoms. The resulting contributions to the downward sloping portion of the EKC via these combined effects have previously been shown for energy use, water quality, including BOD, and air quality in developed countries [124, 125]. Environmental externalities do not bring environmental benefits for poor exporting countries. Developed countries move the pollution of intensive livestock farming away from human populations by enhancing environmental regulations, shifting farms further away from populated centers and investing in wastewater control. Such actions rely on substantial financial investments that are not within reach of many developing countries. Current affordable solutions for improving environmental impacts include tying livestock densities to availability of surrounding environment for waste application, i.e. waste reuse [36], improving animal feed-conversion efficiencies [113], and getting compensation from EU importers for raising investment on increasing food safety and farming sanitation in Brazil [126].

As meat consumption continues to increase due to population growth and changes in diet, reducing impacts of intensive livestock farming requires globally aware policies for changing meat consumption patterns. One option to curb the current global trajectory of livestock intensification is to reflect more accurately actual environmental costs into meat prices [106], even, or especially, if these costs are incurred in places far away from consumers. The study provides a new method to estimate shifts in pollution patterns between countries due to changes in consumption habits, trade and environmental policies. Its particular strengths are (i) quantification of actual concentration in addition to potential loading impacts, and (ii) accounting for spatial heterogeneity of processes and impacts. These two key features are believed that should also form the basis of other environmental analyses related to global trade, such as climate change, and changes in water resources and land use.

5

RISING TO THE CHALLENGES

5.1. INTRODUCTION

The global-scale model developed in this thesis provides a framework for quantifying the spatial distribution of river BOD pollution under different threats. Even the conservative approach used here demonstrates that levels of organic river pollution over the next decades are projected to become more widespread. With developing countries disproportionately affected by river pollution, our analysis points to an urgent need for improved sanitation facilities and affordable wastewater control solutions, which largely depend on technological developments and new government initiatives.

Expected increases in population and meat consumption demand more consensus on how to achieve sustainable farming practices by maintaining high food production while minimizing environmental impacts [127]. Increases in efficiency of natural resources use and integrated environmental management are essential. Growing trade in livestock products can improve relative efficiency in countries that specialize in producing food and export to other countries, thereby yielding an overall saving in water and land use [23, 106]. However, results in Chapter 4 reveal negative environmental impact of trade, as quantified by in-stream organic river pollution, which would affect human health directly. Thus, policy instruments and food prices should reflect actual environmental costs, so as to steer consumers towards environmentally sound decisions [36].

Furthermore, results highlight that ongoing and future climate change creates scientific and policy challenges for the sustainability of aquatic health in the next decades. The impacts of climate change on river and human systems depend not only on subsequent changes of climate, such as river discharge or temperature, but also on the vulnerabilities of these systems to a varying climate. Beyond a more comprehensive understanding of the consequences of climate change, taking socio-economic differences into account is crucial for dealing with this complex issue, and for adapting to future changes [128].

This chapter presents a systematic overview of challenges and opportunities for addressing projected deterioration of river ecosystems. First, an influence diagram is constructed to reveal pathways by which potential policies may impact river BOD pollution [129]. Then, based on the influence diagram, the portfolio of available solutions for addressing projected organic river pollution is discussed, with several examples from around the globe. Finally, the Ganges river is considered in more detail as an example to test effects of different wastewater controlling solution for reducing organic river pollution.

5.2. INFLUENCE DIAGRAM MODEL

An influence diagram model for improving organic river pollution is shown in Figure 5.1. The diagram depicts a directed graph that relates decisions or policies (rectangular nodes) to environmental variables (oval nodes) and resulting outcome or utility (di-

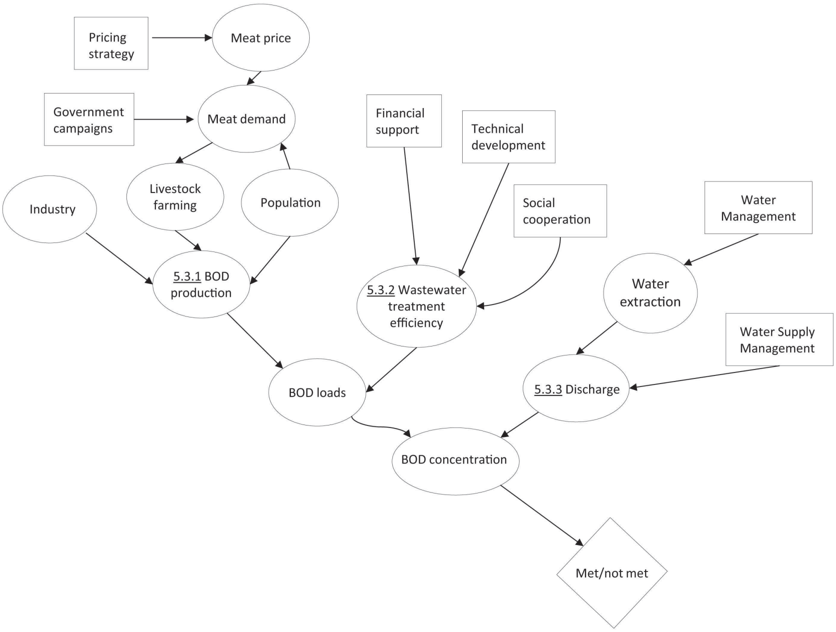


Figure 5.1: Influence diagram model for improving organic river pollution. Oval nodes represent variables, rectangular nodes indicate decisions and the diamond node represents the outcome or utility, in this case the extent to which BOD concentration targets are met.

amond node) in terms of meeting specific target river BOD concentration levels. Instream BOD concentration depends on BOD loads and river discharge. The nodes are described in detail as follows:

BOD loads: BOD loads are impacted by BOD production and wastewater treatment efficiency. Two major point sources of BOD production are livestock farming and human population. Organic pollution from industry was considered as a secondary driver and not included in this thesis. Its local impact may still be important. Meat demand, which is affected by human population and meat price, is an important factor affecting expansion of livestock farming. Given the growing human population, pricing strategies that reflect actual environmental costs and government campaigns which can lead customers to alter their diet habits are two potential strategies. Improving sanitation facilities and waste-removal efficiencies relies on adequate financial support, innovative technical development and suitable social cooperation.

River discharge: a decline in river discharge leads to a decrease of river self-cleaning capacity, which results in deterioration of river water quality. Changes in river discharge result from two major factors: (1) water extraction for socio-economic activities, including domestic use, agricultural practices and manufacturing. Many developing regions are projected to experience large increases in water demand, which points to an urgent need for sustainable water demand management[7]; (2) water flow disturbance. For instance, constructions of dams and reservoirs cause river fragmentation and changes in downstream discharge and affect river self-cleaning capacity along rivers. Thus, water supply management is required to involve dam and reservoir operations to maintain river ecosystems.

5.3. PORTFOLIO OF SOLUTIONS

5.3.1. REDUCTION OF BOD LOADS

HUMAN BOD PRODUCTION

Results in Chapter 3 show that urbanization is the main factor in Africa, India, China and parts of South America. As shown in Figure 5.1, human loads depend not only on population size, but also on average per capita demand of animal products in the diet. World population has tripled since 1950 and is projected to reach 9.6 billion by 2050, with more than 90% of the net growth projected to be in urban areas of developing countries [57]. Although large populations in cities lead to concentrated BOD production, cities may consider implementation of new sustainable development strategies to decrease stress of urban population expansion. For instance, a new urban circular economy (CE) program with 3R principles, which includes reduction, reuse and recycling of human waste/wastewater, was launched in China in 2002, and has been implemented in a number of pilot cities [130]. Like most policy strategies for reducing environmental stresses, the new CE program focuses on technological and composition shifts yet takes future population growth into account. In addition, the uncertainties due to the transition from a ‘one-child’ to ‘two-children’ policy and other demographic changes such as male-female ratios and aging problems should be considered.

Accompanied with increases in human population, economic development, especially the emergence of a middle class in the developing world, results in higher demands for meat. Consumption of meat in China increased from about 55 g/person/day in 1987 to more than 165 g/person/day in 2013 [22]. China consumes 28% of meat in the world, including half of all the pigs. Though meat prices have soared over the last ten years, strong cultural traditions attached to meat diet and growth in the middle class stand in the way of real change in consumer behaviour. Thus, governmental guidance on making environmentally conscious decisions at the consumer level becomes very significant. To meet the goals set out in the Paris agreement, the Chinese government drew up a new dietary guideline in 2016 with a recommended meat consumption between 40g and 75g/person/day, thereby aiming for a 50% reduction in meat consumption by 2030 [131]. The guideline is not only for improving public health, but also for helping the environment. The guideline is not only aimed at improving public health, but also at helping the environment. In order to bolster the government campaign and encourage Chinese people to reduce their meat consumption, the Chinese government solicited the help of Hollywood actor Arnold Schwarzenegger and director James Cameron [132].

LIVESTOCK FARMING

Global food demand from the livestock sector is growing rapidly, and the current trajectory of livestock farm intensification has significant implications for the global environment. Potentially positive consequences of sustainable intensification go beyond increasing yields of products and efficiency of feed inputs. It also encompasses creating financial incentives and improving regulations and management [106]. Beneficial spill-over effects of sustainable intensive livestock farming have been found for reduction of greenhouse emissions and protection of biodiversity [133]. An example is closing N & P cycles by using livestock waste for fertilizing crops, which further can be used as livestock feed. Therefore, sustainable intensification of livestock farming merits a better understanding of the diversity of natural and socio-economic factors involved.

The pathways to sustainable intensive livestock farming are multiple, but existing research suggests that livestock practices must not be managed in isolation [127, 133, 134]. The connection between the livestock sector and other food sectors, as well as ecological systems, implies that an integrated management approach is needed. The pursuit of sustainability and integrated management is firstly based on competent understanding of the interaction between natural resources and livestock farming, and a large body of work on environmental and biological consequences of intensive livestock farming has made some good steps. Quantitative assessments of water availability, including water quality and quantity, land expansion and greenhouse emissions due to intensive livestock farming provide progressively environmental information.

It is also necessary to focus on socio-economic differentiation, because it is critical for establishing convincing cases of sustainable improvement [135]. Analogous to wastewater solutions, any technological evolution, regulation implementation and financial support of sustainable livestock farming development relies on mobilization of financial support and societal resolve. The Netherlands has achieved great success on restraining production of pollutants from intensive livestock farming. The initial proposal of solutions includes a reduction of input of minerals via animal feeds, an incentive to farmers who practise distribution and application of manure, and processing manure on a large scale for exporting [136]. The financial supports come from the government and animal-related commodities. Adoption of sustainable farming practices were supervised by members of research institutes and the feed industry, and the first two solutions have prove to be successful. Processing of manure on a large scale was too expensive to be implemented. Important degradations of organic river pollution due to intensive livestock farming are projected in India, Africa and South America as presented in Figure 3.2(b). Due to public financial limitations in these developing regions, stimulations and solutions applied in the Netherlands require substantial investments from the private sector, which are still widely lacking. To stimulate more investments from private sectors, the value of environmental service must be reflected through reward structures [127].

Potential savings of natural resources and pollution through international trade, including water, land and organic pollutants, are high. Due to the comparative advantages of natural resources and farming practices, it is better to keep exporters exporting. As intensification and growth of livestock farming is driven by the global demand for livestock products, accounting for links between exporters and importers is key to improving environmental outcomes. Success relies on sustainable farming via cooperation between trade partners, pricing approaches and policy synergy.

As discussed above, goals of sustainable livestock farming, especially in poor exporting countries, are difficult to achieve by domestic solutions alone. Turning to corporations and trade partners can help maximize environmental benefits. Besides getting compensation from importers for raising investment on increasing food safety and farming sanitation in exporting countries [126], pollution impacts may also be tackled by setting pricing more accurately reflect environmental and social costs. This is especially important in cases where international trade spatially separates meat consumption from the negative impacts of its production [106]. Such pricing approaches, combined with a focus on raising environmental awareness of consumers, are useful tools for reducing global demand for livestock products and pollution. For example, information on environmental degradation in Brazil due to exporting meat and soybean to China could be included in China's new dietary campaign, which may help to raise public concerns about environmental situations in meat importing countries.

Due to intensification of international trade, international cooperation and agricultural policies, including pricing policies, merit a global coverage and reach. For this extension to be realistic, comprehensive information on specific trade flows between trade partners and socio-economic context must be available [107]. The applicability of agricultural policies must focus on future transformation of environment-trade system, and prepare for potential obstacles in world trade agreements.

5.3.2. IMPROVEMENT OF WASTEWATER TREATMENT EFFICIENCY

FILLING THE FINANCIAL GAP

The stress on BOD production by population and livestock farming also depends on technology used to reduce their loads into rivers. Results in Chapter 3 show that organic river pollution due to inadequate wastewater treatment is projected to threaten at least 26% of global population. Given that projected impacts of organic river pollution are largest in developing regions (Africa, India, Caribbean, South American and China), where advanced urban wastewater treatment is still limited (Fig. A.5), there is an urgent and growing need for affordable sanitation system and wastewater treatment solutions.

The global Millennium Development Goals (MDG) sanitation target of 77% population gaining access to improved sanitation facilities by 2015 has been missed by approximately 700 million people [37]. The slow expansion of sanitation coverage has attracted attention and investment from international development assistance and governments. At the global scale, annual investment in low-cost sanitation is between $11 billion and $20 billion from 2000 to 2015 [137]. However, to achieve universal access to safe drinking water and adequate sanitation by 2030, $114 billion per year is required. People in Africa and Asia would have to spend up to 0.86% of GDP to close the gap [138]. Thus, there is a large need for aligning financial investments from governments and private sectors, with marketing initiatives aimed at poor communities.

Population affected by organic river pollution in the Ganges river is projected to increase from about 220 thousand to 500 thousand in 2050, and growth in urban population along the Ganges river results in the most profound impact, which leads to about approximately 170 thousand increases of affected population, compared to impacts of livestock farming and climate change (Table 3.1). Incomplete sewage and wastewater treatment systems have been notice by India's government, which launched a $3.06 billion programme in 2014 to clean up the Ganges River [139]. Given the large investment, the programme is still largely behind schedule due to the low treatment capacity and inefficient governmental management. Thus, implementation of committed investment should go hand in hand with technical development for controlling pollution and efficient social cooperation.

TECHNICAL INNOVATION

A wide range of sanitation technologies and innovations appropriate for meeting the diverse needs of poor communities, have emerged to minimize costs. Pour-flush latrines, which collect human excreta in a chamber and prevent contamination of surface water, are an example [41]. Beyond separating human excreta and wastewater disposal from human contact, it is also necessary to protect the surrounding neighbourhood and downstream communities from untreated waste and associated adverse health risks [37, 41].

In developed countries, organic river pollution from urban effluents has historically been reduced by a combination of environmental regulation and large-scale wastewater treatment [3]. To make wastewater treatment infrastructures more climate change resilient, a key issue is retrofitting existing infrastructure. For example, New York City has built a comprehensive climate-change adaption system that accounts for climate risks and vulnerabilities, makes existing facilities more robust and educates people about risks [140].

For developing cities, the challenge in the future is how to plan new utilities that take climate change adaptation and urban population growth into account [141]. Moreover, industrial pollution control, sustainable use of water resources and improvement of sanitation in urban slums are required for future urban water management [94]. Compared to nation-wide strategies, water management in cities is more likely to benefit from financial and technical support and comprehensive proactive planning [142]. Investments applied in developed regions are likely not within reach of many developing regions, thus requiring a more decentralized approach [98, 143, 144]. Current efforts in that direction include treating sewage as a resource (e.g. Bill Gates' Omniprocessor for producing water and electricity from human waste [145]) and building planted waterways for cleaning wastewater (e.g. DEWATS constructed wetlands for wastewater treatment [146]).

Approximately 4800 million litres of sewage were collected from more than 100 towns and cities along the Ganges every day. However, only around 20% of these were treated under the National Mission for Clean Ganga (NMCG) programme and the treatment efficiency is still at a low level, resulting in large stretches of contaminated sewage entering the river [139]. Inefficient governmental management has hindered the state administration from constructing new treatment plans. Thus, it is necessary to ensure treatment systems are accompanied by efficient social management.

EFFICIENT SOCIAL COOPERATION

Adequate planning and political mechanisms are key to extending sanitation coverage and increasing effective use of these technologies. The paper by Guiteras et al. [143] shows that subsidizing the cost of installing latrines can increase ownership in Bangladesh, and encourage their unsubsidised neighbours to follow suit. However, generalising these results to other regions, such as neighbouring India, should be done with care. Therefore, a framework is needed for selecting appropriate technologies based on stakeholder consultation, analysis of local resource capacity, requirements of available technologies, and developments of water quality standards and ongoing water quality monitoring.

Mismanagement of the Ganges River clean-up project has led to the decision of personal control by India's prime minister Modi. Victories of his party in state elections have made it easier to launch new clean-up projects in Uttar Pradesh, which includes a stretch of the Ganges. His new chief minister also called for an acceleration of clean-up work at the beginning of 2017. The environmental significance of this political change remains to be seen.

5.3.3. ADJUSTMENT OF HYDROLOGICAL CONDITIONS

WATER DEMAND MANAGEMENT

Increased water use has led to high water stress in a large proportion of the world, especially in emerging countries, such as China and India. Data of river discharge and climate change scenarios used in the calculation of this thesis were taken from outputs of the WaterGAP model. Results of WaterGap show that domestic water use makes the widest contribution (79.9% - 86.4% of global areas) of increasing water resource withdrawals, followed by agricultural and industrial use [147]. Rising domestic water use is expected due to growth of population and income, with the latter stimulating higher per capita water use, especially in urban areas. Through reforming water prices in urban areas since 2002, China has reduced residential water demand up to 5% in the pilot cities [148].

Population growth and longer droughts due to climate change pose dual challenges for water demand management in semiarid and arid regions of Africa, as shown in Figure 2.3 and 2.4. Strategies for influencing water demand implemented in Africa can be grouped into (1) structural measures, for example, implementing cheap rainfall collection systems and reusing rainwater and greywater, and repairing leaks; (2) non-structural measures, such as organizing campaigns for social awareness and education, setting a reasonable water pricing and adequate regulations [149, 150]. The Agricultural Blue Revolution in Africa includes retro-fitting irrigation appliances to increase crop yield per drop of water and has contributed to reducing agricultural water demand.

WATER SUPPLY MANAGEMENT

Precautions for preventing hydrological extremes, such as constructing dams and reservoirs, nowadays tend to be preoccupied with ongoing climate change. Dams and reservoirs change river flow regimes and subsequently hinder conveying adequate environmental flows for sustaining river ecosystems. Re-working dam operating rules to retain economic benefit while protecting aquatic health may help here [151].

Additional pressure in several regions projected reductions in river dilution capacity, which ties pollution control to basin-scale water management [94, 141] and climate adaptation [51, 152]. Making water available for pollution control competes with several other water users and thus a proper balance needs to be found that considers all stakeholders and international cooperation [142]. An example is the Grand Ethiopian Renaissance dam of the blue Nile river, which is designed to generate electricity but is also required to ensure river dilution capacity for downstream countries, namely Egypt and Sudan [153].

5.4. SEEKING SOLUTIONS FOR THE GANGES RIVER

With the third largest discharge in the world, the Ganges is an important lifeline for millions of Indians. Rapid growth of urbanization, population, industrialization and standards of living have resulted in extreme pollution along the river. Raw sewage in urban areas and farming systems, industrial waste, religious offerings and polyethylene are the major pollutants [139, 154]. Cities with large population, including New Delhi, Agra, Kanpur and Varanasi, are located in the upstream part of the Ganges basin as shown in Figure 5.2. The two most productive livestock areas are Uttar Pradesh and Rajasthan [155]. The biggest contributors of industrial pollution on the Ganges are the leather in-

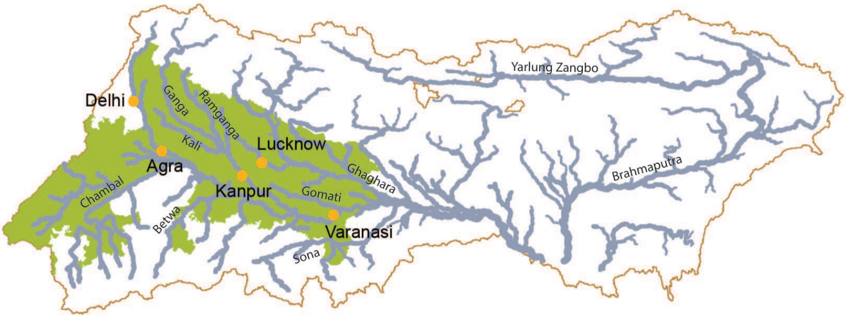


Figure 5.2: Ganges river basin with major tributaries and cities. The green area presents the administrative regions of Uttar Pradesh and Rajsthan.

dustries, following by paper and sugar mills, in the catchments of Ramgana and Kali and Kanpur city [139]. The Indian government launched the NMCG programme in 2016 with the aim of reducing pollution by promoting comprehensive management, and maintaining minimum ecological flows of the Ganges. The programme comprises setting up wastewater treatment plants and a water quality monitoring system, developing public amenities and promoting further scientific research [139].

In this section, based on realistic numbers of the NMCG program and technological limitations, 4 scenarios will be built to test effects of different wastewater control solutions on reducing organic pollution in the Ganges river by the year 2050. The good correspondence between model results in the Ganges river in 2000 and observed river BOD concentrations (98% match across BOD concentration categories), as shown in Figure 2.7, justifies use of the model for evaluating and comparing various pollution reduction scenarios.

- Scenario 1: Percentages of connection to wastewater treatment facilities remain the same, while wastewater treatment efficiency increases to the highest level (99%) in all existing treatment infrastructures, including intensive livestock farms.
- Scenario 2: In addition to measures implemented in Scenario 1, municipal wastewater treatment connection is tripled in all cities. This scenario is based on a planned increase in the NMCG program of average wastewater treatment capacity from about 20% to approximately 60%.
- Scenario 3: In addition to measures implemented in Scenario 2, wastewater treatment connection of intensive livestock farms is tripled.
- Scenario 4: In addition to measures implemented in Scenario 3, the number of buffalo cattle in the Ganges river basin is halved. This scenario assumes that beef

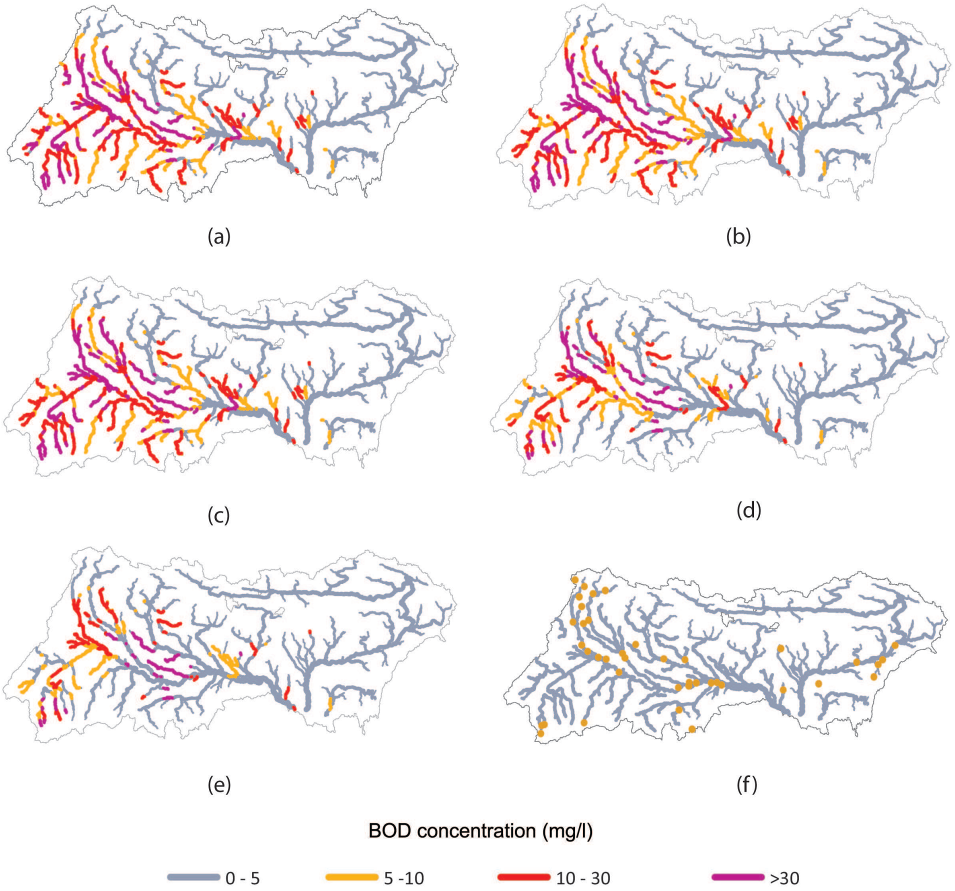


Figure 5.3: Simulated BOD concentrations for different pollution reduction measures. (a) calculated BOD concentrations in 2050 without implementing any measures; (b)-(e): simulated BOD concentrations for scenarios 1 to 4 in 2050; (f): river water quality observed stations in the Ganges basin.

production yield in India increases from about 0.1 ton per animal to 0.2 ton per animal, with the latter close to the average value in Brazil and Europe.

The model was rerun for each of these scenarios. The resulting computed river BOD concentrations are shown in Figure 5.3. Increasing wastewater treatment efficiency and tripling municipal wastewater treatment capacity have little effect on organic pollution in the Ganges river. However, increasing wastewater treatment connection in livestock farms is projected to reduce more than half of polluted river segments, i.e. a decrease from 35.7% to 19.8% polluted river segments is calculated. Increasing meat production yield, which would maintain current meat production but reduce livestock numbers in the river basin, also significantly contributes to controlling organic pollution. These results again highlight the significant role of intensive livestock farming as a major source of organic pollution in the Ganges river. Deterioration of river water quality is most efficiently controlled by increasing wastewater treatment capacity for livestock farms and enhancing feed efficiency and meat production yield.

It is worth noting that even after implementing all measures, water pollution still remains at high levels in some river segments of the western Ganges basin. It notes that the model may underestimate the real pollution because (1) industrial wastewater, for example the industrial pollution in the Ramgana and Kali catchments and Kanpur city, (2) human and animal remains, such as high pollution levels on the river segment near the Varanasi city, and (3) other sources of organic wastes, such as organic trash and open bathing in the river. These important factors were not included in the model and require spatially detailed information for further testing.

Thus, even more comprehensive measures are needed to clean up the Ganges river. Translating these hypotheses into plans and actions and developing best solutions for different catchments require (1) a more detailed modelling effort, targeted specifically at the Ganges basin, using greater spatial resolution and including additional sources of pollution (e.g. industry), and (2) further development of the river water quality monitoring system. As shown in Figure 5.3(f), there is still need to increase coverage of river water quality monitoring over a significant number of polluted river segments.

5.5. CONCLUSION

In this chapter, challenges and opportunities for addressing projected deterioration of organic river pollution were reviewed. The key is to control and limit BOD loads into river networks, combined with appropriate water demand and supply management to maintain and increase river dilution capacities. A portfolio of solutions applied in China, India and other regions for addressing projected river pollution was discussed, pointing to the need for financial incentives, integrated interventions across multiple sectors, and involvement of public, communities and national governments. A case study in the Ganges river highlights that reducing pollutant loads from intensive livestock farming should be the an important focus of the Indian government in its efforts of cleaning up the river. A comprehensive measure comprising different factors, and a complete river water quality monitoring system are needed for the NMCG programme.

In short, coordinated efforts are needed that combine innovative and affordable wastewater treatment with integrated water management, targeted economic policies, and consumer education. Spatially explicit evaluation of the full range of options holds great promise in addressing impacts of global organic river pollution.

6

CONCLUSIONS

6.1. MAIN CONTRIBUTIONS OF THIS THESIS

The importance and the challenges of modelling impacts of human activities and climate change on global organic river pollution have been presented in the first chapter, in the context of fragmented monitoring data on global river water quality, heterogeneous hydrological conditions and socio-economic situations, and variability of climate change. The main contribution of this thesis is that, for the first time, a global scale model was developed for quantifying global anthropogenic impacts on river organic pollution (quantified by in-stream BOD) due to multiple factors, including:

1. wastewater discharge from urban areas due to the global sanitation crisis and intensive livestock farms;

2. reductions in river self-cleaning capacity due to human water extractions and global warming;

3. pollution externalities due to trade of livestock products;

4. uneven development of wastewater technology and economy.

Through modelling organic river pollution, a quantitative understanding of essential effects of these factors and a generic framework for estimating other substances of river water pollution were provided.

6.1.1. GLOBAL-SCALE MODELLING OF ORGANIC RIVER POLLUTION

The conceptual and quantitative modelling strategy was introduced in Chapter 2, with detailed information on model inputs. The model calculates in-stream BOD concentrations along global river networks. In contrast to previous global-scale studies of river organic pollution, the model innovates in three particular aspects. Firstly, in-stream natural purification capacity was taken into account, including spatial heterogeneity in hydrological and biological processes. Secondly, organic pollutants from intensive livestock farms, which are a significant contributor to river pollution, were included. Thirdly, scenarios were developed to assess potential changes in river water quality in the coming future. Other important contributions are (1) assemblage of a unique dataset of measured river BOD concentrations by merging existing global, national and regional datasets, and (2) greater realism in representing the spatial distribution of wastewater treatment by using downscaled wastewater treatment data for countries with large socio-economic heterogeneity, such as China, India and Brazil.

A comparison of computed results for year 2000 to observations from global, continental, and national river BOD datasets showed reliability of the model for predicting global spatial patterns of in-stream BOD concentrations in terms of broad BOD concentration categories. Using multiple scenarios of climate change and urban population growth, the projected changes in in-stream BOD concentrations was simulated for the year 2050. The projections serve to highlight potential hotspots of river water quality deterioration.

Globally, results in Chapter 3 indicate that the number of people affected by organic river pollution is projected to increase from 1.1 billion in 2000 to 2.5 billion in 2050. The most significant impact will be in developing countries, including regions of Africa, India, China, Caribbean and South America. People in mega cities in developed countries are also projected to face deterioration of river water quality. Given the projected impacts and uneven conditions of financial resources, there is an urgent need for appropriate wastewater control solutions.

6.1.2. IMPACTS OF INTERNATIONAL MEAT TRADE ON ORGANIC RIVER POLLUTION

Global demand for meat is growing rapidly, and environmental impacts of meat production are externalized via international trade. Trade can either improve or worsen river water quality, depending on whether moving production to other countries generates less or more pollution than domestic production. Following this idea, in Chapter 4, a new method was presented for quantifying impacts of international meat trade on organic river pollution at multiple scales (national, regional and gridded), by computing spatially distributed organic pollution in global river networks with and without meat trade, where the without-trade scenario assumes that meat imports are replaced by local production. A particular strength of this method compared to previous approaches is that it accounts for spatially distributed hydrological conditions.

Comparison of the with and without-trade scenarios revealed a reduction of livestock population and organic pollutant production at the global scale due to international meat trade. However, the actual environmental impact of trade, as quantified by in-stream BOD concentrations, was negative with trade resulting in an increase in polluted river segments. It illustrates the significance of accounting for self-cleaning capacities of rivers and basin hydrological characteristics when estimating the actual impacts of trade on the environment. These effects are significant for evaluating the real risk humans would face due to changes in trade and climate.

Averaging impacts of wastewater treatment and trade by income category, as done in the EKC analysis in Chapter 3 and 4, hides large variation and skews the effect of trade due to the relatively large influence of small countries. However, the EKC records the combined effects of technological investment in wastewater treatment and international trade for decreasing environmental pollution, and highlights the necessity of accounting for socio-economic differences when developing water management options in different regions. The need for financial commitments to bring about technological innovations remains urgent. Comprehensive scenarios of changes in technology, demography, economy and culture are required for making appropriate political decisions over the long term.

6.1.3. LOOKING FOR SOLUTIONS

Given the escalating deterioration of river water quality, a systematic overview of challenges and opportunities for addressing projected deterioration of river ecosystems was presented in Chapter 5. A portfolio of available solutions, including reduction of BOD production, improvement of wastewater treatment efficiency and adjustment of hydrological conditions, were discussed, pointing to the need for financial incentives, integrated interventions across multiple sectors, and involvement of public, communities and national governments.

Due to the variability of climate change, solutions must be designed and operated keeping other impacts of global warming in mind, such as alteration of natural flow regimes for preventing flooding and drought episodes. The more widespread impacts of intensive livestock farming and international trade further highlight the truly global nature of pollution, which requires international cooperation and sustainable evolution of agricultural policies.

A case study in the Ganges river shows that increasing wastewater treatment connection in livestock farms significantly contributes to cleaning organic pollution. In addition, increasing meat production yield also has a significant effect on controlling organic pollution. However, other factors that affect organic pollution in the Ganges river, including industrial wastewater, human and animal bodies and other sources of organic waste, were not accounted for in the model but could be included in a more detailed regional-scale analysis. In any case, current model results highlight the need for significant efforts and a better river water quality monitoring system for implementing political plans and actions.

6.2. FUTURE RESEARCH AND RECOMMENDATIONS

6.2.1. ON GLOBAL-SCALE MODELLING OF ORGANIC RIVER POLLUTION

Although the model in this thesis provides a crucial step toward the global-scale spatial study of organic river pollution, work remains to be done to improve the approach.

The first urgent task is adding industrial organic pollutant sources to the model. This highly depends on the development of global spatially distributed maps of industrial activities with explicit information on industrial properties, ranges of activities and wastewater treatment. Currently, no such global datasets exist. In the absence of such datasets, model improvement should focus on areas where the model underestimated observed concentrations and where industry is expected to be an important contributor. Several of these regions were identified in Chapter 2. Moreover, data on rural domestic sources and interception and diversion of pollution flows could be added where available.

The model focuses on evaluating long-term average conditions, however, seasonal or shorter-term effects on organic pollution should be accounted for in future studies, in particular, on projected consequences of climate change and potential changes in hydrological extremes and their effect on river pollution.

The model is also based on a constant BOD degradation rate at the global scale. However, in reality the rate may change spatially with river hydraulic conditions and with secondary effects of organic pollution such as eutrophication. A possible model extension is to include these effects, in particular for river networks containing dams and reservoirs.

In the absence of systematic data on wastewater treatment fractions and efficiency, data at country or regional level (and a few at city level) were applied in the model. Moreover, pollutants from domestic, farming and other systems were assumed to be collected and discharged separately, which is not common in all places. Good correspondence between simulated and observed concentrations suggests that the model accounts for the most important sources of BOD. However, additional BOD loads from industrial sources and urban runoff, may alter the existing results. Thus, spatially detailed information on wastewater treatment is needed for further testing and improving confidence in the model.

The model can serve as a better tool for global analysis of river water quality, after the improvements mentioned above will further increase the model's usefulness for pointing out potential hotspots of river pollution and monitoring the success of water management. Uniting the current analysis with global assessments of other pollutants will provide a more complete picture of global river health and improve natural resources management.

6.2.2. ON IMPACTS OF INTERNATIONAL TRADE

The analysis of impacts of international meat trade can be extended in several directions. First, while the range of traded meat products is quite diverse, the current study in the thesis only takes singular raw meat into account. An obvious extension is to include other meat products as well, which may alter the magnitude and pattern of in-stream river pollution. Adding other livestock products from intensive systems, such as egg and milk, may also influence results in some countries. Second, the analysis focused on pollution produced by live animals, thereby neglecting pollution produced during feed production and during processing of meat into final products. As mentioned in the previous subsection, such an analysis requires global datasets of livestock manufacturing and production. Previous studies based on GWF on the other hand focus on nitrogen and phosphorous emissions from fertilizers used for growing crops during the feed production stage, yet neglect impacts during the live animal stage. A more complete pollution picture may emerge by combining these impacts and including total pollution impacts from all production stages. It is worth noting that fertilizer pollutants end up in aquatic systems as non-point source pollution with loading dependent on seasonally varying runoff. Pollution during the live animal stage on the other hand enters into rivers as point sources and the corresponding loading depends more on technological investment rather than seasonal runoff. A third extension would be to consider also pollution of coastal waters and of groundwater, thereby including impacts in countries that play significant roles in international meat trade but that have limited surface water resources, like Saudi Arabia. Fourth, since countries with very limited land areas and large population play significant roles in global trade, locally higher resolution spatial approaches may be required to capture all impacts.

6.2.3. ON SEEKING FOR SOLUTIONS

The current examples in China, India and other regions point out the need for technological investment, financial incentives, government campaigns and international corporation. By adjusting any incentives that improve organic river pollution, the model in this thesis can be used for comparing and evaluating efficiency of different strategies and emerging challenges. However, the success of resolving negative impacts requires spatially explicit evaluation of hydrological, technological and cultural heterogeneities in relevant river basins, and comprehensive understanding of uncertainties of climate change and human activities, such as the ’two-children’ policy in China and changes in trade policy.

It is also important to include results from other examples including results from social science on educating people to alter their living habits in the NMCG programme, and on reducing meat consumption by the Chinese government campaign. The success or failure of these experiments will affect feasibility of potential solutions.

A

APPENDIX

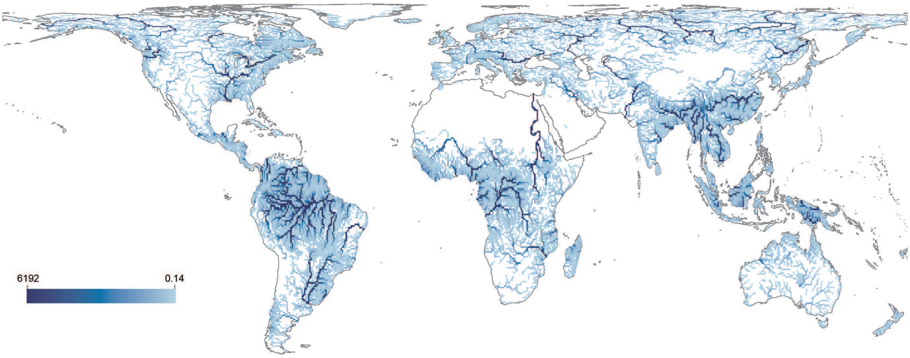


Figure A.1: Average river discharge in 2000 (km^3/yr), using data from [54].

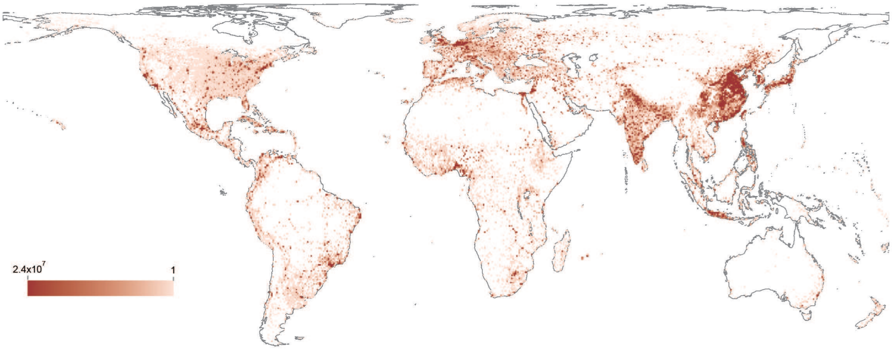
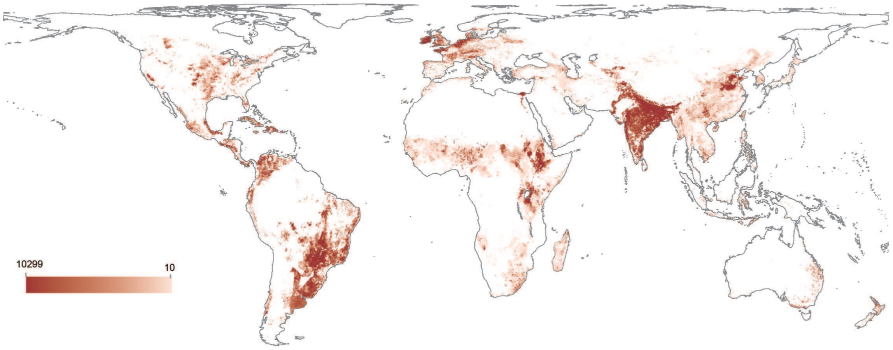


Figure A.2: Urban population in 2000 (people per grid cell), using data from [57, 58].

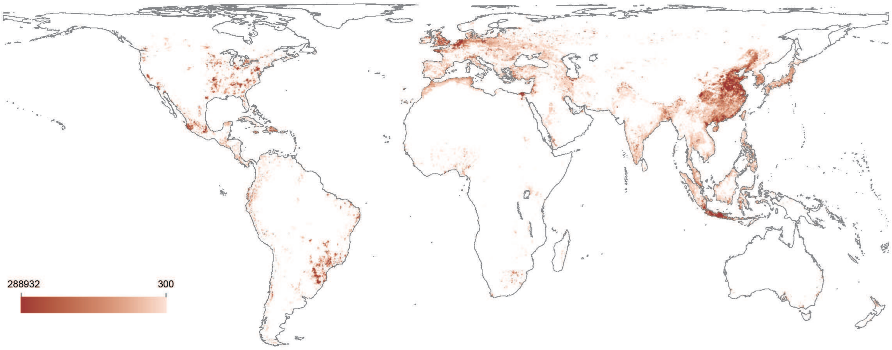
Global distribution of intensive buffalo production systems in year 2000 (stock/km^2)



Global distribution of intensive cattle production systems in year 2000 (stock/km^2)

Figure A.3: Global distribution of intensive buffalo and cattle production systems in 2000 (stock/km^2), using data from [59].

Global distribution of intensive pig production systems in year 2000 (stock/km^2)



Global distribution of intensive poultry production systems in year 2000 (stock/km^2)

Figure A.4: Global distribution of intensive pig and poultry production systems in 2000 (stock/km^2), using data from [59].

Table A.1: Urban wastewater treatment in India in the year 1999 (based on [66]).

	Metropolitan cities	Class I cities	Class II cities	Other cities
Population threshold	≥1,000,000	100,000-999,999	50,000-99,999	<50,000
% Total wastewater treatment	41	25	11	9
% Primary wastewater treatment	50	25	29	19
% Secondary wastewater treatment	50	75	71	38

Table A.2: Ratios of wastewater treated to generated in urban and township areas in China in the year 2000 [67].

	Urban	Town
National	28.6	7
East	55	7.7
West	25.8	4.5

Table A.3: Urban wastewater treatment in Brazil in the year 2000 [61, 156, 157].

	Class I	Class II	Class III	Class VI	Class V
Population threshold	> 300,000	100,000-300,000	45,000-100,000	20,000-45,000	<20,000
% Total sewerage service	49	36	28	20	17
% Sewerage treated	48	28	36	18	18

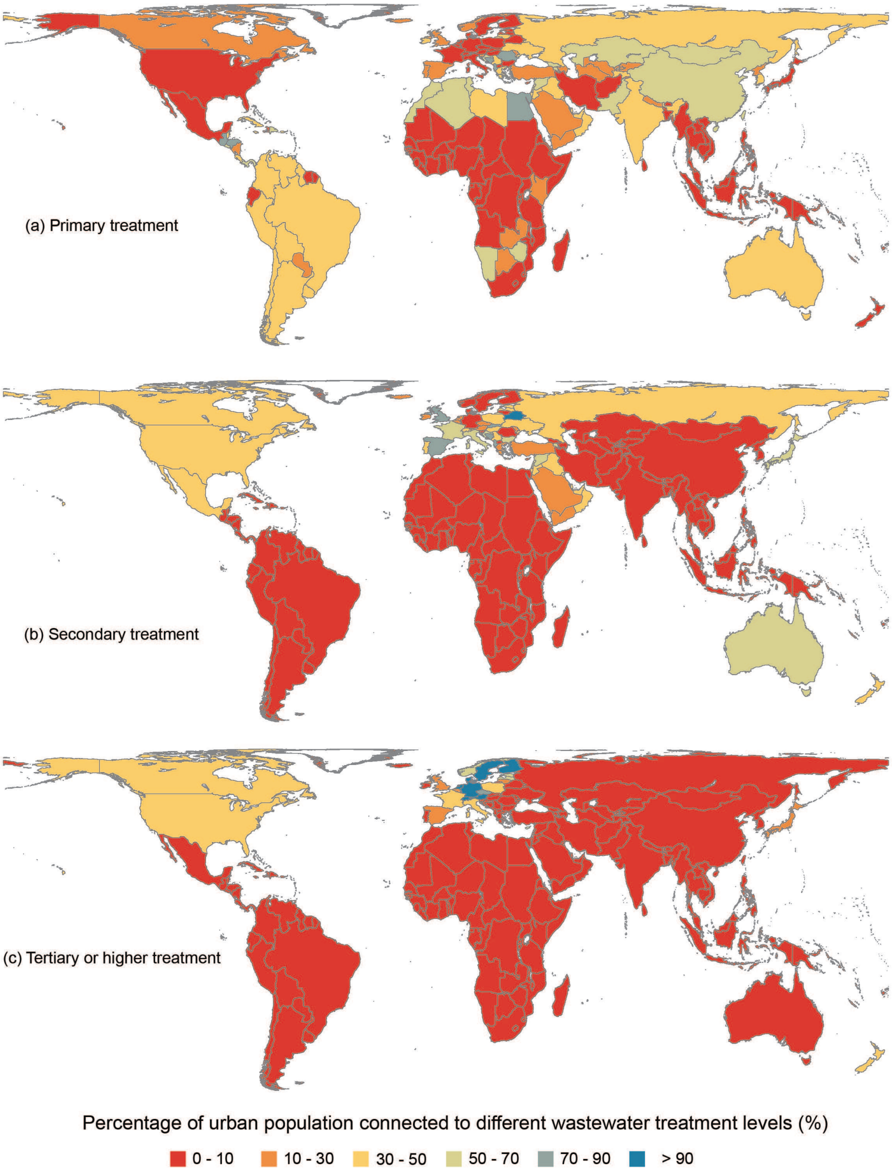


Figure A.5: Percentage of urban population connected to different wastewater treatment levels (%), using data from [27, 61]. Secondary treatment includes primary treatment, while tertiary or higher treatment includes primary and secondary treatment.

Table A.4: List of countries or regions with different income ranges in year 2000 [122].

Income per capita (at constant 2005 prices, US dollar)	Countries or regions
< 500	Congo, Democratic Republic, Burundi, Ethiopia, Myanmar,Niger, Guinea-Bissau, Tajikistan, Afghanistan, Liberia, Eritrea, Chad, Rwanda, Sierra Leone, Burkina Faso, Mozambique, Nepal, Madagascar, Mali, Cambodia, Central African Republic, Togo, Kyrgyz Republic, Somalia, Malawi, Lao People's Democratic Republic, Uganda, Zambia, Republic of Moldova, Benin, Guinea, Sudan, Vietnam, United Rep. of Tanzania, Haiti, Bangladesh, Ghana, India, Kenya, Korea, Dem. People's Rep. of, Mongolia, Senegal, Mauritania
500 - 1000	Angola, Pakistan, Uzbekistan, Cameroon, Nigeria, Yemen, Zimbabwe, Gambia, Armenia, Papua New Guinea, Ivory Coast, Azerbaijan, Ukraine, Lesotho, Georgia, Iraq, Indonesia, Congo, Bhutan, Serbia and Montenegro, Sri Lanka, China, Nicaragua, Bolivia
1000 - 2500	Turkmenistan, Belarus, Honduras, Albania, Syrian Arab Republic, Kazakhstan, Philippines, Morocco (includes Western Sahara), Paraguay, Ecuador, Egypt, Guyana, Swaziland, Occupied Palestinian Territory, Guatemala, Equatorial Guinea, Iran, Bulgaria, Bosnia-Herzegovina, Algeria, Romania, Russia, Jordan, Macedonia, Peru, Thailand, Namibia, Fiji, Tunisia, El Salvador, Suriname, Colombia
2500 - 7500	Dominican Republic, Cuba, Botswana, South Africa, Belize, Lithuania, Panama, Brazil, Costa Rica, Slovakia, Malaysia, Gabon, Estonia, Latvia, Turkey, Hungary, Poland, Croatia, Venezuela, Chile, Lebanon, Czech Republic, Mexico, Uruguay
7500 - 15000	Oman, Argentina, Slovenia, Portugal, Greece, Korea, New Zealand, Spain
15000 - 25000	Brunei Darussalam, Italy, Israel, Australia, Taiwan, Ireland, France, Germany, Kuwait, Canada, Belgium, Singapore, Finland, Austria
> 25000	Hong Kong, United Kingdom, Netherlands, Sweden, Denmark, Iceland, Luxembourg, United States of America, Norway, Japan, Switzerland

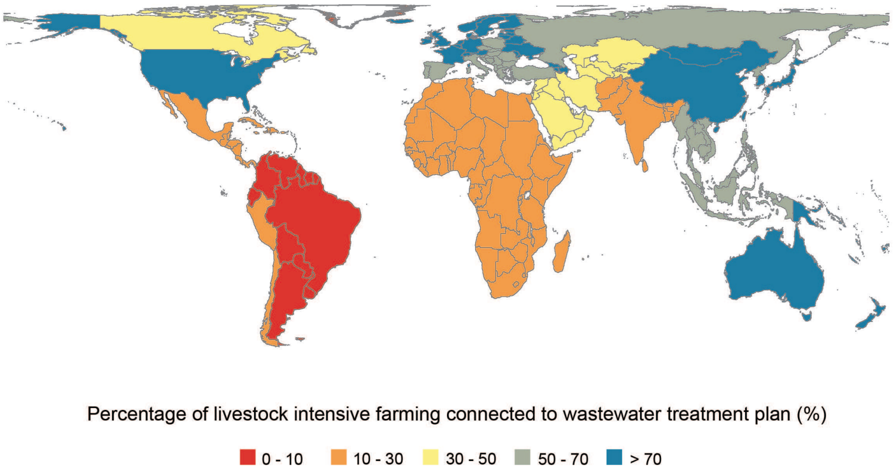


Figure A.6: Percentage of intensive livestock farming subject to wastewater treatment (%), using data from [63].

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